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Special Issue Reprint

Agricultural Land Use and Rural Development

Edited by
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This is a reprint of articles from the Special Issue published online in the open access journal *Land* (ISSN 2073-445X) (available at: https://www.mdpi.com/journal/land/special_issues/Z5B8D5I239).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-7258-0577-8 (Hbk)
ISBN 978-3-7258-0578-5 (PDF)
doi.org/10.3390/books978-3-7258-0578-5

Contents

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Article

Analysis of the Spatial–Temporal Pattern of the Newly Increased Cultivated Land and Its Vulnerability in Northeast China

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Abstract: Ensuring compliance with China's "1.8 billion mu" (120 million hectares) cultivated land preservation policy is a fundamental goal of land policy. Northeast China has experienced significant cultivated land expansion due to rigorous compensation policies over the past two decades, resulting in sustainable increases in grain output. This research employs remote sensing data to examine the spatial–temporal pattern and vulnerability of newly increased cultivated land expansion in Northeast China and its potential impact on food security. Results indicate a 3.08% increase in newly increased cultivated land from 2000 to 2020, with the majority located in the Sanjiang Plain's humid area and Inner Mongolia's arid and semi-arid regions. The low quality of newly added cultivated land makes it highly vulnerable. Temperature instability significantly and negatively correlates with cultivated land expansion. The vulnerability of cultivated land is negatively and significantly related to grain yield, suggesting an adverse impact on national food security. This study focuses on the marginal impact of newly increased cultivated land and proposes policy recommendations.

Keywords: newly increased cultivated land; spatial–temporal pattern; cultivated land vulnerability; food security

Citation: Du, G.; Wang, X.; Wang, J.; Liu, Y.; Zhang, H. Analysis of the Spatial–Temporal Pattern of the Newly Increased Cultivated Land and Its Vulnerability in Northeast China. *Land* **2023**, *12*, 796. https://doi.org/10.3390/land12040796

Academic Editor: Luca Salvati

Received: 8 March 2023
Revised: 26 March 2023
Accepted: 29 March 2023
Published: 31 March 2023

1. Introduction

In response to the growing global population and the desire for an improved quality of life, cultivated land has been expanded and intensified worldwide [1]. China, with only 10% of the world's cultivated land, feeds approximately 22% of the global population. To enhance its food production capacity, the Chinese government has implemented several policies aimed at preserving cultivated land [2,3]. Although these policies have helped to stabilize the overall quantity of cultivated land in China, significant regional differences persist [4]. China's northeast region is a significant contributor to the country's primary grain production area, with its cultivated land experiencing growth in recent years.

Northeast China is a significant region for grain production, with its output accounting for a quarter of China's total grain output, which can support approximately 100 million people. However, the pressure on grain support in this region has increased due to the continual reduction of cultivated land along the southeast coast in recent years [5,6]. To guarantee national food security, the Chinese government has introduced measures to enhance grain production in Northeast China. In 2021, the Chinese government made black soil preservation a national strategy for the northeast region and passed the Black Land Protection Law of the People's Republic of China in 2022 to safeguard cultivated land and ensure food security. The Chinese government has directed its focus towards Northeast China to ensure national food security, with Heilongjiang, Jilin, and Liaoning provinces outlining detailed plans for grain production. Thus, it is crucial to examine the temporal and spatial dynamics of cultivated land expansion in Northeast China and its potential effects on food security.

Since China's reform and opening (1978–present), China's cultivated land resources have been scarce [7–9]. Academic scholars have conducted a systematic investigation into the spatial–temporal patterns [10], fluctuations in quantity, and influential factors related to the dynamic changes to cultivated land resources [11–13]. Earlier research has identified that the evolutionary trajectory of the spatial–temporal patterns of cultivated land holds significant implications for the effective utilization and allocation of cultivated land resources [10,14], as well as food production, while also interacting with policies aimed at facilitating sustainable development at the regional level [15]. Some studies have investigated how the spatial pattern of cultivated land changes in response to various factors such as climatic conditions, technological advancements, and policy institutions [16,17]. Climate warming can alter the temperature and precipitation conditions required for crop growth, shifting the planting boundary northward and necessitating adjustments to the crop planting structure [18]. Technological advancements have also played a significant role in changing the mode of production from manual labor to mechanization, leading to crop variety optimization and the overcoming of obstacle factors [19,20] Additionally, changes in policy systems have influenced the adjustment of agricultural structure and facilitated the dynamic balance of total cultivated land [21].

Limited research has been conducted to investigate the spatiotemporal dynamics of newly added cultivated land in Northeast China. Notably, certain regions in Northeast China exhibit concentrated fluctuations in cultivated land and conversions between dryland and paddy fields, which have been investigated in prior studies [18,22]. Limited research has been conducted on the vulnerability of recently added cultivated land, with most studies focusing on the overall vulnerability of a given region. To investigate the spatial–temporal pattern of cultivated land, scholars have primarily utilized methods such as the land use transfer matrix (LUTM) [23], remote sensing analysis and simulation [24], and GIS spatial statistics [14,25]. In the realm of geographic research, the SRP (ecological stress, sensitivity, and response) and PSR (stress-state-response) models have been commonly employed to investigate ecological vulnerability. This approach has been utilized by scholars such as Manfré in their studies [26]. Few studies have focused on the spatial–temporal pattern, quality characteristics, and dynamics of newly increased cultivated land and their impact on food security in Northeast China. The research hotspots have been concentrated in the Huang-Huai-Hai Plain [12,27]. This paper analyzes the spatial and temporal pattern and vulnerability of newly increased cultivated land, and its possible impact on grain production in Northeast China during 2000–2020 based on previous studies.

This paper employed remote sensing, temperature and precipitation, and socio-economic data from 2000 to 2020 to construct a cultivated land model to reveal the spatial–temporal pattern of cultivated land change and analyze the marginal effect of newly increased cultivated land and its impact on food security in Northeast China. The paper comprises three sections: revealing the spatial–temporal pattern of cultivated land from 2000 to 2020, constructing a cultivated land vulnerability evaluation system to assess the vulnerability of newly increased cultivated land, and constructing an effect model to analyze the impact of dynamic changes in newly increased cultivated land on grain yield. The study explores the marginal effect and proposes specific measures for ensuring national food security and protecting black land. At the same time, it provides a new way of thinking for the evaluation of cultivated land comprehensive quality, considering the marginal effect of cultivated land in the evaluation of cultivated land comprehensive quality, improving the cultivated land quality evaluation system.

2. Materials and Methods

2.1. Study Area

Northeast China (115–135° E, 38–56° N) includes Liaoning Province, Jilin Province, Heilongjiang Province, and Chifeng, and Tongliao, Xing'an Meng, and Hulunbuir in the eastern part of the Inner Mongolia Autonomous Region (Figure 1). The topography of Northeast China [28] is semi-annular and triple-banded, with the Daxinganling Mountains to the west, the Xiaoxinganling Mountains to the northwest, and the Changbai Mountains to the east, and the vast northeastern plains within the mountainous hills. Northeast China has fertile and loose black soil, high organic matter content, and an excellent stratified structure, which is ideal for agricultural production. Northeast China is the most extensive commercial grain base in China and is of great importance to ensuring China's food security. Its grain production was 17,346.88 tons in 2020, accounting for 25.91% of the total national grain production, and about 1/3 of the grain is transferred out.

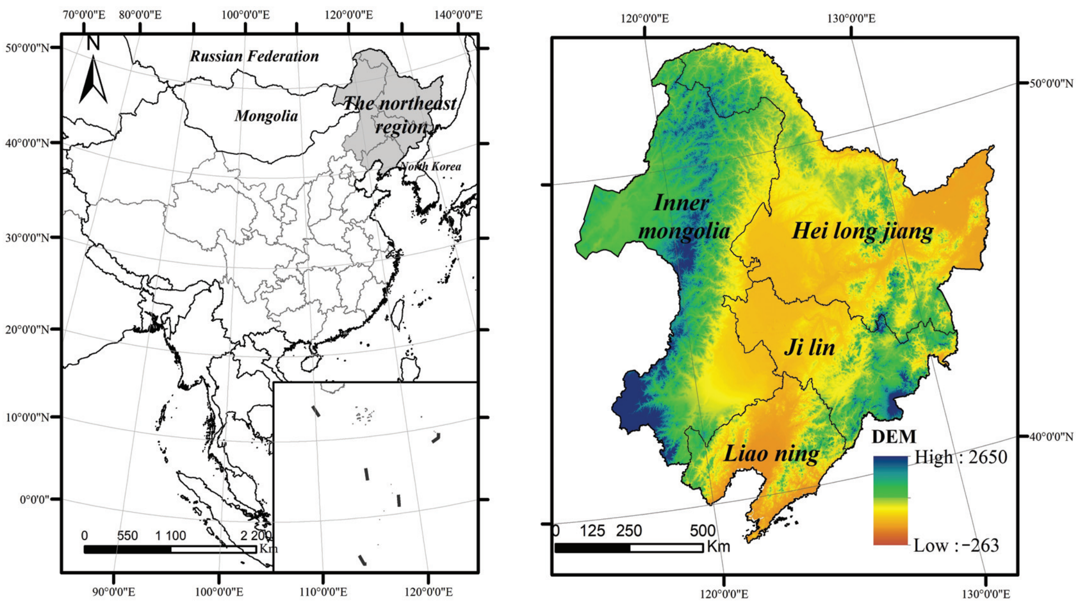

Figure 1. The overview of the study area.

2.2. Data Source and Preprocessing

The data used in this study include cultivated land data, climate data, soil erosion data, and cultivated land quality data. Cultivated land data were from the remote sensing interpretation of land use in the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/Datalist1.aspx, accessed on 6 May 2022), which includes 6 categories and 25 subcategories, of which cultivated land is divided into two subcategories, dryland and paddy land (Table 1). Monthly average precipitation and temperature data from 2000 to 2020 were obtained from the China 1 km monthly precipitation and temperature dataset of the National Tibetan Plateau Science Data Center (http://data.tpdc.ac.cn/zh-hans/, accessed on 6 May 2022). Soil erosion data were derived from spatial raster data in the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/Datalist1.aspx, accessed on 6 May 2022), which includes 3 categories and 16 subcategories. The soil erosion type in Northeast China mainly includes 3 categories and 12 subcategories. Cultivated land quality data sources were from the quality evaluation data of Liaoning, Jilin, and Heilongjiang Provinces and Inner Mongolia. The higher the grade, the worse the quality of cultivated land.

Table 1. Land-Use and Land-Cover Change classification table.

First Class Type		Secondary Type		Meaning
Numbering	**Name**	**Numbering**	**Name**	
1	Cultivated land			Land for planting crops, including cultivated land that has been in use, newly opened cultivated land, leisure land, land for crop rotation, and land for grass field rotation; agricultural fruit, mulberry, and agricultural and forestry land mainly used for planting crops; beaches and tidal flats.
		11	Paddy field	There are related facilities for water source guarantee and irrigation, generally irrigated cultivated land, cultivated land for growing aquatic crops such as rice and lotus root, including cultivated land where rice and dryland crops are planted in turn
		12	Dry land	There are no irrigation water sources and facilities, and the cultivated land for growing aquatic crops depends on natural precipitation; the dry crop cultivated land that has a water source and irrigation facilities and can be irrigated normally under normal conditions; the cultivated land mainly for vegetable cultivation; the idle land for crop rotation planting
2	Woodland			Growing trees, shrubs, bamboos, and forestry land such as coastal mangroves
3	Grassland			All kinds of grasslands with a coverage of more than 5% mainly of growing herbs, including nomadic shrub grasslands and sparse forest grasslands with a canopy closure of less than 10%
4	Waters			Natural land waters and land for water conservancy facilities
5	Urban and rural construction land			Urban and rural residential areas and other lands for industry, mining, transportation, etc.
		51	Urban land	Large, medium, and small cities and built-up areas above counties and towns
		52	Rural settlement	Rural settlements independent of towns
		53	Other construction land	Refers to factories and mines, large industrial areas, and other land and traffic roads, airports, and special land.
6	Unused land			Unused land, including difficult-to-use land.

Cultivated land, temperature, and precipitation data in Northeast China are clipped based on vector boundaries and analyzed comprehensively for the period 2000–2020. The spatial distribution of cultivated land is determined using ArcGIS by correlating and overlaying night-time light, soil erosion type data, and cultivated land quality data. The vulnerability of newly cultivated land is evaluated using the patch shape index of cultivated land, data weights of various indicators are calculated using SPSS, and the relationship between dynamic changes in cultivated land and grain yield is analyzed.

2.3. Methodology

2.3.1. Dynamic Change of Cultivated Land

The land use conversion matrix (LUTM) comes from the quantitative description of system states and state transfers in system analysis [23]. The rows and columns of the LUTM (Table 2) represent the land use types at time points T_1 and T_2. P_{ij} represents the percentage of total land area converted from land type i to land type j during T_1–T_2; P_{ii} represents the percentage of the area where land use type i remains constant during T_1–T_2. P_{i+} represents the percentage of the total area of land type i at time point T_1. P_{+j} represents the percentage of the total area of land use type j at time point T_2.

Table 2. Land use transfer matrix [23].

		T2				**P_{+i}**	**Reduce Area**
		A_1	A_2	…	A_n		
	A_1	P_{11}	P_{12}	…	P_{1n}	P_{1+}	P_{1+}–P_{11}
	A_2	P_{21}	P_{22}	…	P_{2n}	P_{2+}	P_{2+}–P_{22}
T1	…	…	…	…	…	…	…
	A_n	P_{n1}	P_{n2}	…	P_{nn}	P_{n+}	P_{n+}–P_{nn}
P_{+j}		P_{+1}	P_{+2}	…	P_{+n}	1	
Add area		P_{+1}–P_{11}	P_{+2}–P_{22}	…	P_{+n}–P_{nn}		

2.3.2. VSD Model Analysis

A hierarchical analysis-based Exposure–Sensitivity–Responsiveness (VSD) model was employed to calculate the vulnerability index of newly increased cultivated land, where the degree of exposure was determined by natural and socio-economic characteristics (Figure 2). Changes in population and land use patterns were used to reflect the degree of exposure, where a higher degree of exposure was found to increase sensitivity to ecological and environmental risks, resulting in higher vulnerability [17,28]. The sensitivity degree of the newly increased cultivated land is determined by the potential for ecological problems or threats, including soil erosion, heat conditions, and other natural factors. Higher sensitivity indicates a greater likelihood of damage. The responsiveness degree is determined by the ability of the cultivated land to resist external disturbances or stress, which can be affected by human intervention or adaptive management practices [29,30].

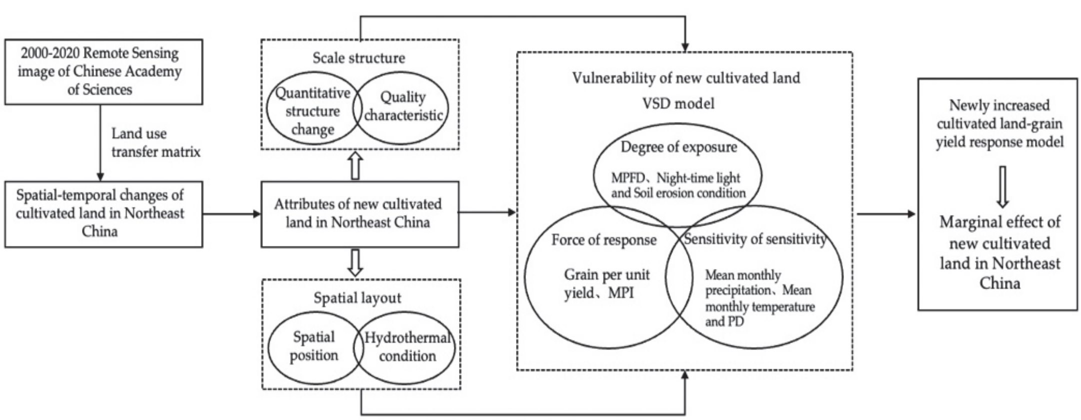

Figure 2. Study flow chart.

This study selected the average surface integral shape dimension and night-time light to represent the exposure sign of newly increased cultivated land. The sensitivity was characterized by changes in soil erosion, water and heat conditions, and patch density of the newly increased cultivated land. The responsiveness was characterized by the patch dominance and grain yield of the newly increased cultivated land [26].

(1) Analytic hierarchy process

Hierarchical analysis is a combined qualitative and quantitative decision analysis method for multi-objective complex problems and is widely used in various types of research [25,31], for example, cultivated land comprehensive quality assessment, village development assessment, etc. This study constructs an evaluation system based on hierarchical analysis to evaluate the ecological vulnerability characteristics of newly increased cultivated land [32].

$$A = (X_{ij})_{n\times n} = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{pmatrix} W_i = \frac{\overline{W}_i}{\sum_{i=1}^{n} \overline{W}_i},\ W = \begin{pmatrix} W_1 \\ W_n \end{pmatrix} CI = \frac{\lambda_{max} - n}{n - 1} CR = CI/RI$$

where A is the orthogonal matrix, X_{ij} is the comparison result of the i relative to the j, W_{ij} is the weight and eigenvector of each evaluation index, CI is the consistency test of the index, the λ is the maximum characteristic root, and RI is the random consistency index.

(2) Landscape pattern indices

a. Density of patches (PD)

$$PD = n_i/A(100)$$

where n_i is the total area of landscape elements of category i; A is the total area of all landscapes [14].

b. Average plaque typing dimension (MPFD)

$$MPFD = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{2Ln\left(0.25p_{ij}\right)}{Lna_{ij}}\right)\frac{a_{ij}}{A}$$

where m is the number of patch types, n is the number of patches of a certain type, p_{ij} is the perimeter of patch ij, a_{ij} is the area of patch ij, and A is the area of the total landscape [27].

c. Largest Patch Index (LPI)

$$LPI = \frac{1}{-\sum_{i=1}^{m}(P_i \ln P_i)}$$

where: P_i is the proportion of landscape patches type i.

(3) Vulnerability index of cultivated land ecosystem

$$V = \sum_{i=1}^{n} X_i \times W_i$$

where V denotes the cropland ecosystem vulnerability index, X_i is the data of each indicator, and Wi is the weight of each indicator data.

2.3.3. Newly Increased Cultivated Land–Grain Yield Response Model

As the concept of sustainable development evolves, cultivated land security now encompasses quantity, quality, and ecological aspects (Figure 2). Thus, ensuring the trinity of cultivated land security is essential for stable long-term food production [24,30]. Studies examining the relationship between cultivated land quality, ecological security, ecosystem vulnerability, and food production are insufficient [8]. Cultivated land quality is typically assessed by its quality class, while the impact of ecological security on food production is evaluated [18]. This study examines the relationship between the comprehensive change of newly increased cultivated land and grain yield. The characterization scale is the area of newly increased cultivated land, the characterization quality is soil erosion, and the degree of vulnerability is characterized by the vulnerability, temperature, and precipitation of cultivated land.

$$r = \frac{l_{xy}}{\sqrt{l_{xx} l_{xy}}} = \frac{\sum_{i=1}^{n} \frac{(x - \bar{x})(y - \bar{y})}{n - 1}}{\sqrt{\frac{\sum_{i=1}^{n}(x - \bar{x})^2}{n-1}}} \times \frac{1}{\sqrt{\frac{\sum_{i=1}^{n}(y - y)^2}{n-1}}}$$

where r is the correlation coefficient, with the range of [−1, 1]. n is the number of factors, x is the data of various indicators of cultivated land dynamics, which characterize the scale, quality, and ecological environment of cultivated land, and y is the grain yield. The correlation model was tested using the chi-square test pair (Sig), which indicates a significant correlation between the two factors when the *p*-value is <0.05 and a highly significant correlation between the two factors when the *p*-value is <0.01 [11].

3. Results

3.1. Spatial–Temporal Pattern Changes of Cultivated Land

3.1.1. Overall Change in Cultivated Land

According to the land use transfer matrix calculation, between 2000 and 2020, Northeast China experienced a 3.08% increase in cultivated land (Table 3), adding 1,778,500 hectares, primarily from previously unused land, forests, and grasslands. The increase in paddy land was approximately 1651,800 ha, while the dry land decreased by about 4844 ha. Notably, 2,122,000 hectares of dry land were converted into paddy fields, accounting for 58.27% of the increase in paddy fields (Figure 3). The newly occupied cultivated land was mainly used for afforestation or reclamation and urban development. In summary, the RSI values are larger in the central part of the plain and smaller in the peripheral areas; the RSI values in the peripheral areas of the cities are significantly higher than those in the other areas, and the area of rural settlements increased significantly due to urban radiation. The topography and proximity to the city may influence the evolution of rural settlements.

Table 3. Land use type area conversion table from 2000 to 2020 (ha).

2000 \ 2020	2	3	4	6	11	12	51	52	53
2	453,846.58	10,782.58	1735.07	11,496.98	2596.69	19,953.17	264.06	813.61	423.65
3	15,174.52	203,016.43	677.82	12,143.82	1410.18	9189.46	129.33	440.62	417.94
4	777.90	598.32	20,044.00	5331.56	1378.22	2828.83	110.54	100.92	234.41
6	2761.97	3331.18	1614.55	51,494.15	4504.95	6626.86	88.28	197.41	162.89
9	0.00	0.00	2.20	0.00	0.00	0.00	0.00	0.00	2.04
11	670.67	348.12	582.44	603.05	29,761.13	11,530.90	390.95	974.09	227.22
12	16,393.51	6163.04	2619.18	3502.85	21,219.98	265,911.95	2144.36	6665.36	1131.02
51	28.86	12.22	17.34	5.56	22.10	177.28	4169.26	167.12	23.43
52	451.74	240.52	119.90	147.43	806.01	4632.80	931.96	15,659.76	161.85
53	47.31	30.97	471.94	23.91	17.42	56.46	237.68	30.60	553.52

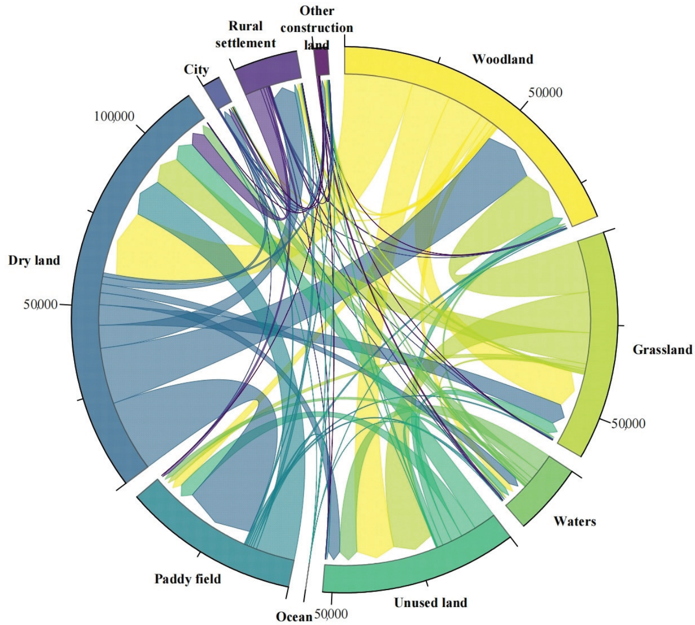

Figure 3. Land type transfer table.

3.1.2. Spatial–Temporal Pattern of Newly Increased Cultivated Land

The spatial distribution of newly increased cultivated land was concentrated in the Northeast Plain and the area between the Lesser Khingan Mountains and the Sanjiang Plain, as well as in the northwest and northeast of Heilongjiang Province, the south of the Eastern Fourth Lian of Inner Mongolia, and the southwest of Liaoning Province (Figure 4). Additionally, in the northeast Sanjiang Plain, there was a phenomenon of returning dry land to cultivated land.

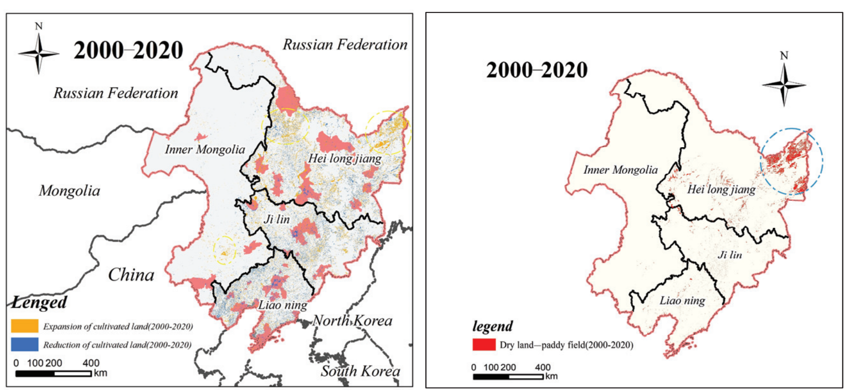

Figure 4. Changes of cultivated spatial land pattern.

In Northeast China, temperature higher generally leads to planting boundary expansion to the north [33]. The newly increased cultivated land due to warming is mainly located in the temperature-limited northern region, where extreme climate conditions may lead to decreased or no crop yield (Figure 5). Over the period 2000 to 2020, Northeast China experienced significant precipitation reduction, with 85% of the region having an average monthly rainfall of less than 5 mm, thereby increasing the likelihood of drought.

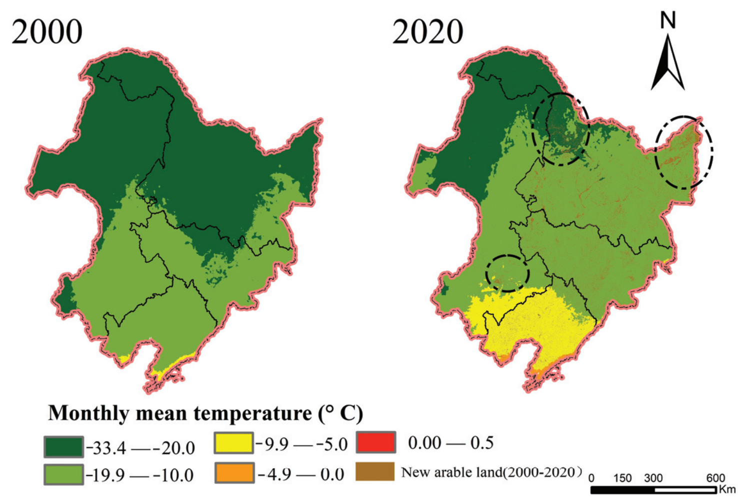

Figure 5. Monthly mean temperature pattern changes.

With the change in water and heat conditions, the cultivated land in Northeast China expanded northward, but most newly increased cultivated land is in low-temperature and arid regions (Figure 6). The yield of cultivated land is significantly affected by temperature fluctuations and stabilizing the yield of newly increased cultivated land is challenging.

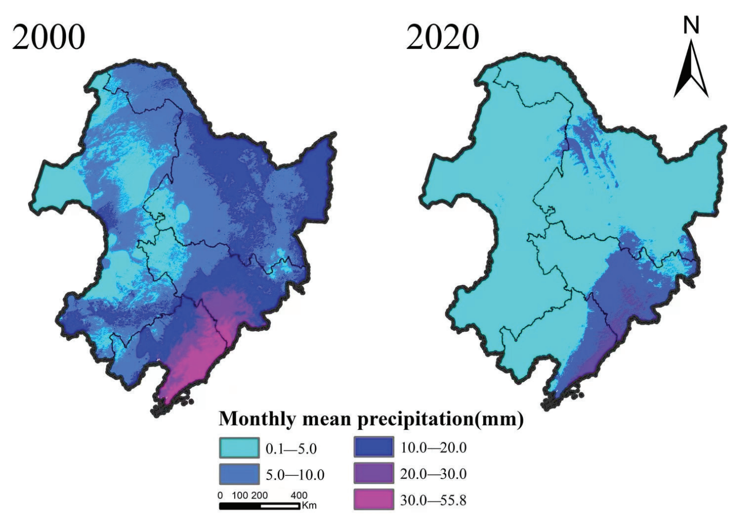

Figure 6. Monthly mean precipitation changes.

3.1.3. Newly Cultivated Land Quality Attributes

The quality of cultivated land in Northeast China ranged from grade 1 to grade 10 from 2000 to 2020, with the Northeast Plain area having the highest concentration of cultivated land (Figure 7), and mountainous and hilly areas having low-quality cultivated land. Most of the newly increased cultivated land in Northeast China falls within grades 6–10.

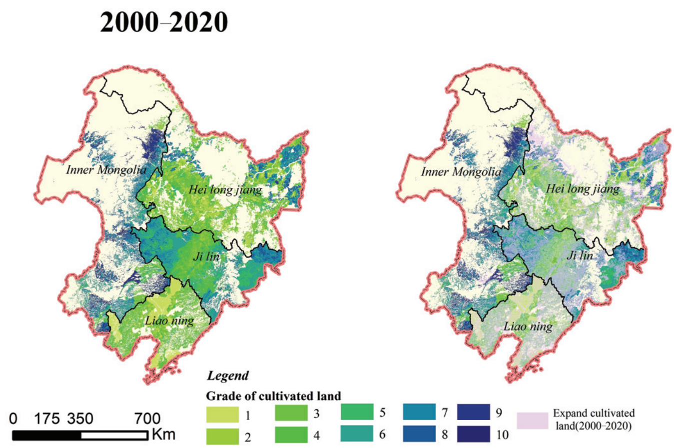

Figure 7. Grade map of cultivated land in Northeast China.

The newly increased cultivated land in Northeast China comprises mainly quality grade 6–10, with 58.54% falling in this range (Figure 8). Within this range, the cultivated land with quality grade 8–10 accounts for 35.58%, and the cultivated land with quality grade 10 accounts for 11.89%. In contrast, the reduced cultivated land is grade 1 high-quality cultivated land. Although the quality of newly increased cultivated land in Northeast China is low, the occupied cultivated land is of high quality.

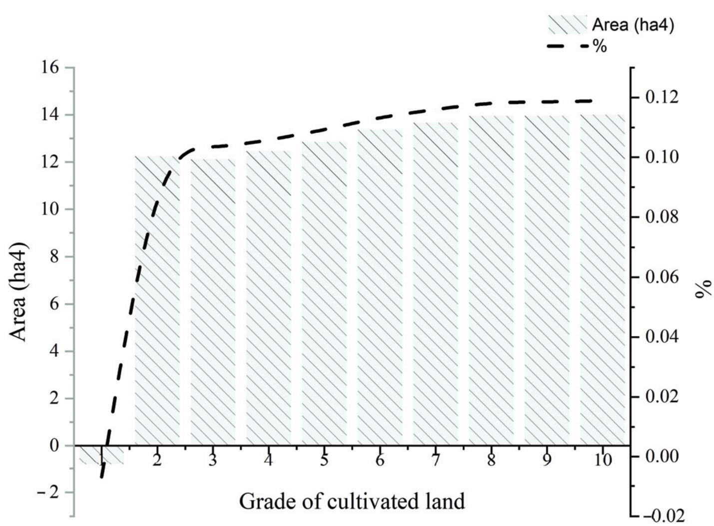

Figure 8. Status of cultivated land expansion in Northeast China.

3.2. Vulnerability of New Cultivated Land

In Northeast China, moderately vulnerable areas of newly increased cultivated land were mainly distributed in the eastern and southwestern regions (740,600 hectares, 62.84%), while mildly vulnerable areas were primarily found in the Northeast Plain and northern and central areas of the Greater Khingan Mountains (395,100 hectares, 33.53%). Severely vulnerable cultivated land was mainly located in the northern part of the Liaodong Peninsula (4.28 million hectares, 3.6%). The proportion of newly increased cultivated land in medium–highly vulnerable areas was twice as high (66.44%) as that in mildly vulnerable areas. The concentration of newly increased cultivated land in Northeast China is in commercial grain production bases, such as the Sanjiang Plain and eastern Northeast Plain. Thus, optimizing the ecological security of the newly increased cultivated land is necessary to ensure its quality and safety and promote stable grain production. The following results demonstrate this (Tables 4–6 and Figure 9).

Table 4. Index judgment matrix.

Index Data	MPFD	Index of Light	Soil Erosion Condition	PD	Mean Monthly Precipitation	Mean Monthly Temperature	LPI	Grain per Unit Yield
MPFD	1.00	0.50	0.67	1.00	1.25	1.25	1.00	0.50
Index of light	2.00	1.00	1.25	1.43	1.67	1.67	1.43	1.11
Soil erosion condition	1.50	0.80	1.00	1.11	0.83	0.83	5.00	0.50
PD	1.00	0.70	0.90	1.00	0.83	0.83	1.00	0.50
Mean monthly precipitation	0.80	0.60	1.20	1.20	1.00	1.00	0.77	0.50
Mean monthly temperature	0.80	0.60	1.20	1.20	1.00	1.00	0.50	0.40
LPI	1.00	0.70	0.20	1.00	1.30	2.00	1.00	0.56
Grain per unit yield	2.00	0.90	2.00	2.00	2.00	2.50	1.80	1.00

Table 5. Random consistency check form.

Random Consistency Table														
n	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RI	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59	1.59
n	17	18	19	20	21	22	23	24	25	26	27	28	29	30
RI	1.6	1.61	1.62	1.63	1.64	1.64	1.65	1.65	1.66	1.66	1.66	1.67	1.67	1.67

Table 6. The index weight of cultivated land ecosystem vulnerability.

Layer of Criterion	Index Data	Index of Weight
Degree of exposure	Mean fractal dimension of plaque (MPFD)	0.10
	Night-time light	0.17
	Soil erosion condition	0.13
Degree of sensitivity	Density of patches (PD)	0.10
	Mean monthly precipitation	0.10
	Mean monthly temperature	0.09
Force of response	Maximum plaque index (MPI)	0.10
	Grain per unit yield	0.20

Heilongjiang Province has the largest area of newly increased cultivated land, followed by Jilin Province, Liaoning Province, and the Inner Mongolia Autonomous Region. Most of the newly increased cultivated land in Northeast China is moderately vulnerable, except for the four alliances in eastern Inner Mongolia where the mildly vulnerable areas are more significant. Severely vulnerable cultivated land accounted for 21.27% of the newly increased cultivated land in Liaoning Province. Heilongjiang Province has the largest increase in cultivated land (677,000 hectares), but 66.62% of the newly increased cultivated land is in moderately vulnerable areas. Jilin Province increased 245,700 hectares of cultivated land, of which 63.13% was in moderately vulnerable areas. Liaoning Province increased 2.03 million hectares of cultivated land, of which 76.68% was in moderately vulnerable areas. In four cities in eastern Inner Mongolia, 54,800 hectares of newly cultivated land were increased, of which 41.97% was in moderately vulnerable areas (Figure 10).

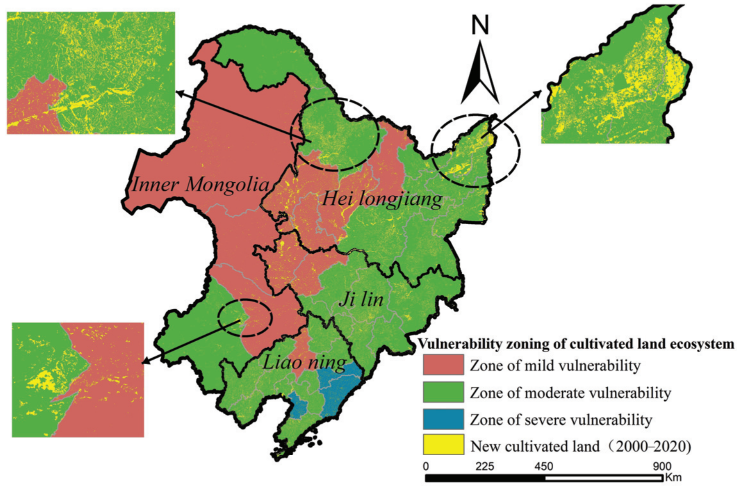

Figure 9. Spatial pattern of ecosystem vulnerability in Northeast China.

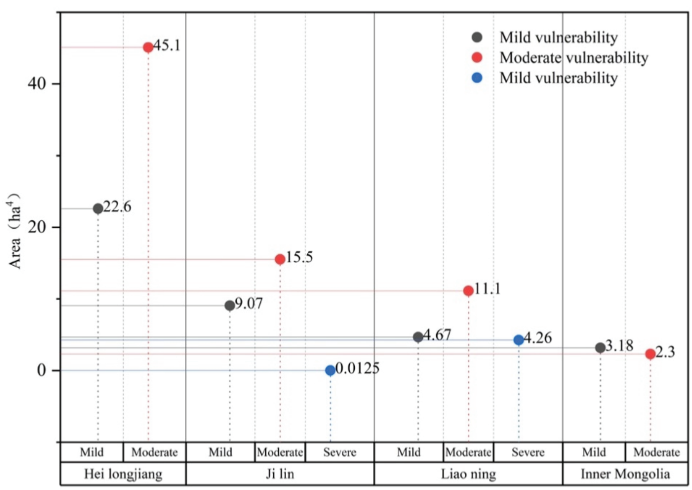

Figure 10. Statistics of cultivated land ecosystem vulnerability in Northeast China.

Most of Northeast China's newly increased cultivated land is in moderately vulnerable areas, leading to concerns regarding the quality and ecological security of the land. Unstable grain production and output from this land may impact overall grain production and potentially pose a threat to food security.

3.3. Marginal Effect of New Arable Land on Grain Yield

In this study, the correlation effect model was used to analyze the relationship between the characteristics of changes in the quantity, quality, and ecological dynamics of cultivated land and grain yield.

Table 7 shows a significant negative correlation between grain yield and vulnerability of newly increased cultivated land, indicating that higher vulnerability of cultivated land leads to higher grain yield and lower regional ecosystem resilience to external interference, which affects the material cycle or energy flow of the cultivated land ecosystem [34]. Higher grain yields in Northeast China are associated with greater ecological environment costs, as demonstrated by a significant positive correlation between grain yield and temperature change, while light conditions remain an essential factor affecting grain yield.

Table 7. The relationship between landscape indicators and variables in rural settlements.

Analysis of Correlation		New Area of Cultivated Land	Ecological Vulnerability	Quality of Cultivated Land	Variation of Temperature	Variation of Precipitation	Production of Grain
New area of cultivated land	Pearson correlation	1.00	0.06	−0.16	−0.373 *	−0.03	−0.25
	Sig		0.73	0.32	0.02	0.84	0.12
Ecological vulnerability	Pearson correlation	0.06	1.00	0.10	−0.417 **	−0.481 **	−0.335 *
	Sig.	0.73		0.54	0.01	0.00	0.03
Quality of cultivated land	Pearson correlation	−0.16	0.10	1.00	0.24	−0.477 **	0.05
	Sig.	0.32	0.54		0.14	0.00	0.75
Variation of temperature	Pearson correlation	−0.373 *	−0.417 **	0.24	1.00	0.15	0.511 **
	Sig.	0.02	0.01	0.14		0.37	0.00
Variation of precipitation	Pearson correlation	−0.03	−0.481 **	−0.477 **	0.15	1.00	0.11
	Sig.	0.84	0.00	0.00	0.37		0.48
Production of grain	Pearson correlation	−0.25	−0.335 *	0.05	0.511 **	0.11	1.00
	Sig.	0.12	0.03	0.75	0.00	0.48	

** At level 0.01 (two-tailed), the correlation was significant. * At level 0.05 (two-tailed), the correlation was significant.

The expansion of cultivated land area is significantly negatively correlated with regional temperature, indicating that temperature stability is a crucial factor affecting cultivated land expansion. The newly increased cultivated land mainly comes from ecological land types such as woodland, grassland, and wetlands, which will inevitably undermine the original ecosystem. The dynamic changes in the spatial and temporal patterns of cultivated land may pose a risk of food production instability. However, large-scale cultivated land reclamation beyond the self-restoration ability of the ecosystem balance can result in severe consequences such as ecosystem disruption or collapse.

4. Discussion

4.1. Newly Increased Cultivated Land Is Unstable Due to External Disturbance

With increasing urbanization, urban expansion will occupy more agricultural land, which is irreversible [14]. The inadequacies of China's cultivated land occupation and compensation balance system are evident, as the replenished cultivated land is of lower quality than the high-quality cultivated land that has been occupied, leading to a significant gap in the quality of cultivated land compensation [15].

Most of the newly increased cultivated land is situated in the northern part of Northeast China, primarily in the terrain fluctuation area where the Sanjiang Plain, the Greater Khingan Mountains, and the Lesser Khingan Mountains converge. Among them, Sanjiang Plain's new arable land area is the largest. Sanjiang Plain, a biodiverse wetland area, is a significant increase area of newly cultivated land in Northeast China from 2000 to 2020 [26]. Most of the newly increased cultivated land in the Sanjiang Plain is converted from wetland, woodland, or grassland [35]. Disturbance beyond ecosystem recovery capacity may cause severe ecological problems, risking soil erosion, increased land degradation, and lower cultivated land stability. Global warming has resulted in a significant increase in the average monthly temperature, causing the northward shift of the crop cultivation boundary [21,36].

From 2000 to 2020, the average monthly precipitation in Northeast China decreased significantly, and the drought trend was evident. The uncertainty of climate conditions may induce flood and drought disasters and affect crop yield [37]. This region experiences an average monthly temperature ranging from −10 °C to −20 °C and an average monthly precipitation of 0.15 mm and 10 mm. The average monthly temperature of the newly increased cultivated land is −10~−20 °C and the average monthly precipitation is 0.15~10 mm. Low temperature, limited precipitation, and unstable hydrothermal conditions may lead to uncertainty and instability of newly increased cultivated land yield [38]. The cultivated land in Northeast China lacks quality and ecological security, exhibits weak stability, and has a low ability to resist external interference. The poor stability of newly increased cultivated land in Northeast China reflects the defects in China's cultivated land occupation and compensation balance system, which cannot guarantee the comprehensive quality of cultivated land and only emphasizes the quantity balance of cultivated land, ignoring the quality of cultivated land and ecological stability. It suggests that scholars should deepen the research on the quality security and ecological security of the newly increased cultivated land to comprehensively measure the newly increased cultivated land and ensure its stability.

4.2. Newly Increased Cultivated Land Vulnerability Poses a Potential Threat to Food Security

Northeast China belongs to the temperate monsoon continental climate, making summer precipitation more and more concentrated and soil erosion more serious. Secondly, the central hinterland of Northeast China is plain, lacking protective forest network obstruction, and some land has wind erosion hazards. Soil and water loss is the main reason for black soil thinning, presenting an urgent problem to be addressed [17]. From 2000 to 2020, 91.61% (1.07 million hectares) of newly increased cultivated land in Northeast China was at risk of water erosion, mainly in the Sanjiang Plain and the confluence of the Greater Khingan Mountains and Lesser Khingan Mountains. In total, 8.11% (95,800 hectares) of cultivated land is at risk of wind erosion, mainly distributed in the arid and semi-arid regions of Inner Mongolia. In addition, about 63.13% of the newly increased cultivated land in Northeast China has medium to high vulnerability, with short-term potential to increase production but long-term risks.

The fragility of the ecological system and uncertainty of climatic conditions raise the risk of the collapse of the cultivated land production system, resulting in reduced crop yields or even complete crop failure, posing a significant threat to food security [39]. The ecological stability of cultivated land can enhance its self-regulation and self-recovery capabilities, thereby preventing or mitigating ecological problems and disasters [16]. Ensuring the quality and ecological security of newly increased cultivated land and improving the resistance and resilience ability of the cultivated land ecosystem to external interference is essential to ensure the stability of the cultivated land production system, increase grain output growth, and guarantee food security [6].

4.3. Proposals for Optimizing Current Cultivated Land Protection Policies

Despite the Chinese government's implementation of strict policies and systems, such as the cultivated land occupation and compensation balance system and the designation of permanent basic cultivated land protection areas, some issues with the protection of cultivated land persist [28]. Song suggested prioritizing the development of high-quality cultivated land to ensure both quantity and quality protection, as the current cultivated land balance system focuses on quantity and may negatively affect crop yield and national food security (Song and Pijanowski 2014). The permanent basic cultivated land construction overlooks the comprehensive development of the cultivated land ecosystem and does not align with the Chinese government's agricultural modernization goals, emphasizing only rural roads and other supporting facilities [40]. Since China's cultivated land has reached a saturation point, it is challenging to increase its quantity further [8,18]. Thus, the focus should shift from quantity protection to quality and ecological protection, and a stable cultivated land output mechanism must be established for the long term [15].

China is experiencing a decline in cultivated land quality, and non-grain cultivated land is becoming increasingly prevalent [13]. To ensure national food security, the Chinese government has developed policies and measures for major grain-producing areas [5]. In 2022, the Chinese government elevated the black land protection strategy in major grain-producing regions of Northeast China to a national strategy. This was achieved through the implementation of strict policies, laws, and regulations aimed at strengthening the protection of black land. The government also encouraged individual farmers to actively practice black land protection measures, establish a long-term and stable protection mechanism, and ensure the sustainable development of cultivated land for food production stability [16]. To ensure the stability of the cultivated land production system and increase grain output in Northeast China, the efficiency and quality of cultivated land should be fully considered when implementing the cultivated land protection policy strictly. Additionally, the construction of high-standard cultivated land should be advanced to improve cultivated land ecosystems, enhance their resilience, and ensure the quantity, quality, and ecological security of cultivated land [36]. Promoting large-scale land management by integrating tenure relations and a clustered spatial structure can provide basic conditions for conservation farming measures and promote cultivated land protection practices [39].

The Chinese government is committed to ensuring national food security and has implemented food security in cultivated land, which is closely related to national food security. This paper focuses on the newly increased cultivated land, analyzes the marginal effect of grain production, and explores the impact on food security. This paper innovatively discusses the potential impact of the marginal effect of newly increased cultivated land on food security, providing direction for the government to develop comprehensive measures to protect cultivated land and strengthen the overall quality of cultivated land.

5. Conclusions

Focusing on the newly increased cultivated land in Northeast China, this paper analyzes the spatial and temporal pattern of newly increased cultivated land. It assesses the marginal effect of newly increased cultivated land's comprehensive attributes on grain production and its potential impact on food security. The study found that from 2000 to 2020, 1.1785 million hectares of newly increased cultivated land in Northeast China were mainly located in the temperature-restricted area in northern Heilongjiang Province, Sanjiang Plain, and the arid and semi-arid area in southern Dongsi League of Inner Mongolia. Most of the newly increased cultivated land had poor quality, with 58.54% of it being at grade 6–10, and the reduced cultivated land was all at grade 1. Additionally, 62.84% of the newly increased cultivated land was in ecologically fragile areas, while the rest was in mildly and severely vulnerable areas. Temperature instability was negatively correlated with cultivated land expansion, while grain production was negatively correlated with cultivated land vulnerability. The increase in grain production at the expense of cultivated land ecology is a potential threat to national food security.

The poor quality of newly increased cultivated land in Northeast China, characterized by ecological fragility, may lead to short-term gains in grain yield but may not guarantee long-term stability. This study found a significant negative correlation between grain yield and cultivated land ecological vulnerability in Northeast China. Therefore, we should take increasing high quality and good ecological cultivated land as the key measures of cultivated land protection. We will give priority to incorporating ecologically sound cultivated land into high-standard cultivated land development zones and strengthen protection. This can not only save the maintenance cost of cultivated land and improve the production efficiency of cultivated land, but also ensure the long-term stability of grain production to the greatest extent.

Author Contributions: Conceptualization, X.W. and J.W.; methodology, J.W.; validation, J.W., G.D. and X.W.; formal analysis, X.W.; data curation, X.W. and H.Z.; writing—original draft preparation, X.W. and Y.L.; writing—review and editing, X.W., G.D. and J.W.; visualization, X.W.; supervision, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA28130400), the National Natural Science Foundation of China (Grant No. 42171266), the National Key R&D Program of China (Grant No. 2021YFD1500101), and the Youth Talent Project of the Northeast Agricultural University of China (Grant No. 19QC35).

Data Availability Statement: Data are available in a publicly accessible repository.

Acknowledgments: We would like to thank the Center for Resource and Environmental Science and Data, Chinese Academy of Sciences (http://www.resdc.cn/Datalist1.aspx, accessed on 6 May 2022) for the interpretation of land use remote sensing data and the Nanjing Institute of Soil Sciences, Chinese Academy of Sciences (http://soil.geodata.cn/, accessed on 6 May 2022) of China's 1 km raster soil organic matter data. In addition, we would like to thank anonymous reviewers for their valuable comments and suggestions to improve this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Utilization Quality Evaluation and Barrier Factor Diagnosis of Rural Residential Areas in Agricultural Regions of the Northeast Plain: A Case Study of Wangkui County, Heilongjiang Province, China

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Abstract: Conducting quality evaluations of rural residential areas and effectively improving their utilization levels is an important aspect of correctly handling the relationship between humans and the land and achieving high-quality rural developments. Taking Wangkui County, Heilongjiang Province, as an example, this study aimed to achieve the "intensive, humanistic, and green" development of rural residential areas. An evaluation index system of utilization quality was constructed using three aspects: intensive land utilization, human settlement environment quality, and ecological environment quality. The comprehensive evaluation results were classified using a multidimensional combination matrix and targeted optimization plans were proposed. Additionally, an obstacle diagnosis model was constructed to identify the factors that hinder the high-quality utilization of rural residential areas. The results demonstrated the following: (1) The utilization quality of the rural residential areas in the study area was mainly at a medium level, followed by low and high levels, with proportions of 20.18%, 51.38%, and 28.44%, respectively. The utilization levels gradually decreased from the town centers to the surrounding areas. (2) Based on the evaluation results, there were 23 combinations of rural residential areas in the study area, which were classified into four types: coordinated control, key development, single leading, and transforming and upgrading. Optimization plans were proposed for the different types. (3) From the perspective of identifying the barrier factors, the top five factors that hindered the high-quality utilization of rural residential areas were the traffic land density, aggregation index, green-coverage rate of built-up areas, completeness of public service facilities, and the proportion of secondary and tertiary industrial land area. This study provides a significant reference for the evaluation of the utilization quality of rural residential areas in plain agricultural regions to effectively raise their levels of intensive land utilization, improve their settlement environments, enhance their ecological quality, and achieve a development of high quality.

Keywords: rural residential areas; utilization quality; type classification; obstacle factor

Citation: Zhang, H.; Cong, R.; Luan, S. Utilization Quality Evaluation and Barrier Factor Diagnosis of Rural Residential Areas in Agricultural Regions of the Northeast Plain: A Case Study of Wangkui County, Heilongjiang Province, China. *Land* **2023**, *12*, 870. https://doi.org/10.3390/land12040870

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 29 March 2023
Revised: 8 April 2023
Accepted: 10 April 2023
Published: 12 April 2023

1. Introduction

Rural residential areas are the basic supporting units of production and living conditions within the rural-area system, and they are important carriers for rural development [1]. For a long time, the layouts of the rural residential areas in China were mostly formed out of independent choices, showing an overall state of disorderly development and lacking scientific planning and guidance, which has resulted in a significant waste of land resources and a low degree of intensive utilization [2,3]. At the same time, there are obstacles to this development, such as the scarcity of public service facilities and infrastructures, as well as an urgent need to enhance production conditions [4,5]. In addition, a series of problems affect the high-quality use of rural residential areas. For example, the environmental pressure brought about by agricultural production has become increasingly prominent [6]. To change the current situation of rural settlement areas and improve their levels of utilization, China introduced a series of policies. In 2017, the concept of high-quality development was officially proposed in the report of the 19th National Congress of the Communist Party of China, emphasizing "quality as the foundation for building a strong country" and "quality-driven transformation". In 2021, the Central Committee of the Communist Party of China and the State Council released the "Opinions on Promoting Rural Revitalization and Accelerating Agricultural and Rural Modernization", which pointed out the need to promote high-quality developments, accelerate agricultural and rural modernization, improve the living environment, and enhance the rural ecological environment. During the 14th Five-Year Plan period, China will adhere to the theme of high-quality development and use it as a measure to promote various aspects of economic and social development. This indicates that, against this background, the development of rural residential areas also presents a valuable orientation of the project of high-quality utilization by adhering to the goal of achieving "land conservation and intensive use, comfortable and convenient living for residents, and healthy and sustainable ecological environment". However, there is a significant gap between the current problems of rural residential areas and the requirements for achieving a high-quality development. As an important grain production area, the plain agricultural regions in our country urgently demand the high-quality utilization of rural residential areas to ensure agricultural production and the efficient utilization of land resources. Therefore, researching the utilization-quality evaluation of rural residential areas in the Northeast Plain agricultural area is beneficial for scientifically and quantitatively describing their utilization statuses; the rational allocation of development factors, such as rural land, population, and industry; and the correct handling of the relationship between humans and the land. This research provides a reference and technical support for achieving the high-quality utilization and sustainable development of rural residential areas.

In recent years, scholars at home and abroad have conducted a large amount of research to achieve the optimal development of rural residential areas. Based on multiple perspectives including geography [7], sociology [8], economics [9,10], and ecology [11], foreign scholars have studied the impact of factors such as landform characteristics, rural economy, population mobility, and environmental governance on the development of rural residential areas. This also guides scholars to pay attention to the optimization and utilization of rural residential areas from a multidisciplinary perspective. Domestic scholars have conducted extensive research on intensive-utilization evaluation [12–14], human-habitat-quality evaluation [15–17], ecological-suitability evaluation [18–20], and other aspects, to achieve the optimal development of rural residential areas. Starting from the perspectives of land use [21], location conditions [22], production and living accessibility [23], the ecological environment [24], policy conditions [25], and other aspects, and combining various natural, economic, social, and other factors, they used the entropy-weighting method [26], the analytic-hierarchy process [27], the factor-analysis method [28], among others, to construct evaluation index systems. They classified and organized villages based on the evaluation results, and then proposed targeted optimization strategies. In the new era of China's entry onto the stage of high-quality development, research on utilization quality was also launched in various fields; however, recent studies mainly focused on the "quality of cultivated land utilization" [29], the "quality of construction land utilization" [30], etc. In the exploration of land-use quality, scholars such as Fang [31] and Wu [32] conducted research based on multidimensional data to achieve the high-quality utilization of the entire land space. Rural residential areas are an important type of territorial space; however, there has been relatively little research on their utilization quality. The development of rural residential areas is no longer limited to layout optimization but now also pays more attention to the development's quality. The scholar Qu [33] defined the connotation of the utilization quality of rural residential areas from the perspective of the relationship between people and the land, and then proposed key points to focus on to enhance it. It can be said that evaluating the utilization quality from the perspective of rural residential areas is an extension and refinement of the land-use quality that can guide their efficient utilization.

Previous studies on the evaluation of rural residential areas by scholars mostly focused on factors such as comprehensive resource endowment and village consolidation losses, and they chose the reduction of the number of rural residential areas as the evaluation goal. They ignored the development quality of rural residential areas and rarely considered the comprehensive aspects of land utilization, living conditions, and the ecological environment. On the other hand, the evaluation of the utilization quality of rural residential areas aims to guide and improve the quality of rural settlements. This study emphasized the coordinated development of the multiple functions—such as production, settlement, and ecological services—that rural residential areas can provide. In addition, previous studies mainly focused on ecologically vulnerable areas [34], typical mountainous areas [35], etc.; however, the rural residential areas in China are widely distributed in the plain regions [36], where the terrain is flat and the main task is grain production. The existing problems in the utilization of rural residential areas cause substantial difficulties in ensuring agricultural production, farmers' livelihoods, and rural ecology. We must urgently establish a scientific evaluation system to improve the utilization quality of the rural residential areas in the plain agricultural regions.

Based on the above, this study took the 109 administrative villages in Wangkui County, Heilongjiang Province, which is a typical agricultural area on the Northeast Plain, as the research area. The study aimed to improve the utilization quality of rural residential areas and guide their development in the direction of intensification, humanization, and greening, and it used a multifactor, comprehensive evaluation method to construct an evaluation index system to assess the degree of intensive land utilization, human settlement environment quality, and ecological environment quality. Next, we coded and combined the evaluation results and used the multidimensional combination matrix to classify the types of rural residential areas, and we then proposed suggestions for the different types. In addition, we used the obstacle diagnosis model to identify the main obstacle factors. This study aimed to provide support and a reference for the high-quality utilization of rural residential areas in the plain regions.

2. Materials and Methods

2.1. Study Area

Wangkui County is under the jurisdiction of the city of Suihua, Heilongjiang Province, and is one of the main typical areas of agricultural production on the Northeast China Plain. Its geographical range is between 126°10′–126°59′ E and 46°32′–47°28′ N. The region has a temperate continental monsoon climate, with a higher elevation in the northeast and lower elevation in the southwest. The total area of Wangkui County is 231656.96 hectares, which includes 10 towns and 5 townships, with 109 administrative villages. At the end of 2019, the total population of the county was 442,900, including 369,100 members of the agricultural population. Wangkui County is an important producer of commodity grain, with a cultivated area of 186,856.52 hectares, accounting for 80.66% of the total land area. In 2019, the agricultural output value of Wangkui County was CNY 357.7 million, accounting for 47.85% of the total output value of the agriculture, forestry, animal husbandry, and fishery industries in the county. The high dependence of farmers' income on the agricultural production space highlights the importance of land resources for rural development in Wangkui County. In addition, there are long-standing problems in the layout and land use of the rural residential areas in Wangkui County, with a per capita rural residential land area of about 280.31 square meters, and prominent tensions between the people and the land. In recent years, Wangkui County has actively carried out village planning and preparation work; however, it urgently needs a scientific basis for planning from the perspective of high-quality utilization to improve the level of intensive land utilization, the living conditions of the villagers, and the ecological environment, to achieve the high-quality utilization of the rural residential areas and implement a strategy of rural revitalization and development. The study area is shown in Figure 1.

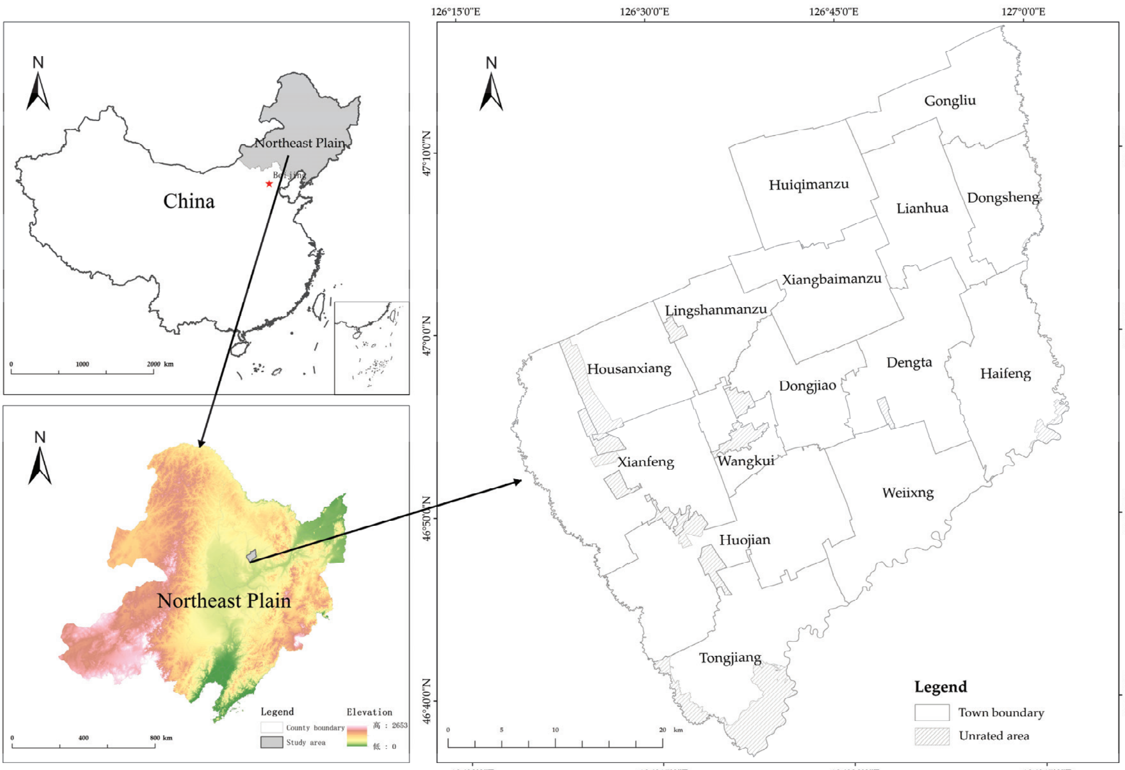

Figure 1. Location map of the study area. Unrated area represents the urban center and forest farm.

2.2. Data Source and Pretreatment

The data used in this study included land-use data, remote sensing image data, and socioeconomic data. The land-use data were obtained from the third national land survey database in 2018. The remote sensing image data were acquired from the high-resolution Satellite 2 in June 2019, with a spatial resolution of 1 m × 1 m. The socioeconomic data were sourced from the Heilongjiang Statistical Yearbook of 2019 and the Wangkui County Statistical Yearbook of 2019. The rest of the data was obtained through field surveys.

The data preprocessing included six steps. First, the extraction of rural residential areas was achieved using ArcGIS 10.2 software. Through visual interpretation, the boundaries of rural residential areas were redrawn based on the color, shape, and texture of the patches of rural residential areas presented in the high-resolution Satellite 2 in June 2019. The redrawn rural residential areas' patch boundary data were overlaid with land-use data from the third national land survey database. Modifications were made to improve the interpretation accuracy by referring to the remote sensing images to address boundary inaccuracies. We then obtained data on the rural residential areas. Second, ArcGIS10.2 software was utilized to extract information on the cultivated land, residential land, idle land, road traffic land, secondary and tertiary industrial land, and ecological land. The near tools in ArcGIS were used to obtain data on the accessibility of the central towns. Third, the extracted rural-residential-area data were transformed into raster data, and FragStats 4.2 software was used to calculate the aggregation index and landscape shape index of the rural residential areas. Fourth, the data on the completeness of public service facilities were obtained through field surveys and interviews with village cadres to understand the construction situation of public service facilities in the village. The number of public service facilities, such as schools, clinics, libraries, cultural squares, shops, and others, was calculated by taking into account feedback from village cadres and conducting field surveys. The statistical results were then categorized into different levels and assigned corresponding scores. Fifth, the data on the amounts of pesticide, fertilizer, and agricultural plastic film usage were provided by the Wangkui County Statistics Bureau. Finally, based on the various obtained data, a unified summary analysis was conducted to construct a utilization-quality evaluation database of the rural residential areas for the study area.

2.3. Explanation of the Utilization-Quality Connotation

The utilization quality of rural residential areas refers to the degree of the quality of their utilization. Under the premise of complying with their natural attributes and development laws, rural residential areas are efficiently developed and utilized to better meet people's needs. In the era of high-quality developments, the construction of rural residential areas should be based on the requirements of "intensification, humanization, and greening". Intensified developments can promote improvements in the land-use efficiency and conservation of precious land resources. Humanized development focuses on the people's pursuit of a better life, and it improves production and living conditions. Green development highlights ecological civilization constructions and places higher demands on ecological livability. Based on this, the evaluation of the utilization quality of the rural residential areas was conducted in terms of three aspects, namely, intensive land utilization, human settlement environment quality, and ecological environment quality, to comprehensively measure their utilization quality levels and achieve the maximization of economic, social, and ecological benefits.

2.4. Research Methods

2.4.1. Evaluation of Utilization Quality of Rural Residential Areas

Based on the understanding of the utilization quality of rural residential areas and the perspectives of "intensive, humanistic, and green" development, and with reference to relevant research on evaluation indicators [37–40], combined with the actual situation of the study area, the utilization-quality evaluation index system of the rural residential areas was constructed in terms of three aspects: intensive land utilization, human settlement environment quality, and ecological environment quality (Table 1).

Table 1. Evaluation index system of utilization quality of rural residential areas.

Goal Level	Criteria Level	Indicator Level	Indicator Weight	Indicator Attribute
Utilization quality of rural residential areas	Intensive land utilization	Per capita rural residential area	0.2373	−
		Aggregation index	0.2979	+
		Landscape-shape index	0.1593	−
		Proportion of residential-land area	0.1520	+
		Proportion of idle-land area	0.1534	−
	Human settlement environment quality	Traffic land density	0.2745	−
		Completeness of public service facilities	0.2095	+
		Accessibility of central towns	0.1186	+
		Land-cultivation rate	0.1665	+
		Proportion of secondary and tertiary industrial land area	0.2309	+
	Ecological environment quality	Green-coverage rate of built-up areas	0.2967	+
		Proportion of ecological land area	0.2346	+
		Intensity of pesticide use	0.1562	−
		Intensity of fertilizer use	0.1562	−
		Intensity of agricultural plastic film use	0.1563	−

Note: + represent positive indicators, − represent negative indicators.

Intensive land utilization reflects the characteristics of the land-use scale, layout, and structure in rural residential areas, and it mainly comprises five indicators: the per capita rural residential area, the aggregation index, the landscape-shape index, the proportion of residential-land area, and the proportion of idle-land area. Among them, the per capita rural residential area reflects the per capita land-use scale of the village. The larger the value, the lower the degree of intensive land utilization. The aggregation index reflects the degree of aggregation of rural residential areas. The larger the aggregation index, the higher the degree of aggregation. The landscape-shape index reflects the complexity of the spatial forms of rural residential areas. The larger the value, the more complex the shape of the rural residential area and the lower the degree of intensive utilization. The proportion of residential-land area reflects the proportion of residential land in the total area of the rural residential areas, which reflects the scale of the village residents' living areas. The larger the scale, the better the land-use condition. The proportion of idle-land area reflects the proportion of idle land in the total area of rural residential areas. The larger the proportion of idle land, the more unreasonable the land use.

The human settlement environment quality reflects the degree of excellence of the production and life services available to the villagers, and it mainly comprises five indicators: traffic land density, completeness of public service facilities, accessibility of central towns, land-cultivation rate, and proportion of secondary and tertiary industrial land area. Among them, the traffic land density reflects the degree of accessibility of the road traffic in the villages. The more developed the traffic, the more convenient the living conditions of the villagers. The completeness of public service facilities reflects the level of supporting public service facilities in the village, representing the conditions of rural education, medical care, and other factors. The accessibility of central towns reflects the distance between the rural residential areas and the central towns. The closer to the central towns, the better the location conditions of the village and the greater the role played by the economic growth driven by urban development. The land-cultivation rate reflects the proportion of cultivated land in the village area, representing the levels of agricultural development space and land resources in the village. The proportion of secondary and tertiary industrial land area reflects the level of development of secondary and tertiary industries in the village, with larger values indicating better conditions of industrial development.

The ecological environment quality reflects the ecological resources and environmental conditions of villages, and it mainly comprises five indicators: green-coverage rate of the built-up areas, proportion of ecological land area, intensity of pesticide use, intensity of fertilizer use, and intensity of agricultural plastic film use. Among them, the green-coverage rate of the built-up areas reflects the degree of greening and coverage of rural residential areas. The higher the green-coverage rate, the more beautiful the ecological environment. The proportion of ecological land area reflects the proportion of ecological space and the natural resource endowment status of the village. The intensities of pesticide use, fertilizer use, and agricultural plastic film use reflect the amounts of pesticides, fertilizers, and plastic films used in the village, respectively, and represent the ecological environmental pressure brought about by the village's agricultural production. The larger the numerical value, the more severe the environmental pollution.

To eliminate the dimensional differences within the index system, the raw data were normalized using Formulas (1) and (2):

$$\text{Positive Indicator}: \; X'_{\text{ij}} = \frac{X_{IJ} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{1}$$

$$\text{Negative Indicator}: \; X'_{\text{ij}} = \frac{\max(X_i) - X_{IJ}}{\max(X_i) - \min(X_i)} \tag{2}$$

where X'_{ij} is the standardized index value, X_{IJ} is the original value of the index, $\max(X_i)$ is the maximum value of the index, and $\min(X_i)$ is the minimum value of the index.

To avoid the interference of subjective factors in the evaluation results, after normalization, the entropy weight method [26] was adopted to find the entropy value and difference coefficient, and the index weight was calculated. Finally, the utilization-quality scores of the rural residential areas were calculated according to the multifactor comprehensive evaluation method. The related Formulas (3) to (6) are given below:

$$P_{\mathrm{ij}} = \frac{X'_{\mathrm{ij}}}{\sum_{m}^{n} X'_{\mathrm{ij}}} \tag{3}$$

$$e_j = -k\sum_{i=1}^{n} P_{ij}\ln(P_{ij}) \tag{4}$$

$$W_{ij} = \frac{(1-e\mathrm{j})}{\sum_{j=1}^{n}(1-e_j)} \tag{5}$$

$$S_{ij} = \sum_{j=1}^{n} X'_{ij} W_{ij} \tag{6}$$

where n is the number of indicators (a total of 15 indicators were selected in this study), P_{ij} is the weight of the i-th village under the j-th index, e_j is the entropy value of the j-th index, W_{ij} is the weight of each indicator, and S_{ij} is the evaluation score of the utilization quality of the rural residential areas. According to the evaluation results, the natural breakpoint method in ArcGIS software was used to divide the intensive land utilization, human settlement environment quality, and ecological environment quality and the utilization quality of the rural residential areas into three levels of high, medium, and low, which were used to analyze their comprehensive utilization.

2.4.2. Classification of Rural Settlement Areas

Based on the evaluation results, the multidimensional combination matrix [41] was used to classify the rural settlement area types according to three aspects: intensive land utilization (I), human settlement environment quality (H), and ecological environment quality (E). The intensive land utilization, human settlement environment quality, and ecological environment quality were divided into high, medium, and low levels based on their numerical values, where 1 represented a high level, 2 represented a medium level, and 3 represented a low level. For example, a type with high intensive land utilization, medium human settlement environment quality, and low ecological environment quality was represented by the code I1-H2-E3. This provides a clear judgment of the specific utilization quality of rural settlement areas. The optimization types of rural residential areas followed the principles of discerning whether the development of intensive land utilization, human settlement environment quality, and ecological environment quality are synchronous. According to the discrimination principles, if the three aspects developed synchronously and were all at the same level, then this was classified as the coordinated-control type. If the development levels of the three aspects were not synchronous and two or more of them were at a high level, then this was classified as the key-development type. If only one aspect was at a high level, then this was classified as the single-leading type. If all three aspects were at a low or medium level, then this was classified as the transforming-and-upgrading type. Finally, optimization schemes were proposed based on the different types of rural residential areas (Figure 2).

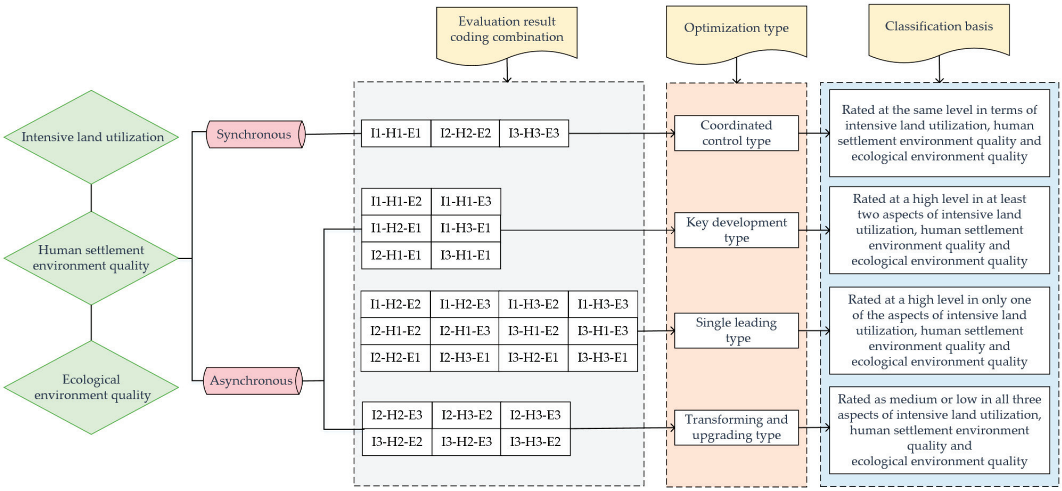

Figure 2. Classification of rural residential areas.

2.4.3. Diagnosis of Obstacle Factors

Based on the quality evaluation of the rural residential areas, an obstacle diagnosis model was constructed, and the deviation, factor contribution, and obstacle degrees were introduced for analysis. The main and secondary relationships of the influencing factors were determined by ranking the obstacle degrees [42]. The larger the obstacle degree value, the higher the degree of constraint on the high-quality utilization of rural residential areas. The related Formula (7) is shown below:

$$H_{ij} = \frac{U_{ij} - W_{ij}}{\sum\limits_{j=1}^{n} U'_{ij} W_{ij}} \tag{7}$$

where U_{ij} is the index deviation degree; $U_{ij} = 1 - X_{ij}$ is the difference between the standardized value of the single-index factor and the target value of 100%; X_{ij} is the standardized value of the i-th index; n is the number of evaluation indicators; W_{ij} is the weight of the i-th index; and H_{ij} is the obstacle degree.

3. Results

3.1. Analysis of the Utilization Quality of Rural Residential Areas

3.1.1. Diagnosis of Obstacle Factors

The scores of the intensive utilization of the rural residential areas in Wangkui County ranged from 0.2163 to 0.8534. As shown in Figure 3a, the numbers of high-, medium-, and low-level rural residential areas in the study area were 37, 49, and 23, respectively, accounting for 33.94%, 44.95%, and 21.10%, respectively. Spatially, the rural residential areas with a high intensive utilization were mainly concentrated around the Wangkui County urban area, including Wangkui Town and the southwest of Xiangbaimanzu Township. These areas had obvious locational advantages, were strongly influenced by the development of the central urban area, had high levels of human and material inputs, and had a good degree of land-use intensification. The rural residential areas with a medium intensive utilization were mainly distributed in the southern and eastern parts of Wangkui County, including Huqimanzu Town and Weixing Town, etc. These areas had average levels of socioeconomic development, their locational advantages were not obvious, and their land-use patterns were extensive. The rural residential areas with a low intensive utilization were mainly distributed in the northwest and southeast, including Xianfeng Town and Haifeng Town, etc. These areas made excessive use of the per capita residential land and had large village areas, high proportions of idle land, and low levels of land-use intensification.

Figure 3. Spatial distribution map of the utilization-quality grades of rural residential areas: (**a**) distribution map of the intensive-land-utilization grades; (**b**) distribution map of the human settlement environment quality grades; (**c**) distribution map of the ecological-environment-quality grades; (**d**) distribution map of the utilization-quality grades.

3.1.2. Analysis of the Human Settlement Environment Quality of Rural Residential Areas

The scores of the living-environment quality of the rural residential areas in Wangkui County ranged from 0.1998 to 0.7887. As shown in Figure 3b, the numbers of high-, medium-, and low-level rural residential areas in the study area were 12, 41, and 56, respectively, accounting for 11.01%, 37.61%, and 52.38%, respectively. Spatially, the rural residential areas with a high settlement-environment quality were mainly concentrated in the villages where the township governments were located, with high accessibility, complete supporting public service facilities, and high suitability for population living. The rural residential areas with a medium settlement-environment quality were mostly concentrated in the middle of Wangkui County, including Xiangbaimanzu Township and Dengta Town, etc. These areas were mainly developed for agriculture, with high rates of land cultivation; however, the development of secondary and tertiary industries was insufficient. The infrastructure and public service facilities barely met the daily needs of the villagers. The rural residential areas with a low settlement-environment quality were mainly distributed on the edge of Wangkui County, including the west of Xianfeng Town and east of Dongsheng Township, etc. With the increase in the distance from the central town, the suitability of the location of rural residential areas decreased. In addition, the eastern part of Wangkui County had backward agricultural production levels and poor living conditions for farmers.

3.1.3. Analysis of the Ecological Environment Quality of Rural Residential Areas

The scores of the ecological environment quality of the residential areas in Wangkui County ranged from 0.2241 to 0.8511. As shown in Figure 3c, the numbers of high-, medium-, and low-level rural residential areas in the study area were 28, 63, and 18, respectively, accounting for 25.69%, 57.80%, and 16.51%, respectively. Spatially, the rural residential areas with a high ecological environment quality were mainly distributed at the central, eastern, and western edges of Wangkui County, including Xianfeng Town and the eastern part of Dongsheng Township, etc. The Tongken River flows through the east of Wangkui County, which has relatively abundant wetland resources, and the Keyin River flows through the west, with a large area of ecological land. The central villages had relatively high greening coverage and good ecological environment quality. The rural settlements with a medium ecological environment quality were distributed in most parts of Wangkui County, including Lingshanmanzu Township and Xiangbaimanzu Township. These areas had vast arable land areas; however, the large-scale use of fertilizers, pesticides, and plastic films led to a decline in soil quality and had negative effects on the ecological environment. The rural settlements with a low ecological environment quality were mainly distributed in the southern areas, including Tongjiang Town and the eastern part of Huojian Town. These areas had fewer ecological land resources and low greening coverage.

3.1.4. Analysis of Utilization Quality of Rural Residential Areas

The comprehensive scores of the quality of the rural residential areas in Wangkui County ranged from 1.1977 to 1.8904. As shown in Figure 3d, the numbers of high-, medium-, and low-level rural residential areas in the study area were 22, 56, and 31, respectively, accounting for 20.18%, 51.38%, and 28.44%, respectively. Overall, the quality was mainly medium, accounting for more than half of the rural residential areas, followed by low quality and then high quality. Spatially, the utilization quality of the rural residential areas showed a circular structure. The utilization level gradually decreased from the town centers to the surrounding areas, and it showed some similarities to the distribution patterns of the intensive land utilization, human settlement environment quality, and ecological environment quality; however, it also possessed some unique characteristics. The rural residential areas with a high utilization quality were mainly distributed in the central and northeastern areas of Wangkui County, including Wangkui Town and Lianhua Town, etc. The economic-development level in the central region was relatively high, and it had strong suitability and convenience for production and living. These areas had better ecological environment quality. The rural residential areas with a medium utilization quality were mainly distributed in the northeast–southwest direction, including Tongjiang Town and Dengta Town, etc. The density of the rural residential areas was low. Public service facilities were lacking, such as education and medical care facilities, and agricultural production caused serious soil pollution. The rural residential areas with a low utilization quality were mainly distributed in the western and southeastern areas, including Xianfeng Town and Haifeng Town, etc. The western region was limited by natural conditions, such as the terrain and agricultural conditions. Moreover, the nonagricultural-production conditions were poor, the green-coverage rate was low, and ecological service facilities were lacking.

3.2. Classification and Optimization Scheme of Rural Residential Areas

This study aimed to improve the utilization quality of rural residential areas, and it followed the principles of the synchronous development of intensive land utilization, human settlement environment quality, and ecological environment quality to classify the optimization types of rural residential areas. First, the three aspects, namely, intensive land utilization, human settlement environment quality, and ecological environment quality, were encoded and combined. There were 27 possible combinations. Based on the actual situation in the study area, 23 types were finally derived. Second, according to the discrimination principles, if the three aspects developed synchronously and were all at the same level, then this was classified as the coordinated-control type. If the development levels of the three aspects were not synchronous and two or more of them were at a high level, then this was classified as the key-development type. If only one aspect was at a high level, then this was classified as the single-leading type. If all three aspects were at a low or medium level, then this was classified as the transforming-and-upgrading type. Finally, optimization schemes were proposed based on the different types of rural residential areas (Table 2 and Figure 4).

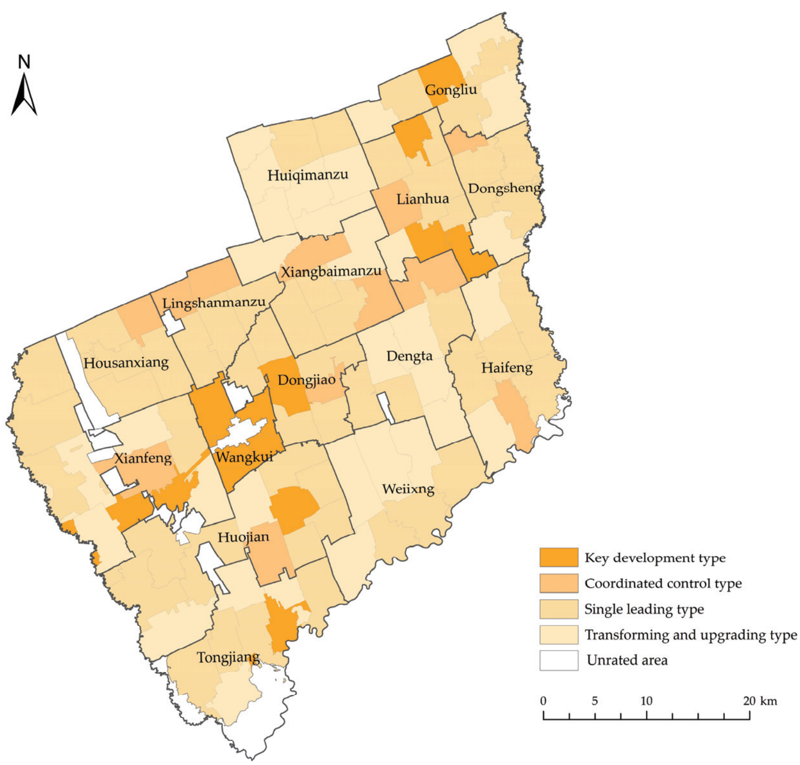

Figure 4. Distribution map of optimized types of rural residential areas.

Table 2. Types and optimization directions of rural residential areas.

Evaluation Result Coding Combination	Optimization Type	Optimization Direction
I2-H2-E2	Coordinated-control type	Insist on multi-functional coordinated development and focus on the effective combination of "quality" and "quantity"
I1-H1-E3 I1-H2-E1 I1-H3-E1 I3-H1-E1	Key-development type	Insist on key development, give full play to advantages and improve weaknesses according to local conditions
I1-H2-E2 I1-H2-E3 I1-H3-E2 I1-H3-E3 I2-H1-E2 I2-H1-E3 I3-H1-E2 I3-H1-E3 I2-H2-E1 I2-H3-E1 I3-H2-E1 I3-H3-E1	Single-leading type	Take advantage of dominant functions while considering improving weak functions
I2-H2-E3 I2-H3-E2 I2-H3-E3 I3-H2-E2 I3-H2-E3 I3-H3-E2	Transforming-and-upgrading type	Insist on transformation and upgrading and make sure to control reasonable development

The I2-H2-E2 combination of rural residential areas belonged to the coordinated-control type. These areas were mostly distributed around villages near town or township governments. Their overall strength was relatively coordinated, and they did not have prominent advantages in intensive land utilization, human settlement environment quality, or ecological environment quality; however, they still had substantial potential for development. In the future, we must adhere to this coordinated control, focus on the effective combination of "quality" and "quantity", rely on the conditions of economic development, and strengthen the communication and cooperation with surrounding villages. Moreover, we should establish pillar industries for the villages' development, thoroughly dig into the added value of agricultural products, strive to build a complete industrial chain for grain production, and construct a modern agricultural production system. In addition, we should improve the service capabilities of the various facilities within the villages and try to achieve the sharing of the construction of infrastructure and public service facilities with nearby towns and townships. Finally, we must reduce the use of pesticides and fertilizers and promote the use of degradable plastic film.

The I1-H1-E3, I1-H2-E1, I1-H3-E1, and I3-H1-E1 combinations of the rural residential areas belonged to the key-development type, which was mostly distributed in villages where the town or township governments were located. The quality of their utilization was relatively good, the land scale structure was reasonable, the degree of livability was high, and the ecological environment was clean. Overall, there were single obstacles in the intensive land utilization, human settlement environment quality, and ecological environment quality. In the future, we must stick to giving full play to each region's advantages, adhering to a high-quality-utilization orientation, and adopting effective strategies based on local conditions to improve shortcomings. We can integrate advantageous resources and industrial foundations, support the development of modern agriculture and rural tourism, seize the opportunity to create agricultural-ecological tourism projects, and achieve industrial integration. Furthermore, we should continue to improve the levels of various facilities, continuously improve the living environment, and focus on green and healthy development to achieve the high-quality utilization of rural residential areas.

The I1-H2-E2, I1-H2-E3, I1-H3-E2, I1-H3-E3, I2-H1-E2, I2-H1-E3, I3-H1-E2, I3-H1-E3, I2-H2-E1, I2-H3-E1, I3-H2-E1, and I3-H3-E1 combinations of the rural residential areas belonged to the single-leading type, which was mostly distributed in the central region. They had certain developmental advantages in one aspect of intensive land utilization, the human settlement environment quality, or ecological environment quality, and they showed obvious directional characteristics. This type of rural residential area should persist with the existing advantages as guidance and consider the improvement of weak functions. For intensive land use, it is necessary to activate the stock land and improve the land-use efficiency, and at the same time, improve the living conditions and ecological environment. For the high-quality living environment orientation, it is necessary to establish a long-term protection mechanism for human settlements and to orderly guide village construction while strengthening environmental governance. For the ecological function orientation, it is crucial to insist on the developmental concept of healthy environmental protection and to deeply explore the connotation value of ecological tourism. Meanwhile, we should strengthen the efficient and intensive use of land and improve the living environment.

The I2-H2-E3, I2-H3-E2, I2-H3-E3, I3-H2-E2, I3-H2-E3, and I3-H3-E2 combinations of rural residential areas belonged to the transforming-and-upgrading type, which was mostly distributed in the peripheral areas. Their utilization quality was relatively poor, and their intensive land utilization, human settlement environment quality, and ecological environment quality were mostly in a weak position. For this type of rural residential area, we should strengthen the transformation and upgrading, control the scale, and promote reasonable development. We must give full play to the guiding role of village planning, integrate low-efficiency and extensive rural residential areas, and strictly control the disorderly expansion of land use. Moreover, we should improve various agricultural production facilities and enhance the effective output of the cultivated land. It is equally important that we should guarantee the daily shopping, medical, and other basic needs of villagers; improve the connectivity between the rural residential areas; strengthen the village environmental governance; and add garbage and sewage treatment facilities to realize the sustainable development of the ecological environment.

3.3. Analysis of Obstacle Factors

According to Formula (7), the main obstacle factors affecting the quality of the rural residential utilization in Wangkui County were diagnosed based on their obstacle degrees. At the same time, based on the high and low obstacle-degree scores, the top five factors were sorted as the main obstacle factors. These factors were the traffic land density, aggregation index, green-coverage rate of built-up areas, completeness of public service facilities, and proportion of secondary and tertiary industrial land area (Table 3).

Table 3. Main obstacle factors of rural residential area utilization quality.

Quality Category		Obstacle Ranking 1	2	3	4	5
High quality	Obstacle factor	Traffic land density	Green-coverage rate of built-up areas	Proportion of secondary and tertiary industrial land area	Completeness of public service facilities	Aggregation index
	Degree of obstruction (%)	12.87	9.97	9.12	9.98	8.14
Medium quality	Obstacle factor	Traffic land density	Aggregation index	Completeness of public service facilities	Green-coverage rate of built-up areas	Proportion of secondary and tertiary industrial land area
	Degree of obstruction (%)	13.53	11.62	9.98	9.63	8.92
Low quality	Obstacle factor	Aggregation index	Traffic land density	Green-coverage rate of built-up areas	Proportion of secondary and tertiary industrial land area	Completeness of public service facilities
	Degree of obstruction (%)	13.87	11.87	10.75	9.24	8.93
Comprehensive	Obstacle factor	Traffic land density	Aggregation index	Green-coverage rate of built-up areas	Completeness of public service facilities	Proportion of secondary and tertiary industrial land area
	Degree of obstruction (%)	12.92	11.56	10.02	9.52	9.05

According to Table 2 and Figure 5, the top-ranked factor in terms of its overall obstacle degree was the traffic land density, with an obstacle degree score of 12.92%. This factor had a significant impact on villages located in high- and medium-quality areas, indicating that the accessibility of transportation in these areas was relatively low. Issues such as damaged road surfaces need to be urgently resolved. This phenomenon substantially affected the convenience of the villagers' travel and agricultural production activities.

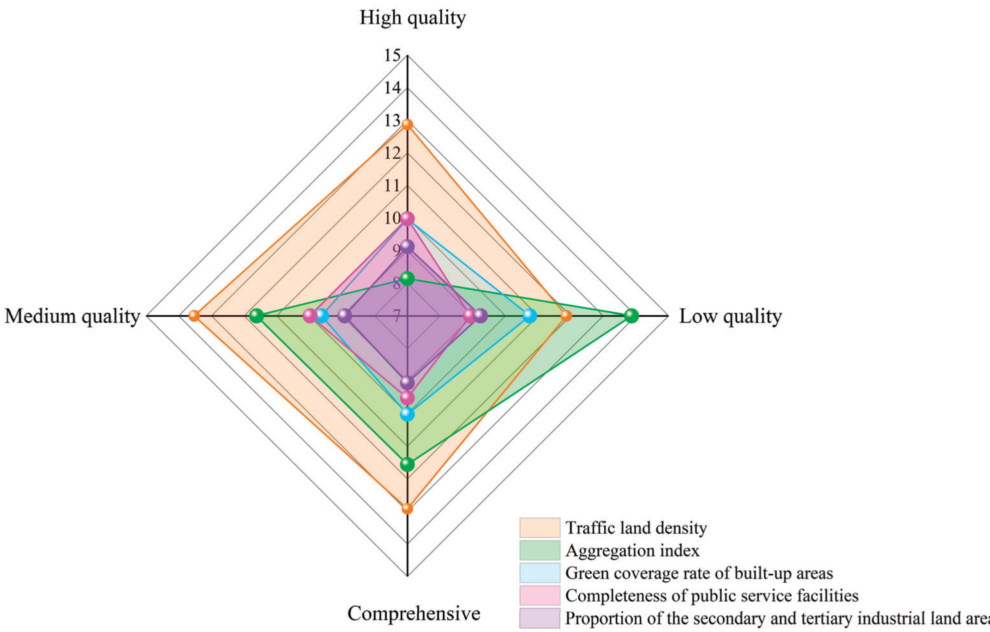

Figure 5. Obstacle degrees of main obstacle factors in rural residential areas' utilization quality. The coordinate axis value represents the degree of obstruction in high-quality utilization areas, medium-quality utilization areas, low-quality utilization areas and comprehensive utilization areas.

The second-ranked factor in terms of its overall obstacle degree was the aggregation index, with an obstacle-degree score of 11.56%. This factor negatively impacted medium- and low-quality areas, indicating that the layouts of the rural residential areas in these regions were dispersed, which made it difficult to plan and manage them uniformly. This extensive use of land resources resulted in wastage and affected the intensive use of the land.

The third-ranked factor in terms of its overall obstacle degree was the green-coverage rate of built-up areas, with an obstacle-degree score of 10.02%. The obstacle degree was higher in the high-quality areas, which indicated that the green-coverage rates in these villages were relatively low and the sanitation conditions urgently need to be improved. As the concepts of healthy and sustainable living become more widespread, people have higher demands for their living environments. Therefore, we should make efforts to accelerate the construction of gardens and green spaces to improve the quality of the ecological environment.

The fourth-ranked factor in terms of its overall obstacle degree was the completeness of public service facilities, with an obstacle-degree score of 9.52%. There was a large gap in the level of public service facilities in rural residential areas, with most villages having only small clinics and a few shops. Medium-quality villages in particular can only provide simple living guarantees for villagers and make it difficult to meet higher-level needs, such as education, medical care, and cultural and sports activities.

The fifth-ranked factor in terms of its overall obstacle degree was the proportion of secondary and tertiary industrial land area, with an obstacle-degree score of 9.05%. Overall, the villages lacked opportunities for the development of secondary and tertiary industries. Traditional agricultural production was still the main source of income for villagers. It was difficult to form a complete industrial chain due to the lack of personnel, technology, policies, and other factors.

In short, to achieve the high-quality development of rural residential areas, we should persist with strengthening the construction of road and transportation networks, rationally optimize their layout, increase their green-coverage rate, improve their level of public services, and accelerate the construction of village industries.

4. Discussion

4.1. Construction of Rural Residential Areas Utilization Quality Index System

Compared with previous studies by scholars such as Chen, Zhu, and Liu, who researched intensive-land-utilization evaluation [12–14]; Lu, Zhu, and Tang, who researched human-settlement-quality evaluation [15–17]; and Hong, Wang, and Zhang, who studied ecological-suitability evaluation [18–20], the quality evaluation of rural residential areas provides a new integrated research perspective for the optimization and development of rural settlements. The evaluation is not limited to the single aspects of intensive land utilization, human settlement environment quality, or ecological environment quality research. Instead, it incorporates elements of land, human habitat, and ecology into the indicator system, and it conducts a comprehensive and systematic quantification and analysis that fully reflects the requirements of the current era of the high-quality development of rural residential areas. At the same time, for the selection of the indicators, we considered the fact that the study area selected for this research was located in the Northeast Plain agricultural region of China and undertook the important task of safeguarding food production. Therefore, the ecological impact of the agricultural production was considered when constructing the ecological indicators for the rural residential areas, and indicators such as the intensity of use of fertilizers, pesticides, and agricultural plastic films were added.

4.2. Classification Analysis of Rural Residential Areas

Taxonomy is a science that is used to distinguish between different categories of things [43]. Determining a reasonable classification scheme for rural residential areas is beneficial for the specific implementation of optimization strategies. Among the existing research on the classification of rural residential areas, the use of matrices that rely on a combination of multidimensional features is a more common method. For example, Chen [41] classified rural residential areas in the Loess hilly–gully region based on the three-dimensional features of size, location, and layout, using the multidimensional combination matrix. Zhang [44] used the multidimensional combination matrix to classify rural residential areas in Pinggu District from the three dimensions of size, morphology, and location. Wang [45] used the combination matrix method to classify the rural residential areas in Feixiang County, Hebei Province, in terms of the three dimensions of size, morphology, and location. Qu [46] implemented the classification of rural residential areas based on multifactor feature coupling in terms of the three dimensions of balance between the rural production and labor structure, suitability of the human-habitat environment, and intensity of land use. The above research showed that the application of the multidimensional combination matrix in the classification of rural settlements was relatively extensive, fully reflecting the multidimensional information of rural residential areas and revealing the organic connections between the different dimensions. Based on relevant research, in this study, we used the multidimensional combination matrix to classify the rural residential areas into different types based on three aspects, namely, intensive land utilization, human settlement environment quality, and ecological environment quality, and then we proposed targeted policy suggestions that can verify the scientific validity and reliability of the research results.

4.3. Obstacle Factors Affecting the Utilization of Rural Residential Areas

In the existing research on the obstacle factors of rural residential areas, Zhang [47] pointed out that the rural road density and proportion of public space area are the main factors that affect rural residential areas. Lv [48] considered that the green-coverage rate has a significant impact on the livability of rural residential areas. Qu [49] demonstrated that the transportation conditions, infrastructure construction, and ecological environment are the main obstacle factors that affect rural residential areas. This study used the obstacle degree model to identify the obstacle factors that affect the high-quality utilization of rural residential areas, and it determined the top five obstacle factors, based on their obstacle degree, as the main obstacle factors. The specific order was as follows: transportation land density > aggregation index > built-up area green-coverage rate > completeness of public service facilities > proportion of secondary and tertiary industrial land area. The research results of previous scholars support the conclusions of this study, and these factors indeed have a certain degree of impact on the high-quality development of rural residential areas and should be improved during the optimization process.

4.4. Limitations and Future Work

It is worth noting that the study area was located in the agricultural region of the Northeast China Plain. In the process of constructing the index system, factors such as the scale, location, and farming conditions of the rural settlements were the main ones considered, while the influences of the topography and terrain were not. The indicators selected for this study were all aimed at achieving the high-quality utilization of rural residential areas in plain agricultural areas. Specific analyses should be conducted according to the local conditions in different regions, and the regional characteristics should be emphasized. Due to the limitations in the data availability, this study should be expanded and improved in the future. In the construction of the index system, there was a lack of consideration for indicators that are difficult to quantify, such as economic development, the villagers' attitude, folk customs, and institutional policies. In addition, the evaluation of the utilization quality of rural residential areas requires comprehensive research that involves many aspects and is still in the early stages of development, with relatively few mature research results. Therefore, in future research, it will be necessary to further reflect on the implications of the utilization quality of rural residential areas in light of modern requirements, to continue to strengthen the quantification of the indicators and enhance their refinement and dynamism, and to put forward more practical and feasible suggestions for the high-quality development of rural residential areas.

5. Conclusions

This study took Wangkui County as the study area—which is located in a typical agricultural area of the Northeast Plain in Heilongjiang Province—and it constructed an evaluation index system to assess the utilization quality of rural residential areas in terms of three aspects: intensive land utilization, human settlement environment quality, and ecological environment quality. Based on the evaluation results, the multidimensional combination matrix was used to classify the rural residential areas. The obstacle diagnosis model was employed to analyze the obstacle factors that affected the high-quality utilization of rural residential areas, providing the basis for their high-quality development. The research conclusions were as follows:

(1) This study demonstrated that the utilization quality of the rural residential areas in Wangkui County was mainly at a moderate level, followed by low-level utilization quality, and, finally, high-level utilization quality. In terms of spatial distribution, the evaluation results of the utilization quality of the rural residential areas showed a circular distribution pattern, with the overall quality of utilization decreasing from the centers of the county towns to the surrounding areas. The central region had relatively intensive land utilization and strong suitability and convenience for production and living. With the increase in the distance from the central town, the advantageous locational conditions became less obvious. Furthermore, various types of service facilities were lacking, and the pollution caused by agricultural production became more severe. This phenomenon led to the poorer utilization quality of rural residential areas.

(2) According to the evaluation results of the utilization quality of the rural residential areas, and using the multidimensional combination matrix to code and combine them, a total of 23 combination types were obtained. Based on the above results, the rural residential areas were divided into four types: the coordinated-control type, the key-development type, the single-leading type, and the transforming-and-upgrading type. Specific optimization measures were proposed for each type according to its characteristics.
(3) Based on the diagnosis results of the obstacle factors, we found that the top five obstacle factors affected the high-quality utilization ranking of the rural residential areas in Wangkui County; these obstacle factors were the traffic land density, aggregation index, green-coverage rate of built-up areas, completeness of public service facilities, and proportion of secondary and tertiary industrial land area. In the future, we must focus on alleviating the main obstacle factors to enhance the utilization quality of rural residential areas.

Author Contributions: Conceptualization, H.Z. and R.C.; methodology, H.Z.; validation, H.Z., R.C. and S.L.; formal analysis, S.L.; resources, H.Z. and R.C.; data curation, R.C.; writing—original draft preparation, R.C.; writing—review and editing, H.Z. and R.C.; visualization, R.C. and S.L.; supervision, H.Z.; project administration, H.Z.; funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Strategic Priority Research Program of the Chinese Academy of Sciences, grant number XDA28130402, the National Natural Science Foundation of China, grant number 41402297, and the Postdoctoral funded project in Heilongjiang Province, grant number LBH-Z12032.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to express our gratitude to the professionals of the Northeast Agricultural University who encouraged us to make this project a success.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Characteristics, Drivers, and Development Modes of Rural Space Commercialization under Different Altitude Gradients: The Case of the Mountain City of Chongqing

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Abstract: The spatial commercialization of rural areas is essential to achieve rural reconstruction and promote overall rural rejuvenation. Through the use of a land use transfer matrix and kernel density, this study uncovers the pattern characteristics, driving forces, and development patterns of rural spatial commodification at various altitudes, providing a scientific reference for rural spatial usage at various altitudes. The main conclusions of this study are as follows: (1) rural spatial commercialization is the result of land use transformation, and the differences in rural spatial commercialization development patterns lead to different characteristics in the local land use changes; (2) the implementation of urbanization, industrialization, and rural revitalization strategies has promoted the development of rural spatial commercialization to some extent; (3) There are significant differences in the characteristics of the land use change and the development pattern of rural space commercialization at various altitudes. The areas below 500 m are mainly for recreational projects that have a repeatable consumption and that are distributed in a concentrated and continuous manner. For such areas, the agglomeration effect should be taken full advantage of, and thus they should be developed in groups. The areas between 500 and 1000 m serve mainly the surrounding residents; the mode is based on the leisure and recreational projects with a block-shaped spatial distribution. In such areas, branded rural spaces with special features should be created. The areas above 1000 m are used primarily to construct tourist attractions and are dispersed in a point pattern. In such areas, the transportation conditions should be improved and the rural resources revitalized by designing reasonable travel routes.

Keywords: rural space commercialization; land use change; drivers; different altitudes; rural revitalization; China

Citation: Lv, Z.; Yang, A.; Wang, Y. Characteristics, Drivers, and Development Modes of Rural Space Commercialization under Different Altitude Gradients: The Case of the Mountain City of Chongqing. *Land* **2023**, *12*, 1028. https://doi.org/10.3390/land12051028

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 15 April 2023
Revised: 2 May 2023
Accepted: 3 May 2023
Published: 8 May 2023

1. Introduction

Due to urbanization and the mass exodus of rural labor, rural areas are facing problems such as the abandonment of arable land and the "hollowing out" of the countryside [1,2]. According to the 2022 Central Rural Work Conference, "Promoting rural revitalization comprehensively is an important task in building a strong agricultural country in the new era, with industrial revitalization being the most important task in rural revitalization. We should implement industrial support policies, rely on the unique resources of agriculture and rural areas, seek benefits from developing multiple agricultural functions and tapping the diverse values of the countryside, seek benefits from integrated development of one, two, and three industries, and improve market competitiveness and capacity for sustainable development". The commercialization of rural space is an important means of realizing the multiple values of the countryside and integrating industrial development [3]. The overarching goal is to shift the mode of rural economic development from agricultural production to comprehensive business development, and from rough development to refined development, to achieve higher incomes for farmers, increased efficiency in agriculture, and prosperity for the countryside [4]. However, the commercialization of rural space in China is still in its infancy, and the methods and approaches are not yet mature enough to play a true role or have real value in rural revitalization. At the same time, the development mode of rural space commercialization varies by region. Therefore, to achieve the goal of rural revitalization, it is critical to explore the characteristics of the pattern, driving factors, and development models of rural space commercialization in various regions.

The definition of "space" has always been complex and multidimensional, and can be divided into material and immaterial space [5]. The book "The Production of Space" pioneered a "theory of spatial production" in which "space" could be continuously produced and re-produced through the practices of production and consumption [6]. The identification of the concept of rural space has always been a popular issue in rural studies [7,8]. Rural space is usually regarded as a synthesis of the physical, social, cultural, ecological, and other elements [9]. In this paper, rural space is defined as the space of rural production, with agricultural production at its core; the space of rural consumption, with rural tourism at its core; the space of rural residence, which includes rural settlements and rural architecture; and the space of rural landscape, with rural culture at its core [10–12]. According to Marx, commodities are the material embodiments of use-value, exchange value, and value, and commodification refers to the process of transforming or mutating things that are not originally part of the sale or circulation of goods, or acts that should not have commercial purposes, into objects that can be bought and sold under the conditions of the market economy [13]. The commercialization of rural space essentially refers to the dynamic process by which rural space acquires the characteristics and value of a commodity [14] and is "sold" for a profit under the conditions of a market economy [15,16]. Developed countries, such as those of Western Europe, the United States [11], and Japan [17], conducted earlier research on the commercialization of rural space [15,18], with a particular emphasis on the investigation of the mechanisms of its occurrence [19]. Furthermore, different stages of socioeconomic development have given rise to different theories of rural space development [20,21]. Following World War II, "productionism" emerged, which was characterized by a view of the countryside as a space for material production, with the production itself regarded as the ultimate measure of value and meaning [22]. In the 1990s, there was a shift away from an overemphasis on land resource production and toward a greater emphasis on diverse land-based economic activities. The countryside was viewed as a territorial spatial system with multiple values, combining material and immaterial production [8,23]. In addition, the theory of the transformation of the multifunctional countryside, which has been used to improve the relationship between the two, considers the countryside as having a variety of functions, including environmental management, ecological conservation, and cultural heritage [24,25]. Simultaneously, foreign scholars have conducted a large number of case studies on the phenomenon of the commercialization of rural space, investigating how to create new tourism resources through the commercialization of rural space to achieve regional development [26].

Chinese scholars' research on the commercialization of rural space is still at an early stage, and their research focuses primarily on the combination of the foreign theories on the commercialization of rural space, the inspiration of typical foreign cases in China, and the empirical research on the reconstruction of rural areas through the commercialization of rural space in developed regions. The research areas are concentrated primarily in the developed plain regions such as Beijing, Jiangsu, and Guangdong; the research methods mainly include the actor-network theory [27], the case study method [28], and the spatial analysis methods, such as kernel density estimation [29,30]. Due to China's rapid urbanization, the vast Chinese countryside has gradually transformed from a single production function to a multi-functional integration of production, living, ecology, aesthetics, and education, and the implicit value of rural space has gradually emerged [31,32]. Since rural development is relatively weak in China's mountainous regions, which make up 69% of the nation's total area, it is especially crucial to realize the commercialization of rural space in these areas to facilitate the realization of rural revitalization. However, the existing research on the commercialization of rural space is focused on the plain regions, and there are fewer studies on the phenomenon of spatial commercialization in the vast mountainous countryside. Moreover, there is a lack of systematic studies on specific cases in typical regions. In studies on the commercialization of rural space in mountainous areas, the current classification method is still based on that of the plains, which is based on the functional zoning of cities or the spatial circle from the inside out, ignoring the unique influence of altitude on rural development in mountainous areas. Due to this, it is challenging to use rural spatial commercialization in mountainous regions as a driving force behind the overall revitalization of the countryside.

In view of this and in the context of the accelerating urbanization and the rising demand for non-farm livelihoods by farming households [28], this paper selects Chongqing as a typical representative region within the mountainous region; takes the spatial commercialization of the countryside as the entry point; uses the land use data and the data on the types of spatial commercialization of the countryside as support; employs the land use change measurement and kernel density estimation methods to clarify the characteristics of spatial commercialization of the countryside at different altitudes; analyses the driving factors behind the formation and development of the spatial commercialization of the countryside; and reveals the problems in the current development model. The aims of this paper are to help raise the income of farming households and to help achieve sustainable economic and social development in the countryside. At the same time, through comparative studies, the development patterns of the commercialization of rural space at different altitudes are considered, the rational and effective use of rural space is promoted, and the path of coordinated regional development is explored.

2. Materials and Methods

2.1. Study Area

Chongqing is in southwest China, near the upper reaches of the Yangtze River, with western Hubei to the east, Sichuan-Guizhou to the southwest, and Sichuan-Shanxi to the northwest. The following are the reasons for selecting it as the topic of this paper: Firstly, the region's mountainous and hilly landscape accounts for 70% of the land area, with an altitude difference of 2723 m, and significant geographical variations in natural resource endowments, which can effectively represent the development of rural spatial commodification at different altitudes. Secondly, by the end of 2021, the city's resident population reached 32,124,300 people, including 9,533,000 rural residents, the per capita disposable income of whom was RMB 18,100, representing only 41.6% of the per capita disposable income of the urban residents; these factors demonstrate the typical geographical background of a "big city, big rural area, and big mountainous area" [30]. Thirdly, progress has been made in the commercialization of the rural space in Chongqing, as demonstrated by the following developments: the development of clusters of advantageous rural industries with special characteristics, the innovative development of rural tourism, and the emergence of new industries and new business models. Due to the large size of the study area and the complex and diverse topography, this paper selects Xiema Town in the Beibei District, Xinglong Town in the Yubei District, and Xianushan Town in the Wulong District as the typical representative areas in three types of altitude intervals: below 500 m, between 500 m and 1000 m, and above 1000 m, all within one to two hours' drive to Chongqing's main city (Figure 1).

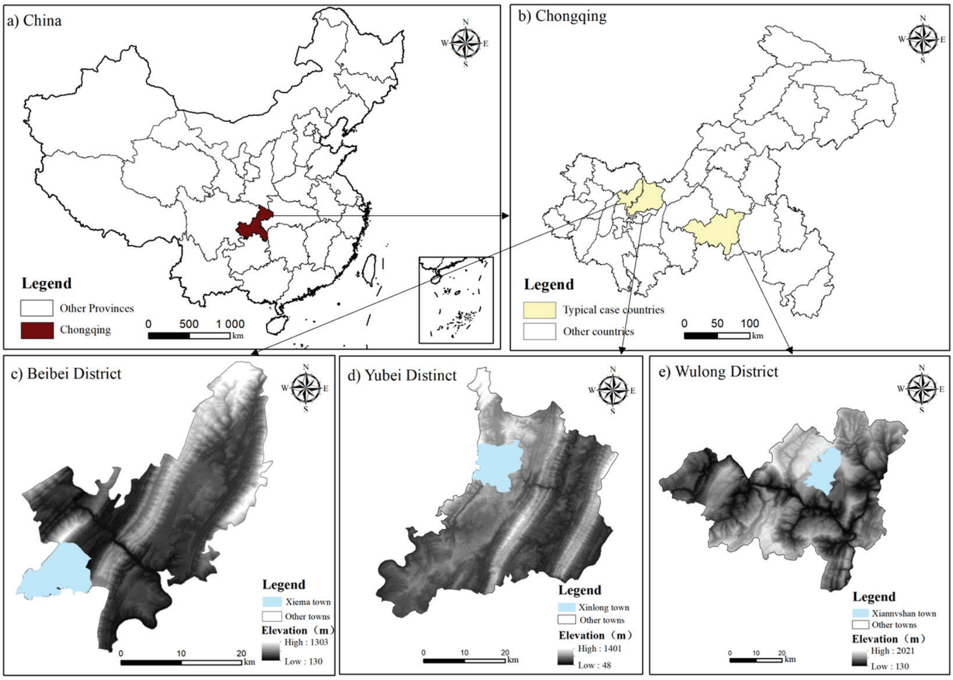

Figure 1. Schematic diagram of the study area.

The Beibei District, one of Chongqing's main urban areas, is a typical case area in an area below 500 m, with unique location conditions and the spatial advantage of integrated scenic and urban areas. Xiema Town, located in the southwest of the Beibei District, is an area of 58 square kilometers and flat and open terrain. The Yubei District, located in the northwest of Chongqing, is a typical case area in the area between 500 m and 1000 m, and belongs to the main urban area of Chongqing and the metropolitan area of Chongqing, and the urban and rural development in the region is very different. Xinglong Town, located in the north-central part of the Yubei District, is one of Chongqing's ecological towns, with the advantage of "facing the city in front and the countryside behind", covering an area of 93.5 square kilometers. The Wulong District, located southeast of Chongqing in the lower reaches of the Wujiang River, the Wuling Mountains, and the Great Lou Mountain Gorge, is a typical case area above 1000 m, and includes the World Natural Heritage Karst Furong Cave and the national 5A tourist attraction of the Tiansheng Three Bridges. Xiannushan Town, located in the north-central part of the Wulong District, Chongqing, as well as 20 km from the Wulong City District, is an important location for economic growth in the Wulong District's "one river, two wings" development strategy. Because of its resource advantages, its rural space commercialization has a higher degree of development than other areas at the same altitude, which can serve as a model for other regions.

2.2. Data

The required data for this article mainly consist of regional land use data and rural spatial commercialization representation data. The land use data used in this article include topographic maps of Chongqing, the current land use map of the study area, and other supporting maps from Wuhan University's research paper "30 m annual land cover and its dynamics in China from 1990 to 2019"; the study area's socioeconomic development data were obtained from the sixth and seventh population censuses, the statistical yearbooks published by the Chongqing Municipal Bureau of Statistics, and the statistical bureaus of the districts and counties; the data on the types of spatial commercialization of the countryside mainly consisted of four types: hotels and lodges, recreation and entertainment, such as farmhouses and picking gardens, scientific and educational culture, such as museums, and tourist attractions. The data are obtained by first using Python to obtain the names, categories, administrative regions, latitude, and longitude of the relevant geographical elements in the Gaode map, and then obtaining the corresponding POI data of rural space commercialization in Chongqing.

2.3. Methods

2.3.1. Estimation of Land Use Change

The total change in land use type is the sum of the transfers in and out of a specific land use type, as well as the sum of a specific land type's net change and exchange change [33]. The following is the formula for this:

$$S_i = S_{gain} + S_{loss} = D_i + C_i \tag{1}$$

$$S = S_{gain} - S_{loss} \tag{2}$$

where Si represents the total change of land-use type i, S_{gain} is the transfer in of land-use i, and S_{loss} is the transfer out of land-use i. Di is the net change of land-use i, where "±" of the Di value indicates the direction of change of land-use i, "+" indicates a net increase, and "−" indicates a net decrease. Ci is the amount of exchange change of land-use i.

The net change in land use is the absolute change in land use and is one of the common indicators of land use change. However, due to the fixed and unique spatial location of land use, the net change volume has limitations and cannot objectively and accurately reflect the dynamic process of the interchange of land classes. Therefore, the amount of land exchange change should be used as one of the measurement indicators that can quantitatively analyze the dynamic amount of change in the interconversion of one land class with another. The greater the degree of change in a land class, the greater the amount of exchange change; conversely, the smaller the degree of change in a land class, the smaller the amount of exchange change.

2.3.2. Measure of Land Use Change

The magnitude of land use change refers to the amount of change in land use type relative to the total area of the study area over a fixed period of time, which can be used to analyze the overall trend for land use change and can directly characterize the rate of land use change. The formula is as follows:

$$U = [(S_b - S_a) \div S \times 100] \times 100\% \tag{3}$$

where U is the magnitude of land use change for a land category, S_a is the area of a land category at the beginning of the study period, S_b is the area of a land category at the end of the study period, and S is the total area of the study area. The "±" value of U indicates the direction of change of land-use i, "+" indicates a net increase, and "−" indicates a net decrease.

Land use change dynamics refers to the rate at which land use types change in quantity over a fixed period, and it can be used to forecast future trends in land use change. The formula is as follows:

$$V = [(S_b - S_a) \div S_a] \div T \times 100\% \tag{4}$$

where V is the dynamic attitude of the change in land use for a particular land category. T For the duration of the study, the same interval of 10 years was used in this study, T = 10. Where the value of "±" indicates the direction of change of land-use i, "+" indicates the net increase, and "−" indicates the net decrease.

2.3.3. POI-Based Kernel Density Estimation

POI data describe a geographic entity's spatial and attribute information, such as its name, category, and coordinates [34]. Kernel density estimation, proposed by Emanuel, is a geographic algorithm for calculating the density of point features or line features. The principle is that the closer the thing is to the core feature, the greater the density expansion value; it is frequently used to study the spatial distribution characteristics of a group of points [35]. As of March 2022, the number of major rural space commoditization such as rural B&Bs and farmhouses in Chongqing is 22,409. This paper investigates the degree of agglomeration of rural space commercialization in Chongqing based on the distribution of the kernel density values using the POI data of country houses and farmhouses in Chongqing. The search radius is set to 10,000 m using the kernel density estimation of the POI data obtained, and the output image element size is set to 40 m. The formula is as follows:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\frac{x - x_i}{h} \tag{5}$$

where $f(x)$ is the kernel density function at the spatial location x; h is the analysis range threshold, i.e., the search radius; K is the default spatial weight kernel function; and $x - x_i$ represents the distance from the valuation point to the output grid.

3. Results

3.1. Characteristics of Land Use Change in the Case Area

The typical case areas of the three elevation intervals, below 500 m, 500–1000 m, and above 1000 m, are Xiema Town in the Beibei District, Xinglong Town in the Yubei District, and Xiannushan Town in the Wulong District, respectively. They present different land use characteristics (Figure 2 and Table 1). The development status of the commodification of rural space varies, as does the impact on the pattern of land use change [36].

Figure 2. Land use change chord map of typical case areas from 2000 to 2020. * The trajectory lines of different colors denote the flow direction of a particular place in a specific period. The thickness of the trajectory lines denotes the variation; the larger the variation, the thicker the trajectory lines.

Table 1. Statistics on the amount and characteristics of land use change in typical case areas from 2000 to 2020.

Land Use Type	Total Change(km^2)			Swap Change(km^2)			Net Change(km^2)			Change Amplitude (%)		
	Xiema Town	Xinlong Town	Xiannushan Town	Xiema Town	Xinlong Town	Xiannushan Town	Xiema Town	Xinlong Town	Xiannushan Town	Xiema Town	Xinlong Town	Xiannushan Town
Cultivated land	8.51	13.24	15.92	14.85	23.90	17.53	−6.33	−10.66	−1.61	−0.69	−0.73	−0.33
Woodland	3.15	12.95	16.13	1.67	2.53	14.94	1.48	10.42	1.20	0.52	2.94	0.06
Shrub	0.00	0.01	0.65	0.00	0.00	1.24	0.00	0.01	−0.60	−5.00		−4.75
Grassland	0.04	0.00	1.38	0.00	0.00	1.01	0.04	0.00	0.37			3.33
Water	0.32	0.26	0.02	0.54	0.10	0.02	−0.23	0.16	0.00	−2.46	7.79	0.15
Building land	5.12	0.09	0.64	0.08	0.01	0.00	5.04	0.08	0.64	19.30	5.01	926.93

First, overall, the typical case areas at all elevations demonstrate mainly a decrease in arable land and an increase in forest land and construction land. Arable land is the land type with the greatest change in terms of magnitude, and forest land and construction land contribute the most to both the transfer-in and transfer-out structures. The exchange of arable land for forest land accounts for most of the change in land use type. Because the background value of rural construction land is low, the change dynamics of construction land are all higher. In particular, the town of Xianushan in the Wulong District is located in a mountainous area above 1000 m, with a small proportion of construction land to the total land area. Social capital has been aggressively introduced for the construction of scenic spots since the commercialization of rural space, and the dynamics of change in the construction land during the study period reached 926.93%, with a much higher rate of change than the other land use types.

Secondly, in comparison, in terms of the number of changes in each category, forest land is the land use type with the greatest increase in area in Xinlong Town, Yubei District, and Xiannushan Town, Wulong District, while construction land is the land type with the greatest increase in area in Xiema Town, Beibei District. This is mainly because Xiema Town in the Beibei District is located in a low-altitude area, below 500 m, where rural commercialization is rapidly developing, concentrated in patches, and has a broad reach. Thus, the modern urban agricultural gardens and farm caravans have a large area of land for construction and are rapidly growing. In terms of the magnitude of change in each category, the magnitude of change in the water bodies is small in Xiema Town of the Beibei District and Xiannushan Town of the Wulong District. Still, it is second only to that of cultivated land and forest land in Xinglong Town of the Yubei District, where the attitude of change in the water bodies is the greatest. This is primarily because Xinglong Town in the Yubei District has constructed an ecological area covering approximately 3000 acres as part of the spatial commercialization process, resulting in a rapid expansion of the water body area.

In summary, the commercialization of rural space is essentially the result of a countryside reconfiguration, which has resulted in an increase in the function of spatial consumption, the root cause of which is land use transformation. The improvement of the land use function is an important way to implement the rural revitalization strategy [37]. By analyzing the characteristics of land use change in different altitude case areas, differences in the development mode of rural spatial commercialization which result in different local land use change characteristics can be found. Therefore, choosing a suitable spatial commercialization development mode for the region can form a rational, efficient, and intensive land use structure by changing the regional land use, and ultimately maximize the comprehensive economic, social, and ecological benefits of land use [38]. At the same time, the original land use structure of the region can, to some extent, reflect the transformation of the regional land functions in a certain period [39] and provide the right direction for the selection of the spatial commercialization development mode.

3.2. Characteristics of Rural Space Commercialization in the Case Areas

Figure 3 shows the distribution of rural space commercialization types in typical case areas. Figure 4 shows the rural space commercialization nuclear density map in typical case areas.

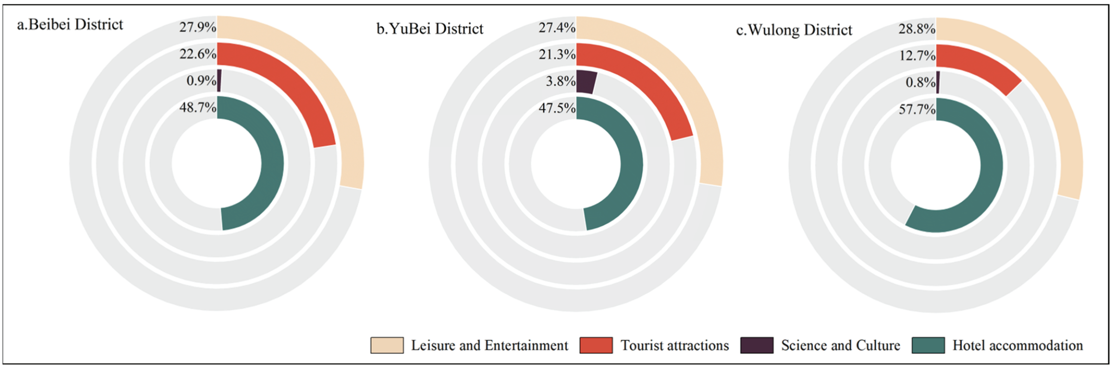

Figure 3. Distribution of rural space commercialization types in typical case areas.

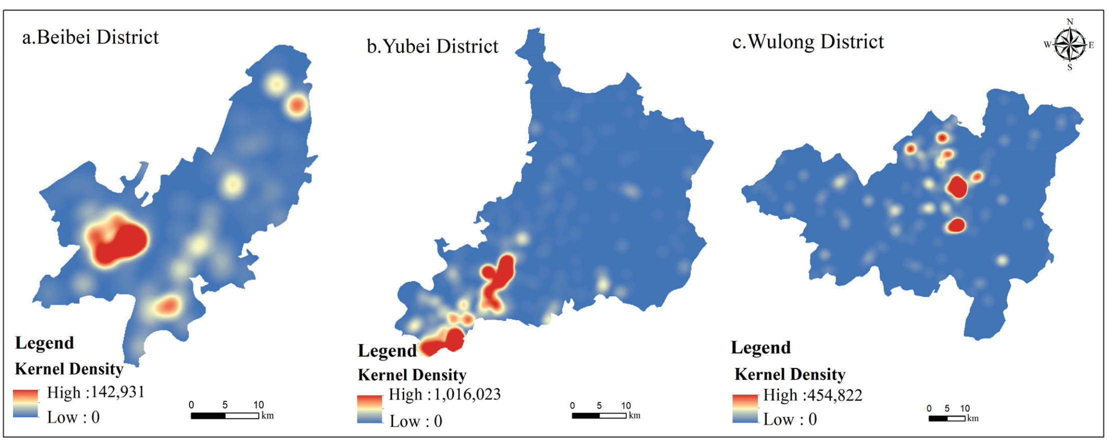

Figure 4. Rural space commercialization nuclear density map in typical case areas.

The Beibei District, located in a low-altitude area below 500 m, has a high concentration of rural space commercialization, and its overall spatial layout is distributed in a faceted manner. Further, its rural space commercialization is dominated by leisure and entertainment venues such as farm caravans and picking gardens. In 2009, Xiema Town in the Beibei District aggressively developed new rural industries and actively guided the development of upscale farmhouse catering services. Overall, this stage of the rural space is still dominated by the production functions, while the rural space consumption function is being gradually developed. In 2018, the comprehensive agricultural leisure demonstration park Jiang Zhou cherry garden opened to the public, attracting visitors from the main city and surrounding areas. In 2019, Chongqing Cloud Agricultural Development Co., Ltd. from Chongqing, China, was introduced to create a collection of leisure, tourism, picking, and holidays in one of the modern urban agricultural parks, and eventually achieved an increase in collective income of 8000 yuan. The Beibei District, Xiema Town, integrated regional resource characteristics in each countryside to create agritourism or special crop picking gardens and other recreational and entertainment projects that can be consumed repeatedly by villagers' self-owned or corporatized rural resource developments. This attracts visitors from the surrounding and main urban areas. Space commercialization characteristics are obvious.

The Yubei District, located in a mid-latitude area of between 500 m and 1000 m, has a block-shaped spatial distribution of the spatial layout of rural space commercialization, including recreational and tourism attractions, two types of rural space commercialization, developed together. In 2004, the town of Xinglong in the Yubei District introduced capital to develop local special agriculture, establishing a foundation for plum cultivation. In 2010, the town held a plum culture festival, shifting from production to the development of rural spaces through the creation of tourism brands. In 2017, Xinglong Town adopted the agricultural park as its core leader and focused on assisting in the construction of projects such as the Xinglong Flower Sea and the outdoor camping base to promote the development of rural commercialization through the integration of multiple industries. In 2020, the town fully exploited the location's advantages, encouraged the deep integration of "agriculture, culture, tourism, and creativity," and effectively tapped into tourism resources, thus promoting the process of the commodification of rural space. In general, the commercialization of the rural spaces in Xinglong Town, Yubei District is slow, and the development potential remains untapped.

The Wulong District, located at a high altitude of above 1000 m, has a dotted pattern of rural spatial commercialization, with a focus on local characteristic alpine resources. Its development of spatial commercialization of the tourist attraction type is remarkable. The town of Xiannushan in the Wulong District emerged earlier than the surrounding areas in the commodification of rural space, becoming a model area for the development of rural space commodification in the region thanks to its unique natural resources. In 2002, the Furong River National Key Scenic Spot in the Wulong District was approved and completed, and the Harbor Peninsula became a popular tourist attraction. In 2012, the Chongqing Intangible Cultural Heritage Base was built. In 2021, the government actively promoted key projects in Xiannushan District, constructing a demonstration base for youth science in Xiannushan District, a town with cultural and artistic characteristics as well as an international ecological recreation town, and fully utilized the "Internet +" and other emerging means to promote the two-way extension of the rural industry chain and drive the sustainable development of rural space commercialization. Overall, the Wulong District is a relatively unique area for the commercialization of rural space above 1000 m, with a much higher degree of development than other areas at the same altitude and a focus on creating tourist attractions.

3.3. Driving Mechanisms of Rural Space Commoditization in the Case Areas

In recent years, the phenomenon of the commercialization of rural space in China has arisen and grown along with the ongoing transformation of the countryside [40]. Earlier studies explicitly attributed the "external aid drive" as the cause of the commodification of rural space, but most scholars today think that the cause should be an "internal and external combined drive" [41]. Since the reform and opening, the rapid development of urbanization and industrialization in China has led to a drastic transformation and reconstruction of rural areas. It has produced specific responses to rural space [23]. Urban capital has flowed into the countryside in large quantities; the market economy has prompted changes in the function of rural land; the traditional production function has been weakened; the consumption function has been continuously developed; the land has continuously increased in value [42]; and the rural industrial structure has gradually shifted from primary industries to secondary and tertiary industries [5,43]. This has promoted the conversion of rural areas from traditional production to contemporary consumption spaces, as well as the formation and growth of the commercialization of rural space in China. The connection between the rural and urban areas in the region is distinct due to the varying location conditions at various altitudes, which also encourages the development of various rural space commercialization characteristics and development paradigms(Figure 5).

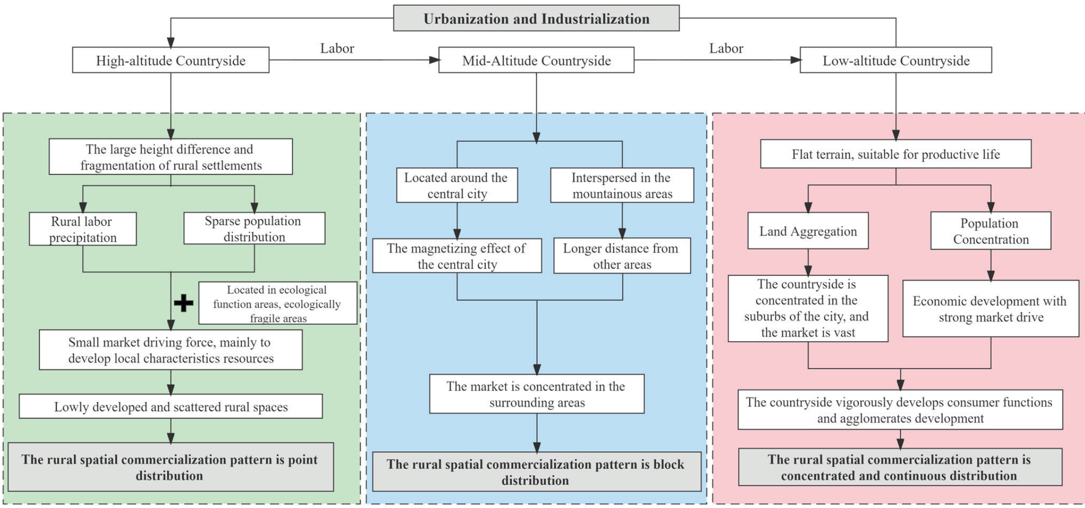

Figure 5. Driving mechanisms of spatial commoditization at different altitudes.

The rural spatial commercialization pattern in low-altitude areas below 500 m is concentrated and contiguous. Such areas in Chongqing are concentrated primarily in the central urban areas, such as the Yuzhong District, the Jiangbei District, and the Nanan District, where the terrain is flat and suitable for human habitation and development, the economy is developed, and the population is concentrated. As a result, the people who benefit from the region's commercialization of rural space are primarily urban residents in central urban areas, where there is a high demand for quality rural tourism. At the same time, the villages in the central urban areas are distributed throughout the suburban areas, with good economic foundations, an early start of habitat improvement, and near-perfect public service facilities, all of which provide a good material foundation and spatial environment for the commercialization of the local rural space.

The spatial commercialization of the rural areas between 500 and 1000 m in elevation exhibits a blocky distribution pattern with a higher density. The area is mostly concentrated around the central urban area or is interspersed with mountainous areas, such as in Xinglong Town in the Yubei District. On the one hand, the rural economy in this altitude range is more backward in comparison to the development in the central urban area. A large number of people have left the area due to the magnetic attraction effect of the core urban region, and therefore the market for the commercialization of the rural territory has dwindled. On the other hand, compared to the areas below 500 m, the villages in areas between 500 and 1000 m in elevation are more dispersed and affected by the influence of driving. Therefore, the market demand for the commercialization of the rural space comes primarily from the residents of the surrounding cities, making it less appealing to the cross-area population.

The rural spatial commodities are dotted, sparse, and scattered in the high-altitude areas above 1000 m. Such areas, represented by Xiannushan Town of the Wulong District, are primarily distributed in the northeastern and southeastern regions of Chongqing, having special geographical locations. Northeast Chongqing is part of the Three Gorges Reservoir Area, which serves as an important ecological barrier in the Yangtze River's upper reaches; southeast Chongqing is a national key ecological function area, an important biodiversity reserve, and an ecological folk culture tourism belt [44]. The villages in this altitude range are both ecologically sensitive and ecologically fragile, and development is based primarily on the "protection on the surface and development on the point" approach. As a result, such locations have experienced some degree of ecological migration, are economically disadvantaged, and are underdeveloped, with a sparse population distribution. At the same time, due to the large difference in terrain height and relatively low accessibility, cross-zone comprehensive development is difficult, and the development of local characteristics is mainly independent.

4. Discussions

4.1. Overall Pattern of Rural Spatial Commercialization in Chongqing

The overall pattern characteristi0063s of rural space commercialization are obtained after analyzing the spatial distribution of rural space commercialization in Chongqing (Figure 6).

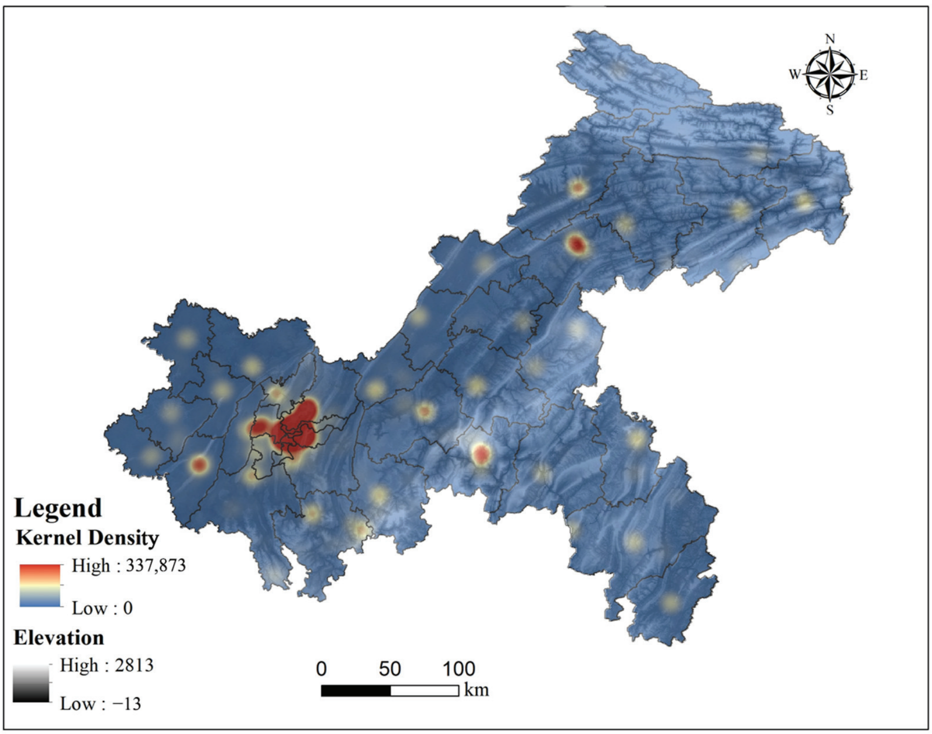

Figure 6. Nucleation density of rural space commercialization in Chongqing.

The commercialization of rural space in Chongqing forms a high-density ring in the main urban area, as well as three high-density zones in the Yongchuan, Wulong, and Wanzhou districts; the medium-density zones are distributed primarily in the hilly areas with small height differences; and low-density zones are scattered and widely distributed. The spatial commercialization of the countryside is concentrated mainly in the central urban area or the countryside around tourist attractions, such as Xiannushan in the Wulong District, based on the distribution characteristics of each density zone. Rural space commercialization is concentrated in the plain areas and sparsely distributed in mountainous areas. The development of rural space commercialization occurs when high-profile tourist and scenic spots exist in the high-altitude mountainous areas. Overall, the regional development of rural space commercialization in Chongqing is uneven.

4.2. Insights into the Commercialization of Rural Space in Different Altitudes

Low-altitude areas—those below 500 m—focus on integrating regional resources and achieving cluster development. Areas in this altitude range should integrate the characteristics of the region's rural resources, take full advantage of the area's topographic advantages, and utilize the clustering effect. For example, when integrating the regional resources to organize the relevant festivals and events, these areas should set up special parks with different themes to achieve a mutual attraction between villages in the region with a series of activities, and thereby help the coordinated development of the commercialization of the rural space in the region using the differences in the agricultural production in different villages in the region. Concurrently, because the land in the region is mostly concentrated and contiguous, with superior agricultural planting conditions, local enterprises should be encouraged to improve the level of science and technology, improve the quality of agricultural products, develop various functional food and health products, develop superior seeds and products, enrich the product line of deep cultural experiences, and realize the transformation of the agricultural products into the tourism industry based on a strict adherence to the red line of arable land.

In middle-altitude areas—those between 500 m and 1000 m—due to the small regional market radiation range, the key to growing rural space commercialization is to build branded rural spaces, improve the rural visibility, and broaden the market radiation range. For example, because such areas typically lack obvious topographic and landscape characteristics, the process of space commercialization can create branded rural spaces through visual image shaping. Simultaneously, the breadth of the rural spatialized products should be investigated and actively promoted to the outside world. The link between the products and the cultural experience, aesthetic services, and artistic creativity should be strengthened, as should the integrated development of various functions, such as rural space idyllic tourism, leisure picking, cultural experiences, and science education.

In high-altitude areas—those above 1000 m—the priority is to increase the investment in road construction, improve the transportation infrastructure, enhance the traffic conditions, and improve accessibility and convenience. Such areas can also carry out the design of tourism routes mainly for the natural experience and sightseeing before the development of the area by transforming mountainous areas to their advantage, attracting tourists who enjoy driving and improving the attractiveness of the areas. Simultaneously, because villages between such altitude zones are dispersed and thus it is difficult to form independent attractions, the core characteristics of each village in the region can be explored deeply and linked together to form a theme promotion during the planning and development. Then, in different villages, the priority is to construct the same type and different series of facilities to deepen the tourists' memory of the association between attractions, so that the tourists' impression of the joint theme of the attractions is continuously deepened and the tourists' return rate is improved.

4.3. Implications of the Rural Space Commodification for Rural Revitalization

The rural revitalization strategy is a major strategic decision affecting China's agriculture and rural farmers; it was proposed in the 19th Party Congress report, which points out the direction for the national government to do a good job with the "three rural areas" in the current and future periods. In the new era, China's agricultural supply-side structural reform has made significant progress, the agricultural production capacity has been significantly increased, new industries and business models are flourishing in the rural areas, and profound changes are occurring in rural society. However, the rural areas remain the weakest link in China's modernization plan, with the most obvious shortcomings in economic and social development concentrated in the "three rural areas." The current situation of a poor rural foundation and lagging development remains a real issue that must be addressed. The 20th Central Document No. 1, "Opinions of the Central Committee of the Communist Party of China and the State Council on the Key Work of Promoting Rural Revitalization in 2023," emphasizes the importance of promoting the high-quality development of rural industries and broadening the channels through which farmers can increase their incomes. The prosperity of industry is the root of the rural revitalization strategy, and the commercialization of rural space is an important practice to revitalize rural space resources and promote the transformation and upgrading of rural areas from traditional production spaces to modern consumption spaces.

The key to rural space commercialization is activating rural resources, and reproducing and recreating the value of rural spatial resources [45]. The first step toward activating rural space is to fully explore local resources, and the key way to realize the transformation of its multi-functional value is to explore the typical path of the commercialization of spatial resources on this basis. Because China's rural areas are vast and the basic conditions vary greatly from place to place, the scientific commercialization model must be based on each place's differentiated positioning. Whether we focus on agricultural production to create special agricultural products or extend the industrial chain, the goal is to promote the transformation of rural space from a single agricultural production space to a multifunctional space combining production and consumption. Concurrently, the process of commercialization of rural space is inextricably linked to the influence of consumer culture and industrial capital intervention, which will hasten the dramatic changes in the countryside and trigger its reconstruction. As a result, to effectively contribute to rural revitalization, we must also be aware of and avoid potential risks associated with the commercialization of rural space [1].

5. Conclusions

In the context of the rural revitalization strategy, the Chinese countryside urgently requires the removal of barriers to development and the resolution of the dilemmas of serious land abandonment, the single inefficient function, and the inadequate improvement of the human living environment. Rural space commercialization is an important means of rural reconstruction and spatial transformation, and it is critical to investigate its characteristics, driving factors, and modes for the implementation of a rural revitalization strategy. In recent years, Chongqing has been aggressively developing rural tourism around rural revitalization and poverty alleviation, as well as promoting the process of rural spatial commercialization. At the same time, Chongqing, a mountain city, has a unique geographical environment with an undulating terrain and strong three-dimensional qualities. Therefore, the development of rural space commercialization varies greatly and has distinct characteristics. This study examines the mechanisms that drive the spatial commercialization in rural Chongqing and discovers that urbanization, industrialization, and rural rejuvenation efforts are major driving forces for the development of spatial commercialization in rural areas. Initially, urbanization and industrialization facilitated a shift in the spatial pattern of rural land use, and the introduction of foreign capital prompted the expansion of rural areas from a single production function to a multi-functional integrated development, resulting in the emergence of rural spatial commodification. Later, the implementation of a rural revitalization strategy improved the material basis and spatial environment for the development of rural space, optimized the rural land use structure, and promoted the integration of rural multi-industries and the re-exploitation of rural space. These factors facilitated the development of rural space commercialization.

This paper uses Chongqing as an example and discusses the characteristics of rural space commercialization at different altitudes, putting forward strategies to optimize the development mode of rural space commercialization, release the vitality of rural space, promote the high-quality development of rural industry, promote the continuous increase in farmers' income, promote rural revitalization, and achieve common prosperity. In addition, in China, the commercialization of rural spaces is still in its early stage of development. The Chongqing Municipality is used as the research object in this paper, which lacks a comprehensive discussion on it. Further research needs to be carried out in combination with the actual situation of different regions in China to carry out more details discussions in theory and practice.

Author Contributions: The authors contributed together to the completion of this article. Specifically, their individual contributions are as follows: conceptualization, Y.W. and A.Y.; methodology, A.Y.; software, Z.L. and A.Y.; validation, Y.W. and Z.L.; formal analysis, Z.L.; investigation, Z.L.; resources, A.Y.; data curation, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, Z.L.; visualization, Y.W.; supervision, Y.W.; project administration, Y.W.; funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Training Program of Innovation and Entrepreneurship for Undergraduates (202210635022), the National Natural Science Foundation of China (42271263, 41901232), and the Fundamental Research Funds for the Central Universities (SWU-KT22008).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Thank you to everyone who contributed to this study.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Influence of Agricultural Technology Extension and Social Networks on Chinese Farmers' Adoption of Conservation Tillage Technology

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Abstract: Agricultural technology extension and social networks are the essential components of formal and informal institutions, respectively, and their influence on agricultural production has been the focus of academics. This article takes conservation tillage technology as an example, based on simple random unduplicated sampling, and uses survey data of 781 farmers in Heilongjiang, Henan, Shandong, and Shanxi provinces of China. This article empirically tests the interaction effects and heterogeneity of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology and analyzes their substitution effect or complementary effect. The results showed the following: (1) From a single dimension, both agricultural technology extension and social networks can significantly promote farmers' adoption of conservation tillage technology, and the promotion effect of agricultural technology extension is greater. The average probability of farmers who accept agricultural technology extension and social networks adopting conservation tillage technology increases by 36.49% and 7.09%, respectively. (2) There is a complementary effect between agricultural technology extension and social networks in promoting farmers' adoption of conservation tillage technology. The two functions complement and support each other, and this complementary effect is more evident in social networks' reciprocity. (3) Further analysis reveals that the interaction effect between agricultural technology extension and social networks has significant group differences, technology type differences, and regional differences in farmers' adoption of conservation tillage technology. Therefore, to facilitate the extension and application of conservation tillage technology, efforts need to be made in both agricultural technology extension and social networks, fully leveraging the complementary effects of the two. In addition, differentiated policies and measures should be adopted according to local conditions, and precise policies should be implemented for different groups and technologies.

Keywords: conservation tillage technology; agricultural technology extension; social networks; substitution effect; complementary effect

Citation: Xu, J.; Cui, Z.; Wang, T.; Wang, J.; Yu, Z.; Li, C. Influence of Agricultural Technology Extension and Social Networks on Chinese Farmers' Adoption of Conservation Tillage Technology. *Land* **2023**, *12*, 1215. https://doi.org/10.3390/land12061215

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 11 May 2023
Revised: 29 May 2023
Accepted: 7 June 2023
Published: 12 June 2023

1. Introduction

Conservation tillage originated in the United States in the 1940s, and by 1988, it had grown to be applied in more than 700 countries [1]. In 2003, the total global conservation tillage area reached 72 million hectares [2], and now the proportion of agricultural production that incorporates conservation tillage in the United States, Canada, Brazil, and other countries has reached 70% [3]. Experimental research on conservation tillage in China began in the 1960s and has developed rapidly, but there is still a large gap compared to developed agricultural countries [4]. In particular, China has a complex and diverse range of cropland types, ecological regions, and cropping systems, and there are significant regional differences in the choice of conservation tillage practices [5]. The practice has proved that conservation tillage is an effective way to protect and utilize farmland and is an important tool to implement the strategy of "hiding food in the land and food in technology", which is an inevitable choice and strategic idea to ensure national food security in the new development stage [6].

Currently, China has achieved significant results in the comprehensive protection and utilization of farmland [7], but the degradation of farmland quality and the intensification of ecological and environmental risks in farmland use are more prominent [8,9], posing a threat to national food security and sustainable agricultural development [10]. Conservation tillage technology can effectively improve soil properties [11,12], enhance soil fertility [13,14], reduce wind erosion and water erosion [15,16], increase grain yield [17,18], reduce greenhouse gas emissions [19,20], and increase farmers' income [21]. It has significant ecological and economic benefits.

Farmers are the main implementers and direct beneficiaries of conservation tillage technology [22]. The key reasons are as follows: on the one hand, farmers have a "second-best" path dependence on traditional farming technology [23]; on the other hand, technological and institutional changes face a series of constraints, including policy factors [24], technological factors, economic factors [25], and individual farmer factors [26]. Therefore, it is of great theoretical significance and practical value to investigate the important factors that motivate farmers' adoption of conservation tillage technology and to scientifically formulate relevant measures to promote the dissemination and application of conservation tillage technology.

Changes in agricultural structures, government decentralization, and the development of emerging information and communication technologies have led to diversified and low-cost agricultural technology extension and advisory services [27]. Public agricultural extension is a key force in supporting the development of modern agriculture and an important policy tool for the government to support agriculture. As an important part of the formal institution, agricultural technology extension refers to the activities of transforming and applying advanced agricultural technologies and scientific and technological achievements to the agricultural production process through experiments, demonstrations, training, guidance and consulting services, etc. It has the advantages of wide coverage, diversified methods, and high accuracy of information, and it mainly relies on government power to facilitate its role. In 2021, the Rural Revitalization and Promotion Law of the People's Republic of China was promulgated and implemented. This law emphasizes "strengthening the construction of agricultural technology extension system, promoting the establishment of incentive mechanisms and benefit-sharing mechanisms conducive to the transformation and extension of agricultural scientific and technological achievements, and provide services for agricultural technology extension". At present, Chinese agricultural extension has achieved remarkable results, with the grassroots agricultural technology team steadily growing, technology supply efficiency steadily improving, and agricultural technology associations with extension channels gradually becoming more prominent, which has become an effective way to promote agricultural science and technology progress and agricultural and rural modernization, while also providing an important driving force to motivate farmers to adopt conservation tillage technology.

At the same time, individual farmers' behavior is not completely isolated; social relationships play an important role in shaping behavior [28]. In the traditional relational society of rural China, farmers, as members of rural society, are not only bound by formal rules in their behavior but are often influenced by rural social networks as well [29]. In the traditional relationship society of rural China, farmers, as members of rural society, are not only bound by formal rules but are often influenced by rural social networks [30]. Social networks are a form of social organization based on "networks" (interconnections between nodes) rather than "groups" (clear boundaries and order) [31]. As an important element of informal institutions, social networks influence the economic behavior of farmers through individual interactions, social relationships, and unwritten norms [32]. It has been shown that social networks are an important factor influencing the agricultural production behavior of farmers [33]. Therefore, when analyzing farmers' adoption of conservation tillage technology, it is necessary to focus not only on the important role of agricultural technology extension but also on the influence of farmers' social networks.

Agricultural technology extension and social networks, as essential components of formal and informal institutions, have received widespread attention in agricultural production. So, what is the impact of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology? What is the relationship between the two in the process of influencing farmers' adoption of conservation tillage technology? Additionally, does this relationship significantly vary in different situations? These are key issues that urgently need to be explored and resolved. Therefore, this article focuses on three core issues: Firstly, what are the separate effects of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology? Secondly, what is the relationship between agricultural technology extension and social networks? Thirdly, does the relationship between agricultural technology extension and social networks vary in different situations?

Compared with previous studies, the innovation of this paper lies in the following: Firstly, an indicator system of social networks is built using the three dimensions of strength, reputation, and reciprocity, incorporating agricultural technology extension and social networks into the same empirical model to study farmers' adoption of conservation tillage technology, accurately measuring the marginal effect of the two, and testing the substitution effect or complementary effect between the two. Compared to existing research, it is more holistic and systematic. Secondly, it is to analyze the relationship between agricultural technology extension and different dimensions of social networks in influencing farmers' adoption of conservation tillage technology. Based on different groups, technologies, and regions, the differences in the interaction effects between agricultural technology extension and social networks were examined, enriching the research on farmers' adoption of conservation tillage technology.

2. Literature Review

2.1. The Relationship between Agricultural Technology Extension and Farmers' Adoption of Agricultural Technology

Regarding the relationship between agricultural technology extension and farmers' adoption, the mainstream view is that agricultural technology extension will promote farmers' adoption of agricultural technology. Feyisa found through a meta-analysis that agricultural technology extension services would significantly increase the adoption rate of agricultural technologies by small farmers in Ethiopia [34]. Li et al. found that a digital extension service based on smartphones significantly increased the probability of farmers adopting soil testing and formulated fertilization technology [35]. Zhao et al. found that an increasing number of agricultural technology extension service organizations promoted biological pesticides through online technical guidance and released technical science videos on new media platforms, which improved the probability of farmers' access to and adoption of bio-pesticide technology [36].

At the same time, some studies also found that the extension of agricultural technology has a partial spillover effect while improving the technology adoption level of farmers, which can promote the technology adoption probability of elderly farmers and small-scale farmers [37]. Different from the studies mentioned above, some studies showed that public agricultural technology extension plays a significant role in the initial stage of new technology dissemination. However, as time goes by, more and more farmers realize the importance of new agricultural technology and begin to adopt it, which leads to the gradual weakening of the marginal effect of agricultural technology extension [38]. Lambrech et al. found that there was significant gender heterogeneity in the effect of agricultural technology extension, female participation in agricultural technology extension was not necessarily conducive to the realization of the agricultural technology extension goal [39]. In addition, other studies showed that government agricultural technology extension services are mainly obtained by farmers with wealth and power, while vulnerable farmers can hardly access agricultural technology extension services [40,41]. To some extent, it hinders the popularization and dissemination of new agricultural technologies.

2.2. The Relationship between Social Networks and Farmers' Adoption of Agricultural Technology

Regarding the relationship between social networks and farmers' adoption of agricultural technology, the mainstream view is that social networks will promote farmers' adoption of agricultural technology. In some developing countries, farmers usually receive agricultural information from local social networks rather than directly from governments and non-governmental organizations [42]. Communication and interaction between farmers are important channels for them to obtain agricultural technologies [43]. Within a single village area, people will face almost the same environmental conditions and factor constraints. Farmers have similar production and management cognition and working habits, as well as high homogeneity of technical interaction [44]. Therefore, in the implementation of multi-party agricultural protection projects, farmers are more inclined to interact with participating farmers in local social networks [45]. Oriana and Imran found that farmers' neighbors and friends have a significant impact on their decisions for new technology adoption [46].

Social learning exists in the diffusion processes of new agricultural technologies; that is, farmers may follow the agricultural production behaviors of farmers who have been successful in their social networks [47]. In addition, social networks can effectively promote farmers to adopt agricultural technology by reducing the uncertainty of technology adoption [48] and functioning as an information channel [49]. In contrast to the above views, some scholars believe that although the training of demonstration farmers can encourage other farmers to imitate the agricultural technology adopted by demonstration farmers, the difference in socioeconomic status among farmers cannot ensure effective communication between ordinary farmers and demonstration farmers in a village [50]. It makes it impossible for ordinary farmers to imitate and learn the adoption of agricultural technology by demonstration farmers. Munshi discussed the learning problem of a heterogeneous population in the spreading process of the "green technology revolution" in India and found that the heterogeneity of social networks will rapidly weaken the information flow [51], which is not conducive to farmers' learning of new agricultural technology. In addition, the decision delay caused by the externality of social network information will also defer farmers' adoption of new agricultural technologies [52].

2.3. Literature Review and Research Directions

After reviewing the literature, it can be seen that although there have been many studies exploring the impact of agricultural technology extension and social networks on farmers' adoption of agricultural technology, there is still room for further expansion and improvement. Firstly, the conclusions on the impact of agricultural technology extension and social networks on farmers' adoption of agricultural technology are not consistent. Therefore, this article takes conservation tillage technology as the research object and conducts further empirical tests. Secondly, existing research generally overlooks the inherent relationship between agricultural technology extension and social networks in influencing farmers' adoption of agricultural technology and has not included them in the same framework for overall systematic research, making it difficult to present the interactive logic between the two. Thirdly, existing research has not yet examined the differential impact of the relationship between agricultural technology extension and social networks on farmers' adoption of agricultural technology in different situations.

Therefore, this article uses survey data of 781 farmers in Heilongjiang, Henan, Shandong, and Shanxi provinces of China, empirically explores the effect of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology, and examines their interaction effect. At the same time, the heterogeneities of the interaction effect between agricultural technology extension and social networks in different situations were further investigated. These works provide useful references for the government to formulate relevant policies to promote conservation tillage.

3. Theoretical Analysis

3.1. The Separate Effects of Agricultural Technology Extension and Social Networks on Farmers' Adoption of Conservation Tillage Technology

As one of the "green box policies" encouraged by the World Trade Organization for investment, agricultural technology extension is considered by most scholars as an important political measure to improve agricultural productivity [53–55]. After more than 70 years of development, China has formed an agricultural technology extension system with national, provincial, municipal, county, and township departments, which has made great contributions to agricultural development. The agricultural technology extension has the advantages of wide coverage, diversified methods, and high accuracy of information, which are conducive to the extension and application of agricultural technology. The theoretical logic is proposed in the following three aspects:

First, the direct promotion effect of agricultural technology extension. The replacement of old technologies with new technologies and the extension of new technologies both depend on the promotion strategy of government departments, which combines compulsion and inducement. The compulsory promotion strategy is reflected in the fact that agricultural technology extension is a top-down process. The government can effectively gather dispersed farmers and ensure the timely and orderly development of technology promotion by relying on the institutional advantages of administrative power. The inductive promotion strategy is manifested in that the government actively supports demonstration farmers through interest publicity and policy support and promotes them to play a leading role in demonstration, to reform the agricultural technology [56], and to promote farmers to adopt advanced agricultural technology.

Second, the indirect promotion effect of agricultural technology extension. According to Schulz's human capital theory, the effective way to transform traditional agriculture is to educate and train farmers. The process of agricultural technology extension is also the process of improving farmers' cognition and learning ability. When farmers accept and learn new technology, they often face the problem of a lack of cognition and ability. Dissemination of knowledge and technology through the agricultural technology extension not only improves the cognition of farmers but also expands and enriches the knowledge reserve of farmers, enhances the ability of farmers to learn and apply technology, and contributes to the improvement of the efficiency and level of technology extension.

Third, the diffusion effect of agricultural technology extension. According to the theory of agricultural technology diffusion, technology diffusion can be divided into four stages: the breakthrough stage, the critical stage, the following stage, and the following general trend stage. With the passage of the diffusion stage, more and more farmers adopt the new technology, and the new technology begins to be popularized [57]. Accordingly, this article proposes the first hypothesis:

Hypothesis 1: *Agricultural technology extension has a positive effect on farmers' adoption of conservation tillage technology.*

The social networks of farmers are a relatively stable relationship system formed by connecting them through certain relationships with high-density and short transmission paths [29]. It plays an important role in farmers' technology adoption decisions [58]. Rural China is a typical acquaintance society, where the relationship network between farmers and acquaintances, such as relatives, friends, and neighbors, is built upon factors such as blood, kinship, and geography. By extending, expanding, and maintaining social network relationships, farmers' advantages in accessing resources and opportunities are significantly improved [47]. In terms of the adoption of agricultural technology, the following can be said:

On the one hand, farmers who adopt new agricultural technologies will face high information search and learning costs [59]. Expanding information channels through social networks can reduce information asymmetry in technology adoption, promote information dissemination and sharing, improve farmers' understanding of technology, and ultimately promote their decision-making on technology adoption. At the same time, through communication and learning with farmers who have already adopted new technologies, more knowledge about new technologies can be obtained, the learning cost of technology adoption can be reduced, and the time for technology application can be greatly shortened.

On the other hand, social networks have a risk-sharing mechanism, which is a powerful supplement to resist risks [60]. There will be certain risks and uncertainties in the implementation process of new technologies, and farmers' extensive communication and cooperation through social networks can help resolve technical risks, reduce uncertainty, and, to a certain extent, ensure the effectiveness and quality of technology implementation. In addition, the mutual benefit and assistance formed by farmers in long-term interaction can enhance trust among farmers and help achieve resource sharing and optimized allocation, which not only promotes the diffusion and dissemination of new technologies but also reduces the transaction costs of technologies. Accordingly, this article proposes the second hypothesis:

Hypothesis 2: *Social networks have a positive effect on farmers' adoption of conservation tillage technology.*

3.2. The Influence of the Interaction Effect between Agricultural Technology Extension and Social Networks on Farmers' Adoption of Conservation Tillage Technology

There is a substitution effect between agricultural technology extension and social networks, which means that social networks form a certain substitution for agricultural technology extension.

On the one hand, although agricultural technology can be transferred "top-down" by relying on the extension system of agricultural technology, it cannot obtain positive responses from farmers "bottom-up". That reduces the contribution rate of agricultural technology to agricultural production [61]. The close social networks among farmers can effectively break the asymmetry of technical information transmission. Relying on strong networks, farmers can form interest groups, which can more quickly express their appeals and opinions to the grassroots government to promote farmers' extensive participation in agricultural technology extension, access to technical training, guidance, and relevant services, and receive effective feedback. At the same time, the production characteristics of small-scale decentralized management increase the difficulty of agricultural technology extension. Social networks such as villagers, relatives, and friends can promote the spread of agricultural technology, promote the spread and extension of technology to rural areas in remote areas, and form a substitution effect for agricultural technology extension.

On the other hand, because farmers' knowledge and cognition levels are generally low, the technology dissemination formed through agricultural technology extension can ensure the accuracy of information [37]. However, compared with this one-sided form of technology dissemination, farmers can learn and apply agricultural technology through social networks, and the interactions will be more frequent and in-depth. The inherent trust and understanding among farmers are the most likely to trigger their real emotions, which is conducive to the formation of a stable community of interests. They can also significantly reduce the risk of farmers adopting new technologies, thus improving the efficiency and sustainability of technology adoption. Accordingly, this article proposes the third hypothesis:

Hypothesis 3: *Agricultural technology extension and social networks have a substitution effect on farmers' adoption of conservation tillage technology.*

There is a complementary effect between agricultural technology extension and social networks, and their functions are also complementary. Agricultural technology extension and social networks, as two different communication modes of agricultural technology extension and application, can complement each other in their influences on farmers' adoption of conservation tillage technology.

On the one hand, as technology dissemination is led and implemented by the government, agricultural technology extension has the advantages of high information accuracy and diversified methods [62]. As the leader and implementer, the government can effectively guarantee agricultural technology extension and carry out the extension of agricultural knowledge and agricultural technology through training, publicity, and guidance, which helps to improve the knowledge level and cognition of farmers. In this way, farmers can easily adopt and apply conservation tillage technology.

On the other hand, social networks form a beneficial supplement to agricultural technology extension [63]. Through the extension of social networks, farmers have expanded their social relationships, deepened their understanding of technology through continuous communication and exploration, and presented a clear "herd effect". At the same time, the stable and close social network relationships between farmers provide intellectual, financial, and material support for technology application, question answering, and process assurance, which helps to improve the technology adoption rate of social networks' members and form functional complementarity with the government-led agricultural technology extension. Accordingly, this paper proposes the fourth hypothesis:

Hypothesis 4: *Agricultural technology extension and social networks have a complementary effect on farmers' adoption of conservation tillage technology*.

4. Materials and Methods

4.1. Data

The data are based on a survey of farmers in Heilongjiang, Henan, Shandong, and Shanxi provinces in China from January to February 2022. According to the "Code for the Implementation of Conservation Tillage Projects" and "Key Technical Points of Conservation Tillage", there are six suitable areas to research the implementation of conservation tillage technology within the Northeast Plain monopoly area: the Great Wall along the agricultural and pastoral areas, the northwest loess plateau area, the northwest oasis agricultural area, the Huang-Huai-Hai plain cropping area, and the southern water and dry continuous crop area. Heilongjiang belongs to the Northeast Plain monopoly crop area and the western arid and wind-blown sand area, Henan and Shandong belong to the Huang-Huai-Hai plain cropping area, and Shanxi belongs to the Northwest loess plateau area and the North China Great Wall along the area. At the same time, Heilongjiang, Henan, and Shandong are typical representatives of the main grain-producing areas, and Shanxi is a representative of the grain production and marketing balance area, so the selection of the above four provinces as the research area is both typical and representative.

The research follows the principle of simple random unduplicated sampling, obtaining the list of farmers in advance and selecting the sample of farmers in the surveyed area by machine selection. The respondents include small farmers, large-scale professional farmers, family farms, and other new types of agricultural businesses. The food crops planted mainly include corn, rice, wheat, soybeans, etc. A total of 819 questionnaires were collected, and 781 effective questionnaires were obtained by sorting out the collected questionnaires, with an effective rate of 95.36%. Among the questionnaires, 230 were from Heilongjiang, together with 197 from Henan, 187 from Shandong, and 167 from Shanxi. The survey was mainly conducted in the form of one-to-one interviews with farmers, and questionnaires were filled out by trained researchers to fully ensure the authenticity of each questionnaire. The subjects of this survey are all heads of farmers, and the questionnaire covers individual characteristics of farmers, family characteristics, production and management characteristics, technology adoption and farmers' social networks, etc.

As shown in Table 1, male heads of farmers accounted for 85.28% of the survey samples. Those aged 50 to 59 years old accounted for 46.22%. The education level of the farmers is generally low, and 79.77% had an education level of junior high school or below. More than half of the farmers are in good health, accounting for 50.06%. Most of the farmers had an income that was less than 100,000 RMB, accounting for 78.87%. The number of agricultural laborers concentrated on 2 or 3 people, accounting for 76.18%. Farmers' scale of the land operation was generally small, accounting for 66.58% of the total of 1 hectare or less. In addition, only 17.29% of farmers joined cooperatives.

Table 1. Basic sample characteristics.

Basic Features	Options	Frequency (%)	Basic Features	Options	Frequency (%)
Gender	Male	666 (85.28)	Education level	Primary school and below	238 (30.47)
	Female	115 (14.72)		Junior high school	385 (49.30)
Age	(0, 29]	10 (1.28)		Senior high school or secondary school	129 (16.52)
	[30, 39]	30 (3.84)		Associate college and above	29 (3.71)
	[40, 49]	185 (23.69)	Number of agricultural laborers	1	165 (21.13)
	[50, 59]	361 (46.22)		2 or 3	595 (76.18)
	[60, +∞)	195 (24.97)		[4, +∞)	21 (2.69)
Health status	Very poor	2 (0.26)	Farmers' income	(0, 50,000 RMB]	309 (39.56)
	Comparatively poor	44 (5.63)		(50,000, 100,000 RMB]	307 (39.31)
	General	226 (28.94)		(100,000 RMB, +∞)	165 (21.13)
	Comparatively well	391 (50.06)	Scale of land operation	(0, 1 hm^2]	520 (66.58)
	Very well	118 (15.11)		(1–2 hm^2]	100 (12.80)
Cooperatives	Yes	135 (17.29)		(2–3 hm^2]	48 (6.15)
	No	646 (82.71)		(3 hm^2, +∞)	113 (14.47)

4.2. Models

To test the effect of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology, the following econometric model was established:

$$Tech_{ij} = \alpha_0 + \beta_1 Exten_{ij} + \gamma X_{ij} + \lambda_j + \varepsilon_{ij} \tag{1}$$

$$Tech_{ij} = \alpha_1 + \beta_2 Net_{ij} + \gamma X_{ij} + \lambda_j + \varepsilon_{ij} \tag{2}$$

$$Tech_{ij} = \alpha_2 + \beta_3 Exten_{ij} + \beta_4 Net_{ij} + \gamma X_{ij} + \lambda_j + \varepsilon_{ij} \tag{3}$$

In Equations (1)–(3), i and j denote the farmer and the province where the farmer is located, respectively. $Tech_{ij}$ is the explanatory variable, indicating whether the farmer adopts conservation tillage technology or not. $Exten_{ij}$ and Net_{ij} are the core explanatory variables, denoting agricultural technology extension and social networks, respectively. X_{ij} denotes a set of control variables. The intercept terms are represented by $\alpha_0, \alpha_1, \alpha_2$, ε_{ij} is the random error, and $\beta_1, \beta_2, \beta_3, \beta_4, \gamma$ are a series of coefficients to be estimated. In addition, a range of unobservable variables at the provincial level may simultaneously affect farmers' adoption of conservation tillage technology, agricultural technology extension, and social networks, leading to biased estimation results. In this regard, the model controls for area effect at the provincial level λ_j.

To further explore the substitution or complementary effect of agricultural technology extension and social networks in influencing farmers' adoption of conservation tillage technology, the interaction terms of agricultural technology extension and social networks were constructed, and the following econometric model was established:

$$Tech_{ij} = \alpha_3 + \beta_5 Exten_{ij} + \beta_6 Net_{ij} + \beta_7 Exten_{ij} \times Net_{ij} + \gamma X_{ij} + \lambda_j + \varepsilon_{ij} \tag{4}$$

In Equation (4), the meaning of the variables is the same as in Equations (1)–(3), where $Exten_{ij} \times Net_{ij}$ denotes the interaction term between agricultural technology extension and social networks. In the empirical analysis, observing β_7 helps to determine the substitution effect or complementary effect between agricultural technology extension and social networks. If β_7 is positive, it means that there is a complementary effect between the agricultural technology extension and social networks; if β_7 is negative, it means that there is a substitution effect between the agricultural technology extension and social networks. As the explanatory variables in the above models are binary categorical variables, the baseline regressions are analyzed using a binary Probit model.

4.3. Variables

4.3.1. Explained Variables

The explained variable represents whether the farmer adopts conservation tillage technology. Referring to existing studies [64–68], this article defines conservation tillage as follows: conservation tillage is a system engineering and comprehensive technology system combining agricultural machinery and agriculture. It is the integration of multiple technologies. The core technologies of conservation tillage not only cover tillage technologies, such as straw returning to the field, sowing with less and no-tillage, and subsoiling, but also cultivation and planting technologies, such as intercropping, strip planting, and crop rotation, as well as green production technologies such as integrated prevention and control of diseases, pests and grasses, soil testing and fertilizer formula, and increased application of organic fertilizers. Therefore, farmers who adopted any one or more of these conservation tillage technologies were assigned a value of 1, and those who did not were assigned a value of 0. In the survey sample, 60.18% of farmers adopted conservation tillage technology.

4.3.2. Explanatory Variables

This article selects agricultural technology extension as the proxy variable of the formal institution. The survey asked farmers, "does the local government promotes conservation tillage technology to you, and assigned the value Yes = 1 and No = 0". At the same time, this article constructs the variable of agricultural technology extension degree to carry out the robustness test. Through the survey, farmers were asked "how much do you think the government promotes conservation tillage technology, and assigned values of none = 0, less = 1, average = 2, and more = 3" for measurement. Social networks were chosen as a proxy variable of the informal institution, mainly from the "interaction with friends and relatives", "interaction with local villagers", "whether you are the village cadre", and "communication experience of conservation tillage technology implementation with others", along with four aspects and descriptions, and the four equally weighted averages were calculated as observed values of indicators of social networks.

Social networks are variables that are difficult to observe directly. Based on different research data and analysis perspectives, scholars also have some differences in the measurement dimensions of social networks. Based on relevant studies [69], this article constructs measurement indicators of social networks from three dimensions: strength, reputation, and reciprocity. The content of social networks' strength mainly includes the situation of interacting with their relatives and friends and the situation of interacting with their local villagers. In rural areas of China, farmers with a higher reputation are more likely to become the "forerunner" and "guide" in the application of agricultural technology, thus helping to drive other farmers to follow and emulate. Therefore, the village cadre status of farmers is selected as the proxy variable of social networks' reputation. Social networks' reciprocity is also considered to be an important dimension of social networks. Reciprocity among farmers will promote the rapid diffusion and dissemination of new agricultural technologies. This study measured social network reciprocity among farmers by asking them, "How often have you communicated experience of conservation tillage technology implementation with others?"

4.3.3. Control Variables

This article constructs control variables from four aspects: individual characteristics of farmers (gender, age, education level, and health status), family characteristics (farmers' income and the number of agricultural laborers), production and management characteristics (scale of land operation and cooperatives), and policy cognition. In addition, to control the influence of differences in resource endowment and economic development level among regions on farmers' adoption of conservation tillage technology, this article fixed the provincial control variables. Variable definitions and descriptive statistics are detailed in Table 2.

Table 2. Variable definitions and descriptive statistics.

Variables	Definition	Mean	S.D.
Technology adoption	Whether to adopt conservation tillage technology. Yes = 1; No = 0	0.6018	0.4898
Agricultural technology extension	Does the local government promote conservation tillage technology to you? Yes = 1; No = 0	0.4699	0.4994
Degree in agricultural technology extension	How much do you think the government promotes conservation tillage technology? None = 0; Less = 1; Average = 2; More = 3	0.8169	0.9397
Social networks	Interaction with friends and relatives. Never = 1; Infrequently = 2; Usually = 3; More often = 4; Very often = 5	3.9283	0.7268
	Interaction with local villagers. Never = 1; Infrequently = 2; Usually = 3; More often = 4; Very often = 5	3.7785	0.7801
	Whether you are the village cadre. Yes = 1; No = 0	0.0602	0.2380
	Communicating experience of conservation tillage technology implementation with others. Never = 1; Infrequently = 2; Usually = 3; More often = 4; Very often = 5	3.3457	0.9020
Gender	Male = 1; Female = 0	0.8528	0.3546
Age	The actual age of the farmer (years)	54.3892	9.6255
Education level	Primary school and below = 1; Junior high school = 2; Senior high school or secondary school = 3; Associate college and above = 4	1.9347	0.7842
Health status	Very poor = 1; Comparatively poor = 2; General = 3; Comparatively well = 4; Very well = 5	3.7414	0.7892
Farmers' income	Annual farmers' income (RMB) expressed as natural logarithms	10.9491	0.8646
Number of agricultural laborers	Number of family farming laborers (pcs)	1.9078	0.6174
Scale of land operation	Area of family-run farmland (hm^2)	2.1398	5.7855
Cooperatives	Whether to join a cooperative. Yes = 1; No = 0	0.1729	0.3784
Policy cognition	Cognitive situation of conservation tillage policies: not familiar = 1, not very familiar = 2, average = 3, relatively familiar = 4, very familiar = 5	2.4277	0.7789
Provinces	Is it Heilongjiang? Yes = 1; No = 0	0.2945	0.4561
	Is it Henan? Yes = 1; No = 0	0.2522	0.4346
	Is it Shandong? Yes = 1; No = 0	0.2394	0.4270
	Is it Shanxi? Yes = 1; No = 0	0.2138	0.4103

5. Analysis and Discussions

5.1. Analysis of the Separate Effects of Agricultural Technology Extension and Social Networks

5.1.1. Analysis of Benchmark Regression Results

The binary Probit model is used to test the separate effect of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology. To overcome the potential heteroscedasticity, the robust standard error is adopted for empirical analysis. The results are shown in Table 3. Model 1 to Model 4 included a single core explanatory variable (agricultural technology extension or social networks), while Model 1 and Model 3 merely considered the individual characteristics of farmers. Model 2 and Model 4 added the family characteristics, management characteristics, and policy cognition of farmers. Model 5 included agricultural technology extension, social network variables, and all control variables. At the same time, the province fixed effect is introduced into the model, which can better solve the endogenous problem of the model. The results show that both agricultural technology extension and social networks can significantly promote farmers' adoption of conservation tillage technology, and Hypothesis 1 and Hypothesis 2 are verified.

Table 3. Baseline regression results for agricultural technology extension and social networks.

Variables	Model 1 (Individual Characteristics)	Model 2 (All Characteristics)	Model 3 (Individual Characteristics)	Model 4 (All Characteristics)	Model 5 (All Characteristics)
Agricultural technology extension	1.2679 ***	1.2788 ***			1.2907 ***
	(0.1161)	(0.1280)			(0.1281)
Social networks			0.2015 *	0.1909 *	0.2510 **
			(0.1041)	(0.1105)	(0.1139)
Gender	0.1547	0.0894	0.1815	0.0498	0.1131
	(0.1499)	(0.1573)	(0.1332)	(0.1406)	(0.1573)
Age	0.0046	0.0040	−0.0137 **	−0.0012	0.0043
	(0.0062)	(0.0066)	(0.0057)	(0.0061)	(0.0066)
Education level	−0.1845 **	−0.1045	0.0123	0.0371	−0.0957
	(0.0744)	(0.0813)	(0.0665)	(0.0757)	(0.0814)
Health status	−0.0436	−0.0097	−0.1234 *	−0.1076	−0.0307
	(0.0745)	(0.0764)	(0.0702)	(0.0710)	(0.0756)
Farmers' income		0.1794 **		0.3381 ***	0.1967 ***
		(0.0714)		(0.0719)	(0.0716)
Number of agricultural laborers		0.2619 ***		0.1967 **	0.2510 **
		(0.0981)		(0.0882)	(0.1000)
Scale of land operation		−0.0014 *		−0.0019 **	−0.0016 *
		(0.0008)		(0.0009)	(0.0008)
Cooperatives		−0.5138 ***		−0.4439 ***	−0.4888 ***
		(0.1446)		(0.1502)	(0.1488)
Policy cognition		−0.1322 *		0.0405	−0.1583 **
		(0.0768)		(0.0682)	(0.0782)
Provincial control	Yes	Yes	Yes	Yes	Yes
Constant term		−2.5632 **		−4.3332 ***	−3.3549 ***
		(1.0082)		(1.0324)	(1.0631)
Observations	781	781	781	781	781
Pseudo R^2	0.2091	0.2471	0.0871	0.1417	0.2514

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

According to the results of Model 5, agricultural technology extension and social networks can significantly improve the probability of farmers' adoption of conservation tillage technology at the level of 1% and 5%, respectively, and the calculated average marginal effect is 0.3649 and 0.0709. The probability of farmers' adoption of conservation tillage technology increased by 36.49% and 7.09% on average for farmers who accepted agricultural technology extension and had strong social networks. On the one hand, grassroots agricultural extension organizations have promoted the dissemination and diffusion of conservation tillage technology through various forms of technology publicity and extension work, reducing the search cost and access cost of farmers, thus increasing the probability of farmers obtaining the technology. On the other hand, the social networks formed by farmers relying on the inherent blood and geopolitical ties in rural areas realize the sharing and diffusion of conservation tillage technologies and exert a significant spillover effect. At the same time, the exchange and cooperation among farmers and reciprocal mutual assistance effectively reduce the risk of technology implementation, ensure the effectiveness of technology implementation, and promote the sustainable and stable adoption of technology. The research showed that formal and informal institutions play an important role in the promotion and application of conservation tillage technology, but whether there is a substitution effect or complementary effect between agricultural technology extension and social networks needs to be tested empirically.

Among the control variables, farmers' income had a significant positive effect on farmers' adoption of conservation tillage technology, indicating that the higher the farmers' income, the more willing farmers were to adopt conservation tillage technology. This is consistent with the research conclusions of Gideon et al. [70] and Cai et al. [71]. The possible reason is that higher incomes of farmers help ease the financial constraints of technology adoption and lower the threshold of technology use, thus promoting farmers' adoption of conservation tillage technology. The number of agricultural laborers has a significant positive effect on farmers' adoption of conservation tillage technology, indicating that the more agricultural laborers, the more willing farmers are to adopt conservation tillage technology. Conservation tillage technology requires a certain amount of labor. A household with a larger agricultural labor force indicates a more productive household.

The scale of land operation has a significant negative effect on the adoption of conservation tillage technology. Guo et al. [65] and De Souza Filho et al. [72] also reached the same conclusion. On the one hand, the larger the scale of land operation, the higher the labor and material cost required by farmers to adopt conservation tillage technology. To reduce agricultural production costs, farmers will reduce or give up the adoption of technology. On the other hand, farmers with a larger scale of land operation will face higher income uncertainty and risk in agricultural production, which inhibits the enthusiasm of farmers to adopt conservation tillage technology. Participation in cooperatives has a significant negative impact on farmers' adoption of conservation tillage technology, which may be due to the lack of service capacity of cooperatives in the sample areas, leading to the lack of technical guidance and services for farmers to participate in cooperatives and the decrease of their enthusiasm in adopting conservation tillage technology.

In addition, policy cognition has a significant negative impact on farmers' adoption of conservation tillage technology. Although some farmers have a clear understanding of conservation tillage policies, conservation tillage technology, as an important means under the new model of green agriculture, is uncertain and risky. To avoid risks, farmers will reduce their willingness to adopt it to a certain extent.

5.1.2. Robustness Test

To test the reliability of the above empirical analysis results, this article mainly uses the methods of replacing models, winsorize treatment, replacing core explanatory variables, and sub-sample regression to test the robustness of the benchmark regression conclusions. The results are shown in Table 4. Among them, Model 6 is the result of using OLS regression. Model 7 is the result of using 1% and 99% percentile narrowing for continuous variables in the sample. Model 8 is the result of using the degree of agricultural technology extension to replace the core explanatory variable for regression. Model 9 is the result of excluding samples aged 65 and above for regression. It should be noted that considering the older age of farmers, their physical strength and management ability may decline, which will have a negative impact on agricultural production and operation. Therefore, this article excluded samples aged 65 and above for re-regression. The results show that after the above robustness test, agricultural technology extension and social networks still have a significant positive impact on farmers' adoption of conservation tillage technology, which is consistent with the above benchmark regression results. Therefore, it can be considered that the promotion effect of agricultural technology extension and social networks is stable.

Table 4. Robustness test results.

Variables	Model 6 (Logit Model)	Model 7 (Winsorize Treatment)	Model 8 (Replacing Core Explanatory Variable)	Model 9 (Sub-Sample Regression)
Agricultural technology extension	0.3940 ***	1.2819 ***	0.6527 ***	1.2655 ***
	(0.0352)	(0.1282)	(0.0693)	(0.1361)
Social networks	0.0621 *	0.2615 **	0.2235 **	0.2393 *
	(0.0341)	(0.1131)	(0.1100)	(0.1224)
Control variables	Yes	Yes	Yes	Yes
Provincial control	Yes	Yes	Yes	Yes
Constant term	−0.4707	−3.7571 ***	−3.3188 ***	−3.6672 ***
	(0.3142)	(1.0681)	(1.0448)	(1.2223)
Observations	781	781	781	677
R^2/Pseudo R^2	0.2915	0.2534	0.2389	0.2520

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

5.2. Analysis of Interaction Effect between Agricultural Technology Extension and Social Networks

The baseline regression results confirm that both agricultural technology extension and social networks significantly promote farmers' adoption of conservation tillage technology. However, whether there is a substitution effect or a complementary effect between agricultural technology extension and social networks still needs an empirical test. This article constructs the interaction terms of agricultural technology extension and social networks for regression. In the empirical analysis, the interaction variables were centralized to overcome the multicollinearity problem and ensure that the interaction effect has strong explanatory power. The empirical results are shown in Table 5. Model 10 is the baseline regression result of the interaction effect between agricultural technology extension and social networks. Models 11 to 14 are the robustness test results of OLS regression, 1% and 99% quantiles of continuous variables, agricultural technology extension degree instead of core explanatory variables, and results excluding samples over 65 years old. The research results show that the interaction coefficients between agricultural technology extension and social networks in Models 10 to 14 are significantly positive and are significant at the levels of 10%, 10%, 10%, 10%, and 5%, respectively. This indicates that there is a complementary effect between agricultural technology extension and social networks, where formal institutions with agricultural technology extension as the proxy variable and informal institutions with social networks as the proxy variable jointly play a role in promoting farmers' adoption of conservation tillage technology, achieving mutual complementarity and support. Hypothesis 4 has been verified.

Grassroots agricultural technology extension organizations fulfill the public welfare responsibilities of agricultural technology extension, relying on professional service teams, demonstration bases, and other entities and platforms to actively implement the task of fine technology promotion. They fully leverage the advantages of high accuracy, diversified methods, and wide coverage of agricultural technology extension information, providing practical guarantees for promoting the implementation and application of conservation tillage technology. At the same time, the social networks of farmers provide useful supplements for agricultural technology extension organizations to carry out technology promotion work. Social networks have obvious advantages in information acquisition, social learning, and risk-taking. In rural acquaintance societies, the probability of farmers accessing and learning conservation tillage technology through social networks increases, and their cognitive and knowledge levels also improve, thereby increasing their enthusiasm for technology adoption. In addition, the stronger the social networks of farmers, the stronger their ability to resist risks, which can reduce the risks and uncertainties of adopting conservation tillage technology and ensure the effectiveness of technology implementation. Moreover, social networks can effectively exert spillover effects and help promote the learning and adoption of conservation tillage technology by surrounding farmers.

Table 5. Regression results of the interaction effect between agricultural technology extension and social networks.

Variables	Model 10 (Probit Model)	Model 11 (Logit Model)	Model 12 (Winsorize Treatment)	Model 13 (Replacing Core Explanatory Variable)	Model 14 (Sub-Sample Regression)
Agricultural technology extension	1.2941 *** (0.1276)	0.3955 *** (0.0351)	1.2848 *** (0.1277)	0.6485 *** (0.0699)	1.2710 *** (0.1353)
Social networks	0.2679 ** (0.1165)	0.0637 * (0.0335)	0.2765 ** (0.1153)	0.2480 ** (0.1146)	0.2550 ** (0.1248)
Agricultural technology extension × social networks	0.4005 * (0.2345)	0.1200 * (0.0643)	0.3874 * (0.2338)	0.2252 * (0.1320)	0.6162 ** (0.2513)
Control variables	Yes	Yes	Yes	Yes	Yes
Provincial control	Yes	Yes	Yes	Yes	Yes
Constant term	−1.8901 * (1.0179)	−0.0631 (0.3084)	−2.2810 ** (1.0194)	−2.1015 ** (1.0131)	−2.2134 * (1.2090)
Observations	781	781	781	781	677
R^2/Pseudo R^2	0.2540	0.2944	0.2559	0.2417	0.2583

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

Furthermore, social networks include three dimensions: strength, reputation, and reciprocity. What is the relationship between agricultural technology extension and various dimensions of social networks? Based on this, this article constructs interactive terms for agricultural technology extension and social networks in three dimensions for empirical analysis. Among them, the weighted average values of "mobility with relatives and friends" and "mobility with local villagers" are taken as the observed values of the social network strength index. The regression results are shown in Table 6. From the table, it can be seen that the interaction coefficient between agricultural technology extension and social networks' reciprocity is significantly positive, indicating that agricultural technology extension and social networks' reciprocity have complementary effects on farmers' adoption of conservation tillage technology. However, the interaction terms between agricultural technology extension, social networks strength, and social networks reputation did not pass the significance test. Research has shown that social networks' reciprocity promotes the dissemination and diffusion of conservation tillage technology through the exchange of experience among farmers, exerting significant spillover effects and thus forming a synergistic and complementary effect with agricultural technology extension. The strength of social networks reflects the mobility of farmers with local villagers, relatives, and friends. Studies have shown that communication and interaction with relatives, friends, and neighbors have a significant promoting effect on farmers' choice of non-agricultural-dominated livelihoods and are important inducing factors for farmers to go out and engage in non-agricultural work. Therefore, the role of social network strength in agricultural production is not significant, and its impact on farmers' adoption of conservation tillage technology is not significant, making it difficult to generate complementary effects with agricultural technology extension. The reputation of social networks reflects the role of farmers' political identity in the rural economy and society. Farmers who serve as village cadres bear more responsibilities in rural governance, resource coordination at the village level, and the implementation of higher-level policies. However, they have achieved little in promoting conservation tillage technology and still need to be strengthened.

Table 6. Regression results of interaction effects between agricultural technology extension and social networks in different dimensions.

Variables	Model 15	Model 16	Model 17	Model 18
Agricultural technology extension	1.2880 *** (0.1294)	1.2867 *** (0.1296)	1.3026 *** (0.1293)	1.3025 *** (0.1295)
Social networks strength	0.0677 (0.0862)	0.0615 (0.0857)	0.0702 (0.0861)	0.0688 (0.0867)
Social networks reputation	−0.3213 (0.2100)	−0.3968 * (0.2331)	−0.2831 (0.2088)	−0.3708 (0.2316)
Social networks reciprocity	0.1621 ** (0.0679)	0.1622 ** (0.0676)	0.1652 ** (0.0679)	0.1668 ** (0.0678)
Agricultural technology extension × Social networks strength	0.1163 (0.1661)			−0.0226 (0.1773)
Agricultural technology extension × Social networks reputation		0.4534 (0.4446)		0.4615 (0.4384)
Agricultural technology extension × Social networks reciprocity			0.3022 ** (0.1197)	0.3067 ** (0.1268)
Control variables	Yes	Yes	Yes	Yes
Provincial control	Yes	Yes	Yes	Yes
Constant term	−1.9870 * (1.0129)	−2.0879 ** (1.0099)	−1.8090 * (1.0149)	−1.8603 * (1.0155)
Observations	781	781	781	781
Pseudo R^2	0.2570	0.2574	0.2623	0.2632

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

5.3. Heterogeneity Analysis

5.3.1. Heterogeneity Analysis of Different Groups

The above research indicated that agricultural technology extension and social networks have a complementary effect in promoting farmers' adoption of conservation tillage technology. Then, does this complementary effect present a differentiation effect in different groups? This article examines the differences in the interaction effect of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology from three aspects: the scale of land operation, household income, and intergenerational differences. Referring to the practice of Chen et al. [73] taking the scale of land operation and median farmers' income as a dividing basis (the median scale of land operation and the median farmers' income is 0.51 hectares and 64,000 CNY, respectively), farmers who are below the median level are defined as small farmers and low-income farmers, and farmers who are equal to or above the median level of farmers are defined as scale farmers and high-income farmers. Referring to the research of Liu et al. [74], farmers born in 1975 and later are defined as the new generation, and those born before 1975 are defined as the old generation.

The regression results are shown in Table 7, Models 19 to 24. The interaction coefficient between agricultural technology extension and social networks was negative and significant at the level of 10% for small-scale farmers, indicating that there was a significant substitution effect between agricultural technology extension and social networks. In scale farmers, the interaction coefficient between agricultural technology extension and social networks was positive and significant at the 1% level, indicating a significant complementary effect between agricultural technology extension and social networks. Large-scale households have a large scale of operation, and their technology promotion can play a good role in demonstration and leadership. At the same time, large-scale households often have certain resource advantages and a strong social network. Therefore, large-scale households are more likely to adopt conservation tillage technology. Due to the small scale of farming, it is difficult for small farmers to become demonstrators and leaders of agricultural technology extension. In this case, social networks can effectively play a substitution role.

Table 7. Group heterogeneity regression results of the interaction effect between agricultural technology extension and social networks.

Variables	Model 19 (Small Farmers)	Model 20 (Scale Farmers)	Model 21 (Low-Income Farmers)	Model 22 (High-Income Farmers)	Model 23 (Old-Generation Farmers)	Model 24 (New-Generation Farmers)
Agricultural technology extension	1.4490 ***	1.0584 ***	1.2597 ***	1.2550 ***	1.5479 ***	0.4120
	(0.2008)	(0.1870)	(0.1863)	(0.1934)	(0.1538)	(0.2722)
Social networks	0.2926	−0.1502	0.4429 **	−0.0068	0.3931 ***	−0.0576
	(0.2269)	(0.1741)	(0.1751)	(0.1789)	(0.1377)	(0.2449)
Agricultural technology extension × Social networks	−0.8183 *	1.4485 ***	0.2920	0.8770 ***	0.3818	1.1555 **
	(0.4369)	(0.3440)	(0.3520)	(0.3345)	(0.2706)	(0.4715)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Provincial control	Yes	Yes	Yes	Yes	Yes	Yes
Constant term	−1.7909	−0.7612	−0.2261	0.1697	−1.7440 *	−0.1717
	(1.5244)	(1.5329)	(0.8500)	(1.0289)	(0.8956)	(2.2172)
Observations	390	391	389	392	632	149
Pseudo R^2	0.3319	0.2922	0.2370	0.2683	0.3041	0.2038

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

Among low-income farmers, the complementary effect of agricultural technology extension and social networks was not significant but was significant at the level of 1% among high-income farmers, indicating that the complementary effect of agricultural technology extension and social networks would significantly promote the adoption of conservation tillage technology by high-income farmers. High-income farmers have relatively strong capital, so they face lower financial constraints. At the same time, high-income farmers have strong social networks and can easily become the arbiter of technology extension and application.

From the perspective of intergenerational differences, the complementary effect of agricultural technology extension and social networks exists significantly in the new generation of farmers but not in the old generation of farmers. On the one hand, the new generation of farmers has a higher level of education and technical learning ability, so they have a higher degree of acceptance of agricultural technology extension. On the other hand, the new generation of farmers pays more attention to the accumulation and expansion of social networks in interpersonal communication.

In the survey, it was found that the new generation of farmers showed higher enthusiasm for strengthening social networks through modern information technology such as the Internet. In conclusion, the complementary effect of agricultural technology extension and social networks exists for large-scale farmers, high-income farmers, and the new generation of farmers but is not obvious for low-income farmers and the old generation of farmers, and it has a substitution effect in small farmers.

5.3.2. Heterogeneity Analysis of Different Technology Types

Conservation tillage is a comprehensive technical system that includes four major technical systems [67,68], namely, protective crop planting technology (intercropping, strip planting, etc.), protective soil tillage technology (less or no tillage, deep loosening, etc.), protective surface covering technology (straw coverage, plastic film coverage, etc.), and protective farmland comprehensive management technology (disease, pest, and grass control, fertilization technology, irrigation technology, etc.). Based on field research, this article divides conservation tillage technologies into the four categories mentioned above and examines the heterogeneity of the interaction effect between agricultural technology extension and social networks in farmers' adoption of different technologies. Table 8 shows that compared to surface cover technologies, the interaction between agricultural technology extension and social networks is significantly positive in crop planting, soil cultivation, and comprehensive farmland management technologies, with complementary effects. Further comparison of coefficient values reveals that the complementary effect of agricultural technology extension and social networks has the greatest promoting effect on farmers' adoption of farmland comprehensive management technologies, followed by crop planting technologies and, finally, soil tillage technologies. Overall, due to the different nature and characteristics of different types of conservation tillage technologies, there are certain technological differences in the interaction effect between agricultural technology extension and social networks on farmers' adoption of conservation tillage technology.

Table 8. Regression results of technological heterogeneity in the interaction effect between agricultural technology extension and social networks.

Variables	Model 25 (Crop Planting)	Model 26 (Soil Tillage)	Model 27 (Surface Covering)	Model 28 (Farmland Comprehensive Management)
Agricultural technology extension	1.3103 *** (0.1281)	1.2863 *** (0.1282)	1.2879 *** (0.1284)	1.2996 *** (0.1277)
Social networks	0.2483 ** (0.1201)	0.1991 (0.1382)	0.2843 ** (0.1201)	0.2063 (0.1263)
Agricultural technology extension × Social networks	0.1043 (0.2934)	0.1190 (0.3218)	0.6527 ** (0.3267)	0.2116 (0.2658)
Agricultural technology extension × Social networks × Crop planting	1.2186 *** (0.4236)			
Agricultural technology extension × Social networks × Soil tillage		0.9799 * (0.5794)		
Agricultural technology extension × Social networks × Surface covering			−0.6775 (0.4599)	
Agricultural technology extension × Social networks × Farmland comprehensive management				1.3018 ** (0.6140)
Control variables	Yes	Yes	Yes	Yes
Provincial control	Yes	Yes	Yes	Yes
Constant term	−1.9822 * (1.0180)	−1.9787 * (1.0170)	−1.8180 * (1.0220)	−1.9946 * (1.0218)
Observations	781	781	781	781
Pseudo R^2	0.2584	0.2569	0.2559	0.2572

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

5.3.3. Heterogeneity Analysis in Different Regions

The results in Table 9 show that for farmers in Heilongjiang and Henan, the interaction coefficient between agricultural technology extension and social networks is positive, and both are significant at the level of 1%, indicating a complementary effect between agricultural technology extension and social networks in promoting farmers' adoption of conservation tillage technology. Therefore, by extending and expanding the social networks of farmers, a synergistic and complementary effect can be formed with agricultural technology extension, maximizing the enthusiasm of farmers to adopt conservation tillage technology. For Shandong farmers, there is no significant interaction effect between agricultural technology extension and social networks, while in Shanxi farmers, social networks can play a good substitution role. The above research indicates that there are significant regional differences that impact the interaction between agricultural technology extension and social networks and farmers' adoption of conservation tillage technology. Therefore, when formulating relevant policies and measures, the government needs to tailor them to local conditions, provide technical services based on actual local conditions, and continuously optimize and improve them based on local economic development level, social culture, local customs, and other factors, to improve the adoption rate of conservation tillage technology among farmers.

Table 9. Regional heterogeneity regression results of the interaction effect between agricultural technology extension and social networks.

Variables	Model 28 (Heilongjiang)	Model 28 (Henan)	Model 28 (Shandong)	Model 28 (Shanxi)
Agricultural technology extension	0.8670 ***	3.5326 ***	1.6258 ***	0.8118 *
	(0.2174)	(0.7356)	(0.3183)	(0.4135)
Social networks	−0.3166	2.2350 ***	0.7192 **	−0.0261
	(0.1955)	(0.4417)	(0.3253)	(0.4040)
Agricultural technology extension × Social networks	1.7662 ***	3.1825 ***	−0.1705	−1.7755 **
	(0.4172)	(0.8161)	(0.5668)	(0.7443)
Control variables	Yes	Yes	Yes	Yes
Constant term	1.0421	−2.3614	3.9981	−4.2157
	(1.8164)	(2.1746)	(2.6805)	(3.3611)
Observations	230	197	187	167
Pseudo R^2	0.1579	0.4281	0.6388	0.4231

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. Robust standard errors are in parentheses.

6. Discussion

6.1. New Findings Compared to Previous Studies

Given the important role of the dissemination and application of conservation tillage technology in ensuring national food security in the new development stage, this paper continues to explore the key factors influencing farmers' adoption of conservation tillage technology based on existing studies. Unlike previous studies, this paper has several new findings, which are as follows:

First, unlike the previous studies that focused on conservation tillage technology [75,76], this paper looks at the implementation of conservation tillage technology and farmers' adoption, with farmers being the direct beneficiaries, to find specific initiatives that can improve farmers' adoption and make the dissemination and application of conservation tillage technology more direct and effective, thus achieving the purpose of protecting farmland, raising farmers' incomes, ensuring national food security, and comprehensively promoting sustainable agricultural development.

Second, the impact of agricultural technology extension and social networks on agricultural production has received wide attention as important elements of formal and informal institutions, respectively. However, few studies have examined its impact on farmers' adoption of conservation tillage technology. Through theoretical analysis and empirical tests, this paper finds that agricultural technology extension and social networks are important factors influencing farmers' adoption of conservation tillage technology. Additionally, this paper tries to find a new path for the dissemination of conservation tillage technology.

Third, based on the empirical test that both agricultural technology extension and social networks have a positive influence on farmers' adoption of conservation tillage technology, this paper also compared which channel of agricultural extension and social networks have a greater promotion effect and how the two are related. Complementary effects exist, but they do not always exist and vary across groups, regions, and technology types.

6.2. Research Deficiencies and Prospects

Although we have concluded through theoretical analysis and empirical tests that agricultural technology extension and social networks have important effects on farmers' adoption of conservation tillage technology, there are certain shortcomings in this study, which also provide important research directions for our next study, in two aspects:

On the one hand, as mentioned above, conservation tillage technology contains many types, not only cover tillage technologies, such as straw returning to the field, sowing with less and no-tillage, and subsoiling, but also cultivation and planting technologies, such as intercropping, strip planting, and crop rotation, as well as integrated farm management techniques such as integrated prevention and control of diseases, pests and grasses, soil testing and fertilizer formula, and increased application of organic fertilizers. Practice shows that there are great differences in the effects of different technologies. However, in this paper, when examining farmers' adoption of conservation tillage technology, farmers are considered to have adoption behavior as long as they adopt one technology, Ignoring the differences between different technologies. Therefore, in future research, the relationship between agriculture technology extension and social networks and farmers' adoption of specific technologies can be examined comprehensively to pinpoint extension initiatives for different types of conservation tillage technologies.

On the other hand, the data used in the current empirical study are from a survey of 781 farmers in four Chinese provinces, which are typical and representative but have not yet covered the six suitable regions for conservation tillage technology in China, namely, northeast plain monopoly area, the agricultural and pastoral areas along the Great Wall, the northwest loess plateau area, the northwest oasis agricultural area, the Huang-Huai-Hai plain cropping area, the southern water and dry continuous crop area. At the same time, there is a lack of a large sample of practice surveys to obtain more survey information and make the empirical research conclusions more precise. Therefore, in future studies, we will conduct continuous follow-up surveys in areas that have been investigated and supplemental surveys in areas that have not been investigated and researched to provide Chinese experience for the comprehensive promotion of conservation tillage technology.

7. Conclusions and Suggestions

Agricultural technology extension and social networks are important components of formal and informal institutions, respectively, and their influence on farmers' adoption of agricultural technology has received widespread attention. However, the analysis of the relationship between the two has not received sufficient attention. This article is based on 781 survey data from farmers in Heilongjiang, Henan, Shandong, and Shanxi provinces. It not only empirically tests the individual effects of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology but also examines the interaction effects of the two. Research has found the following:

Firstly, both agricultural technology extension and social networks significantly promote farmers' adoption of conservation tillage technology, and the promotion effect of agricultural technology extension is greater. The average probability of farmers who accept agricultural technology extension and social networks adopting conservation tillage technology increases by 36.49% and 7.09%, respectively.

Secondly, the impact of agricultural technology extension and social networks on farmers' adoption of conservation tillage technology presents a complementary effect. That is, the two functions complement and support each other, jointly playing a promoting role, and this complementary effect is more evident in the reciprocity of social networks.

Thirdly, the interaction effect between agricultural technology extension and social networks has heterogeneity in farmers' adoption of protective farming techniques by farmers, with significant differences among different groups, technology types, and regions. Specifically, there is a complementary effect between the two for large-scale farmers, high-income farmers, and new-generation farmers and a substitution effect for small farmers. The complementary effect of the two has the greatest promoting effect on the adoption of comprehensive farmland management technologies by farmers, followed by crop planting technologies and, finally, soil tillage technologies. There is a complementary effect between the two for farmers in Heilongjiang and Henan provinces. Additionally, there is a substitution effect for farmers in Shanxi.

Based on the above research conclusions, the following policy recommendations are proposed:

Firstly, agricultural technology extension has promoted the dissemination and diffusion of conservation tillage technology, increased the enthusiasm of farmers for technology adoption, and become an important measure to promote sustainable agricultural development and assist rural revitalization. In the future, it is still necessary to further improve and optimize the construction of the grassroots agricultural technology extension system. It is also necessary to implement diversified agricultural technology extension and dissemination strategies, continuously expand the scope, function, and content of agricultural technology extension services, and innovate agricultural technology extension service methods. Additionally, this will thereby improve the quality and efficiency of agricultural technology extension. At the same time, we will accelerate the reform of grassroots agricultural technology extension institutions and the construction of extension teams, adopt targeted training, graded training, and other measures to improve the professional level and workability of agricultural technology extension personnel, and fully play the leading role of agricultural technology extension.

Secondly, there is a complementary effect between social networks and agricultural technology extension in the adoption of conservation tillage technology by farmers. Therefore, it is necessary to accelerate the construction of an effective mechanism for mutual support between agricultural technology extension and social networks. Whilst strengthening agricultural technology extension, we are constantly strengthening the construction of rural social networks. By building various communication and mutual assistance platforms, organizing rural collective activities, and other means, we are gradually forming a long-term mechanism of cooperation, mutual benefit, and benefit sharing among farmers, thereby enhancing their enthusiasm for adopting conservation tillage technology. In addition, we need to accelerate the promotion and application of modern information technology and promote widespread communication and information sharing among farmers by actively creating a harmonious and orderly rural social networks environment, continuously expanding the social networks relationships of farmers, and promoting the dissemination and diffusion of conservation tillage technology.

Thirdly, it is necessary to implement differentiated conservation tillage technology extension strategies. We should pay attention to the differences among different regions and types of farmers. Additionally, we should implement policies tailored to local conditions, people, and precision, and develop and implement targeted promotion plans based on local conditions and farmers' actual needs, especially strengthening assistance to vulnerable groups such as small farmers, low-income farmers, and elderly farmers, providing more professional technical guidance and services and reducing the risks and costs of adopting conservation tillage technology. At the same time, it is necessary to combine the nature and characteristics of different types of conservation tillage technology and adopt differentiated promotion methods to improve the applicability of farmers' technology adoption and ensure the effectiveness and quality of technology extension.

Author Contributions: Conceptualization, J.X.; methodology, Z.C. and J.W.; formal analysis, J.X. and Z.Y.; writing—original draft preparation, J.X.; writing—review and editing, J.X. and Z.C.; investigation, T.W.; funding acquisition, C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Natural Science Foundation of China (project number 71673042), the National Social Science Foundation of China (project number 21BJY249), the Social Science Foundation of Heilongjiang Province (project number 21JYA440), and the Social Science Foundation of Heilongjiang Province (grant number 22JYH053).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Evolving Trends and Influencing Factors of the Rural Green Development Level in Chongqing

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Abstract: Rural green development is a concrete practice of rural revitalization. Currently, research on quantitative evaluation methods for rural green development levels are not well developed. In this study, an evaluation model of the rural green development level in Chongqing City, China was developed based on the parameters of ecology, living, and production. An entropy weight method, Theil index, optimal scale regression model, and GIS were used to analyze the spatio-temporal characteristics, trends, and influencing factors of the rural green development level from 2018 to 2020 in Chongqing City. The results showed that: (1) the overall "ecology, living, and production" dimensions and the comprehensive index of the development level in the city were generally increasing, and the proportion of counties at a high-level increased from 23.68% in 2018 to 81.58% in 2020; (2) the Theil index of the city in was 0.0185, 0.0121, and 0.0114 in 2018, 2019, and 2020 respectively, indicating that the differences in development level among regions decreased as the development level increased; (3) the level of rural green development showed a clear upwards trend, and the proportion of counties with low-speed growth, medium-speed growth, and high-speed growth from 2018 to 2020 was 5.26%, 81.58%, and 13.16%, respectively; and (4) the optimal scale regression analysis showed that the factors with greater impacts on the rural green development level are social security and employment expenditure level of government finance, health expenditure level of government finance, with their contributions is 40.3% and 26%, respectively. The results from this study demonstrate the significance of exploring research methods for rural green development and ways to improve the level of rural green development.

Keywords: Chongqing; green development; Theil index; optimal scale regression analysis; GIS

Citation: Zhu, K.; Song, D.; Zhang, L.; He, Y.; Zhang, S.; Liu, Y.; Tian, X. Evolving Trends and Influencing Factors of the Rural Green Development Level in Chongqing. *Land* **2023**, *12*, 1333. https://doi.org/10.3390/land12071333

Academic Editor: Tao Liu

Received: 5 April 2023
Revised: 17 May 2023
Accepted: 17 May 2023
Published: 3 July 2023

1. Introduction

The economic and social development of rural areas is as important as environmental protection, and it is crucial to coordinate the relationship between ecology, living, and production to achieve high-quality green development and promote the transition from disconnected to orderly rural development [1]. In 2018, the Chinese government released the National Rural Revitalization Strategic Plan (2018–2022), which requires achieving ecological beauty with clear mountains and clean water, moderate and comfortable living, and intensive and efficient production. Its core concept is to lead rural revitalization through the prioritization of green development in rural areas [2,3]. Currently, research on green development in rural areas mainly focuses on areas such as rural revitalization, beautification of countryside, green development, and rural tourism [4,5]. The key research directions include: (1) Exploration of the path and mode of rural green development—this makes up the highest proportion of the research and mainly identifies problems with regional green development at the macro level. It proposes to promote industrial green development in aspects such as clean production, environmental protection, and economic promotion, and explores how to achieve green development from the perspective of policy optimization and management decision-making [2,6]. (2) Study of the distribution patterns and influencing factors of green development at the macro level—this type of research rarely focuses on rural areas. Instead, it uses panel data, geospatial regression models, and other methods to explore the dynamic evolution laws of the spatio-temporal dimensions of regions, mainly in aspects such as economic development and industrial structures [7]. (3) Comprehensive evaluation of green development at the macro level. As a research hotspot in the field of green development, various evaluation methods such as green GDP, green development efficiency, and the human green development index have been established, focusing on the green level of economic development at the macro level [8]. Internationally, scholars pay more attention to urban green development, green economy, green industrial development, and other aspects [9–12]. The current research on green development mainly focuses on the national and regional levels. For example, Bilgaev comprehensively evaluated the impact of socio-economic factors on the green economic development of the Republic of Briat (Russia) by constructing composite indicators, and believes that the environmental status has the greatest impact [6]. Wang used a system dynamics model to analyze the impact of policies in the Tibetan areas of Sichuan on green development, believing that population and investment policies have a significant impact [2].

Overall, researchers have conducted a series of studies on green development at the global, national, provincial, and regional levels, forming clear research methods and paths [13,14]. However, research in the field of green development in rural areas mostly focuses on exploring and discussing the path and mode of achieving rural green development, lacking suitable quantitative evaluation methods for the green development levels of rural areas [15]. There is also insufficient research on spatiotemporal evolution laws and influencing factors of green development levels in rural areas, resulting in a lack of data and reference materials in line with the concept of rural green development during the implementation of the rural revitalization strategy. Rural areas are an important environment for human life, and the current proportion of rural areas in China is over 90%. The contradiction between "production–living–ecological space" in rural areas is significant, and there are many research results on the relationship between them. Zhao et al. conducted a functional balance study on the "production–living–ecological space" in rural areas [16]. Based on the perspective of "production–living–ecological", Liang et al. analyzed the impact of land use on landscape ecology risk in the Three Gorges Reservoir Area [17]. Liang et al. conducted a study on potential land use conflicts in the Chongqing region from the perspective of "production–living–ecological"[18]. These studies all believe that there are significant contradictions in the "production–living–ecological", and it is necessary to balance the relationship between them. Therefore, the green and sustainable development of rural areas is very important for the economic sustainability of the entire country, and is also an important foundation for China's rural revitalization strategy. Currently, scholars focus on national, provincial, or regional green development assessments and pay less attention to rural areas. Conducting green development assessments in rural areas can effectively compensate for the shortcomings. The purpose of rural green development is to improve the ecological environment quality, living standards, and reduce the amount of pollutants generated and resources consumed in rural areas. Therefore, rural green development is the only way for China to achieve rural revitalization strategy.

As a significant ecological barrier in the upper reaches of the Yangtze River, Chongqing attaches great importance to promoting rural green development in the region. In recent years, with the implementation of pollution control, beautification of countryside construction, the creation of eco-friendly residential areas, the rural revitalization strategy, and other work, the ecological and environmental quality of the region has significantly improved, with an overall surface water quality rating of excellent in 2021 and with 326 days of good air quality [19]. However, as a typical mountainous area, Chongqing still faces multiple complex, rural issues, such as environmental pollution, uneven development, and resource waste, as the green development model is yet to be fully formed. At the same time, it is still unclear about the changes in the level of green development in rural areas of Chongqing after the implementation of the 2018 rural revitalization strategic plan. Therefore, compared to previous studies, we have conducted a more comprehensive evaluation model for the level of green development in rural areas from the three dimensions of "ecology, life, and production". In this study, 38 districts and counties in Chongqing Municipality were selected as the research area. Geographic and statistical methods, such as an entropy weighting method, Theil index, spatial clustering analysis, and regression model, were used to analyze the spatiotemporal characteristics and developing trends of rural green development in Chongqing from 2018 to 2020. We identified the contributions of different influencing factors to the level of rural green development, including urbanization level, aging level, contribution level of total assets, education expenditure level of government finance, health expenditure level of government finance, social security and employment expenditure level of government finance, etc. The results of this study provide a reference for promoting and achieving rural revitalization under the guidance of rural green development in Chongqing Municipality.

2. Materials and Methods

2.1. Study Area

In total, 38 districts and counties in Chongqing were selected in this study, among which Yuzhong was not included because there is no rural area available, and Wansheng Economic Development Zone was treated as a separate district (it is directly managed by the Chongqing government and does not have spatial conflicts with other districts). For convenience of description, the study areas were divided into "one area and two groups (the main urban area, southeast area, and northeast area)". The main urban area includes 21 districts and counties (i.e., Changshou, Fuling, Nanchuan, and all districts and counties located to the west of Nanchuan), the southeast area includes 6 districts and counties (i.e., Wulong, Pengshui, Shizhu and all areas located to the south of Shizhu), and the northeast area includes 11 districts and counties (i.e., Dianjiang, Fengdu, Zhong, Liangping, Wanzhou, and areas located to the north of Wanzhou) [20]. In 2021, the GDP of Chongqing was CNY 2.789 trillion, an increase of 8.3% from the previous year. The rural population was 9.533 million, accounting for 29.68% of the total population, and the per capita disposable income of rural residents was CNY 18,100, an increase of 10.6%. The energy consumption per CNY 10,000 GDP decreased by 3.5% compared to the previous year. The environmental air quality is good, with an average concentration of $PM_{2.5}$ at 35 $\mu g/m^3$. The water quality is relatively good, with 95.9% of the sections having class I–III water quality, and the centralized drinking water sources meet the national standard. However, due to complex terrain and uneven distribution of resources in Chongqing, there are significant differences in the level of rural development in different regions. The main urban area has a higher level of economic development due to its transportation and geographical advantages, while some districts and counties in the southeast and northeast areas are not as developed.

2.2. Data Sources

The data were obtained from Chongqing Statistical Yearbook (http://tjj.cq.gov.cn/, accessed on 7 November 2022), Water Resources Bulletin (http://slj.cq.gov.cn/, accessed on 27 November 2022), Soil and Water Conservation Bulletin (http://slj.cq.gov.cn/, accessed on 30 November 2022), Ecological Environment Status Bulletin (http://sthjj.cq.gov.cn/, accessed on 18 November 2022), and various districts and counties' National Economic and Social Development Statistics Bulletin (the website of each district and county government).

2.3. Methods

2.3.1. Construction of the Evaluation Model for Rural Green Development Level

The steps to develop the evaluation model for the green development level in rural areas of Chongqing include initial and secondary selection of indicators, determination of indicator weights, and model construction.

1. Index Selection and Screening

Relevant literature and data on rural green development research at home and abroad are consulted extensively to ensure completeness and comprehensiveness as much as possible. The ecology dimension generally focuses on the conditions of water, atmosphere, soil, and ecology, the living dimension generally focuses on the conditions of medical, educational, economic, and transportation, and the production dimension generally focuses on the conditions of production efficiency and material consumption. Yang et al. mainly considered factors such as rural per capita income, transportation network, and agricultural output value in their research on rural vitality [3]. Maja et al. constructed a smart rural assessment method from aspects such as housing, environmental change, education, culture, and water resources [21]. However, rural areas are highly integrated areas of ecological, living, and production space. Constructing evaluation methods from these three perspectives can comprehensively identify the level of green development in rural areas. For example, Kong et al. constructed a comprehensive evaluation model for village protection based on the three dimensions of "production, life, and ecology" [22]. Nie et al. conducted research on spatial reconstruction and evaluation of driving factors in tourism rural areas from three dimensions: production, life, and ecology [23]. Therefore, an evaluation model for the rural green development level in the southwestern mountainous area is constructed, which includes ecological, living, and production dimensions. The index selection mainly uses theoretical analysis methods to comprehensively sort out the indicators in the "ecological, living, and production" aspects. The index screening is based on the initial selection and involves screening necessary indicators through expert questionnaire surveys.

Initially, 39 indicators were selected around the 3 dimensions of ecology, living, and production (Table A1). After obtaining advice from experts, the indicators were optimized to 23. The initial 39 indicators, as well as the 23 indicators formed after expert consultation, are listed in the Appendix A. These 23 indicators were synthesized into 12 comprehensive indices through index synthesis, with each dimension involving 4 indices. The ecological dimension includes water, air, soil, and ecology. The living dimension includes medical care, education, consumption, and transportation. The production dimension includes overall efficiency, economic energy consumption, economic water consumption, and agricultural material consumption. The specific indicators and their meanings are shown in Tables 1 and 2.

Table 1. Meaning and weight of the "ecological, living, and production" dimension.

Primary Index	Explanation	Properties	Weight
Ecological Dimension	Water, air, soil, ecology and other ecological dimensions supporting the ability for rural green development.	Positive	0.30
Living Dimension	Medical, education, consumption, transportation, and other living dimensions supporting the ability for rural green development.	Positive	0.35
Production Dimension	Energy consumption, material consumption, human consumption, water consumption, and other production dimensions supporting the ability for rural green development.	Positive	0.35

Table 2. Meaning and weight of evaluation indicators for rural green development level.

Primary Index	Order Number	Secondary Index	Explanation	Calculation	Properties	Weight
Ecological Dimension	1	Water resource carrying index	Reflects the water resource status, production water capacity, and the ability to resist the risk of water pollution based on natural conditions and meteorological conditions.	Calculated by (1) the production water coefficient and (2) the production water modulus	Positive	0.285
	2	Air comfort index	Reflects the air quality status and the ability to resist the risk of atmospheric pollution.	(3) Comprehensive environmental air quality index	Negative	0.225
	3	Soil disturbance index	Reflects the status of surface soil resources and the ability to resist the risk of soil erosion and pollution caused by it.	(4) Soil erosion area ratio	Negative	0.265
	4	Green coverage index	Reflects the forest resource reserve status, ecological resource quality, and the ability to resist ecological destruction risks.	(5) Forest coverage rate	Positive	0.225
Living Dimension	5	Medical development index	Reflects the degree of health care resources and the ability to resist health risks in residents.	Calculated by (6) the permanent population and (7) the number of hospital beds	Positive	0.26
	6	Educational development index	Reflects the degree of compulsory education resources and the level of the teachers' qualifications.	Calculated by (8) the number of students in ordinary middle schools, (9) the number of students in primary schools, (10) the number of teachers in ordinary middle schools and (11) the number of teachers in primary schools.	Positive	0.26
	7	Consumption capacity index	Reflects the economic status of residents, their economic level, and consumption capacity.	Calculated by (12) per capita GDP and (13) per capita disposable income of rural residents	Positive	0.29
	8	Transportation convenience index	Reflects the level of convenience of residents' transportation and travel.	Calculated by (14) the length of highways and (15) the area of the region	Positive	0.19
Production Dimension	9	Overall efficiency Index	Reflects labor productivity and the level of economic growth dependence on human resources.	Measured by (16) the overall labor productivity.	Positive	0.20
	10	Economic energy consumption index	Reflects the energy consumption of the economy and the dependence of the economy on energy.	Calculated by (17) the output value of the secondary industry and (18) energy consumption of industrial enterprises with annual revenue over a certain amount.	Negative	0.215
	11	Economic water consumption index	Reflects the water consumption status of economic and agricultural activities and the dependence of economic and agricultural development on water resources.	Calculated by (19) the water consumption per CNY 10,000 of GDP and (20) the Effective utilization coefficient of irrigation water in farmland.	Negative	0.27
	12	Agricultural material consumption index	Reflects the intensity of input of fertilizers and pesticide pollutants and the dependence of agricultural development on fertilizers and pesticides.	Calculated by (21) the sown area of crops, (22) the amount of fertilizer applied, and (23) the amount of pesticides used.	Negative	0.315

2. Determination of Index Weights

To ensure the scientific validity of the index weights involved in the evaluation of rural green development levels, this study uses a combination of subjective and objective methods to determine the index weights, employing expert scoring [24] and entropy weighting methods [25]. Finally, the weights of all indicators are determined through a comprehensive weighting method (as shown in Tables 1 and 2). The entropy weighting method is an objective weighting method that can effectively avoid the bias of subjective human factors in assigning index weights [26]. The specific calculation steps are as follows: (i) calculate the proportion of the kth sample under the rth index (PP_{kr}, using Formula (1)); (ii) calculate the entropy value of the rth index (e_r, using Formula (2)); (iii) calculate the redundancy of information entropy and the weight of each index (Q_r, using Formula (3)). Here, x_{kr} represents the value of the kth sample under the rth index.

$$PP_{kr} = x_{kr} / \sum\nolimits_{k=1}^{n} x_{kr}, k = 1, \ldots, n, r = 1, \ldots, m \tag{1}$$

$$e_r = -(1/\ln(n)) \sum\nolimits_{k=1}^{n} PP_{kr} \ln(PP_{kr}), r = 1, \ldots, m \tag{2}$$

$$Q_r = (1 - e_r) / \sum\nolimits_{r=1}^{m} (1 - e_r) \tag{3}$$

3. Model Construction for Evaluating Rural Green Development

Since the level of green development in rural areas should reflect developmental aspects, it is crucial to consider the development status of the region. Thus, to incorporate both the current level and the inter-annual changes of regional indicators (i.e., trends), a combined approach is employed to construct a model for evaluating the level of rural green development and to reflect the resource status of various indicators in the region.

$$E_{it} = Q_W \times W_{it} + Q_A \times A_{it} + Q_S \times S_{it} + Q_G \times G_{it} \tag{4}$$

$$L_{it} = Q_M \times M_{it} + Q_{Edu} \times Edu_{it} + Q_C \times C_{it} + Q_R \times R_{it} \tag{5}$$

$$P_{it} = Q_{Eec} \times Eec_{it} + Q_{Cec} \times Cec_{it} + Q_{Mc} \times Mc_{it} + Q_{Wc} \times Wc_{it} \tag{6}$$

$$RGD_{it} = Q_E \times E_{it} + Q_L \times L_{it} + Q_P \times P_{it} \tag{7}$$

$$RGDL_i = GD_{i,t} - GD_{i,t-1} \tag{8}$$

where, i is the region, t is the year, E_{it}, L_{it}, and P_{it} are the ecological dimension index, living dimension index, and production dimension index of region i in year t, respectively. Q is the weight of the corresponding index. W, A, S, G, M, Edu, C, R, Mc, Eec, Wc, and Cec are the water resource carrying index, air comfort index, surface disturbance index, green coverage index, medical development index, education development index, consumption capacity index, transportation convenience index, overall efficiency index, economic energy consumption index, economic water consumption index, and agricultural material consumption index, respectively. RGD_{it} is the comprehensive index of rural green development level in region i in year t, and $RGDL_i$ is the change index of rural green development level in region i from previous year to year t. The comprehensive index of rural green development level is divided into four levels: low level, relatively low level, relatively high level, and high level, using the natural breakpoint method of ArcGIS software. The trend of rural green development level change is divided into four levels: level degradation, level slow growth, level moderate growth, and level high-speed growth according to <0, [0,0.01 N), [0.01 N,0.05 N), and ≥0.05 N, where N is the number of years between intervals.

2.3.2. Theil Index

The Theil index can measure the differences in regional development using entropy from information theory. It can measure overall differences, differences within regions, and differences between regions [27,28].

$$T_{theil} = \sum \frac{Y_i}{Y} \times \ln \frac{(Y_i/Y)}{(X_i/X)} \tag{9}$$

$$T_{inter\text{-}theil} = \sum \frac{Y_z}{Y} \times \ln \frac{(Y_z/Y)}{(X_z/X)} \tag{10}$$

$$T_{in\text{-}theil} = \sum \frac{Y_i}{Y} \times \ln \frac{(Y_i/Y_z)}{(X_i/X_z)} \tag{11}$$

T_{theil} is the overall difference among regions, Y_i is the composite index of rural green development level of the *i*th county, Y is the total number of counties (i = 1, 2, 3 . . . n), X_i is the number of counties included in the *i*th region, and X represents the total number of counties. $T_{inter\text{-}theil}$ and $T_{in\text{-}theil}$ are the differences between and within regions, respectively. Y_z is the total composite index of rural green development level in the *z*th area (three areas were divided in this study, including the main urban area, northeast urban area, and southeast urban area), and X_z is the number of counties included in the *z*th area.

2.3.3. Optimal Scale Regression Method

The optimal scaling regression model is an extension of the standard linear regression model. The basic idea is to use the principle of optimization to iteratively assign the best quantified value to each influencing factor based on analyzing the strength of the impact of the influencing factors on the dependent variable and obtain the best regression equation [29]. Its advantage is that it can obtain the importance coefficient and visually display the degree of influence of each independent variable on the dependent variable. In this study, the comprehensive index of a rural green development level is taken as the dependent variable, and 6 indices such as the urbanization level, aging level, contribution level of total assets, education expenditure level of government finance, health expenditure level of government finance, social security and employment expenditure level of government finance. The optimal scaling regression analysis tool is selected in SPSS for calculation.

3. Results

3.1. Rural Green Development on Ecology, Living, and Production

The results of green development on ecology, living, and production dimensions are shown in Figure 1, where clear upward trends were found for all dimensions. In the ecological dimension, a clear "low in the west, high in the east" feature is evident. Except for Hechuan, Yubei, Jiangbei, and Dadukou, which maintained a low level during the 2018–2020 period, other districts and counties had different degrees of improvement. In 2020, the proportion of districts and counties with high, relatively high, relatively low, and low levels were 26.31%, 34.21%, 28.95%, and 10.53%, respectively. Regarding the living dimension, a clear "low in the central area, high in the north and south" feature is observed. During the 2018–2020 period, Nanan, Kaizhou, Chengkou, Wuxi, and Youyang consistently maintained a low level. Jiangbei, Changshou, and Wansheng Economic Development Zone consistently maintained a high level. The level of districts and counties such as Shizhu and Yunyang fluctuated. In 2020, the proportion of districts and counties with high, relatively high, relatively low, and low levels were 10.53%, 39.47%, 36.84%, and 13.16%, respectively. As for the production dimension, it shows a clear "dispersed distribution" feature. During the 2018–2020 period, Shizhu, Wansheng Economic Development Zone, Jiangjin, and Yongchuan consistently maintained a low level. Yubei and Bishan consistently maintained a high level. The level of counties and districts such as Chengkou, Wushan, and Qianjiang fluctuated. In 2020, the proportion of districts and counties with high, relatively high, relatively low, and low levels were 28.95%, 31.58%, 28.95%, and 10.52%, respectively.

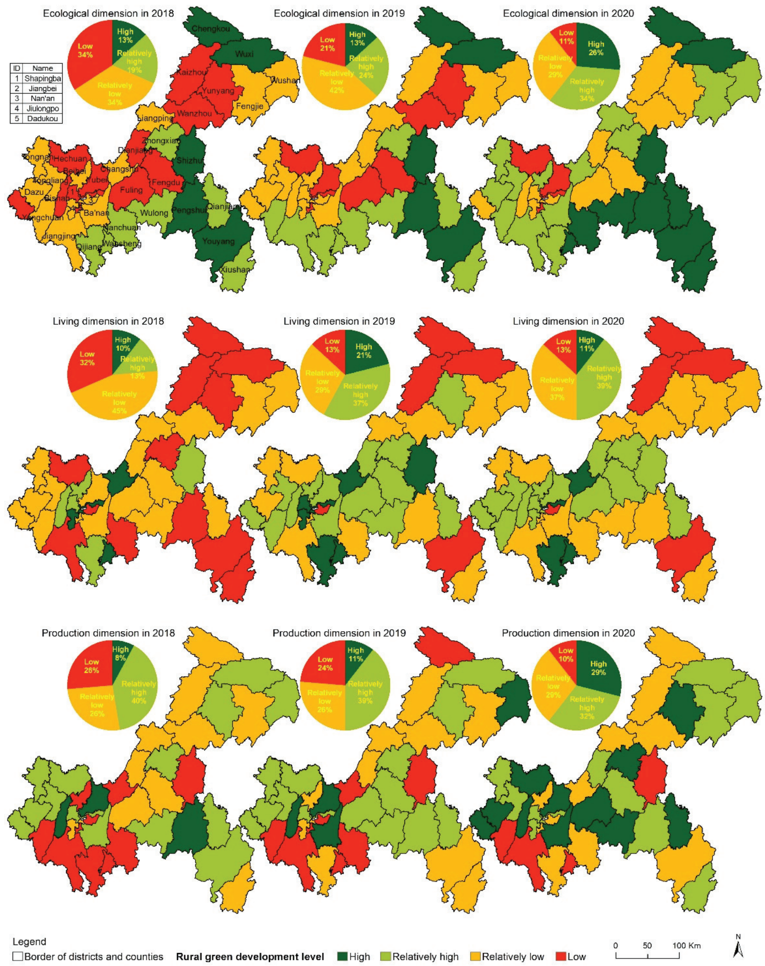

Figure 1. The distribution of the development level on ecology, living, and production dimensions in Chongqing from 2018 to 2020.

3.2. Comprehensive Index of Rural Green Development

3.2.1. Temporal and Spatial Evolution of Various Districts and Counties

The comprehensive index of the rural green development level shows a clear, overall, upwards trend (Figure 2). The proportion of districts and counties with high, relatively high, relatively low, and low levels were 5.26%→21.05%→47.37%, 18.42%→34.21%→34.21%, 39.48%→31.58%→10.53%, and 36.84%→13.16%→7.89% in 2018, 2019, and 2020, respectively. In 2018, only Pengshui and Qianjiang were in the high-level category. In 2019, Wulong, Shizhu, Zhong, Wansheng, Jiulongpo, and Bishan were added to the high-level category. In 2020, there were 18 districts and counties in the high-level category, including Qijiang. During 2018 and 2020, Dadukou, Nanan, and Kaizhou were all at low levels. The low levels in Dadukou and Nanan were mainly related to low green coverage, medical development, and agricultural consumption index, while the low level in Kaizhou was because of the low land surface disturbance and living dimension level. This indicated that a high economic level was not necessarily correlated with a high level of rural green development.

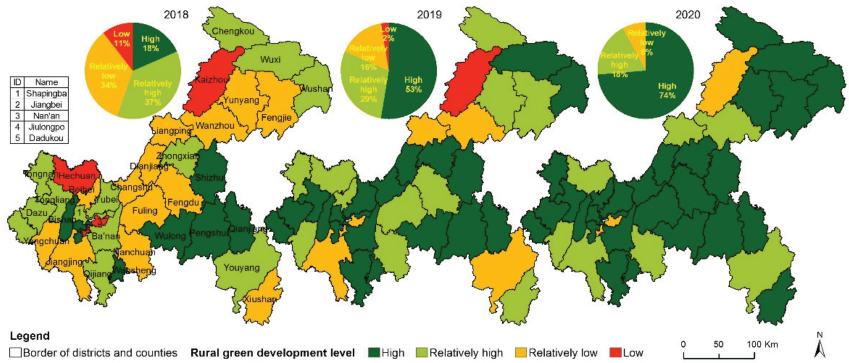

Figure 2. Distribution of rural green development level in Chongqing from 2018 to 2020.

3.2.2. Regional Disparity Evolution

The results of the Theil index (Figure 3) showed that the Theil index of Chongqing City in 2018, 2019, and 2020 was 0.0185, 0.0121, and 0.0114, respectively, indicating a downward trend year by year. This suggests that the regional differences in the green development level of rural areas at the city level are narrowing, which is closely related to the promotion of the rural revitalization strategy, ecological civilization, and the beautification of rural construction work. The results of regional differences showed a trend of decreasing differences followed by an increase in the city level between 2018 and 2020 (0.0069, 0.0033, and 0.0041, respectively). The results of intra-regional differences showed that both the city and each region were showing a trend of gradually decreasing in differences. The Theil coefficients of intra-regional differences in the city in 2018, 2019, and 2020 were 0.0116, 0.0088, and 0.0073, respectively. Overall, the Theil coefficient in the main urban area was higher, indicating that the difference within the region is the largest. This is related to factors such as uneven economic development, large differences in ecological background, and differences in agricultural production intensity. Secondly, in the northeast urban agglomeration of Chongqing, the southern region of Liangping District, Dianjiang, and other areas are mainly agricultural, while the northern region of Chengkou, Wuxi, Wushan, and other areas belong to regions with abundant forest resources. This is an important factor leading to large differences within the region. The intra-regional differences in the southeast urban agglomeration of Chongqing are the smallest, mainly because the ecological background and economic development of each district and county within the region are relatively similar. They are all in the Wuling Mountain area, and except for Qianjiang District, the economic level differences among other districts and counties are relatively small.

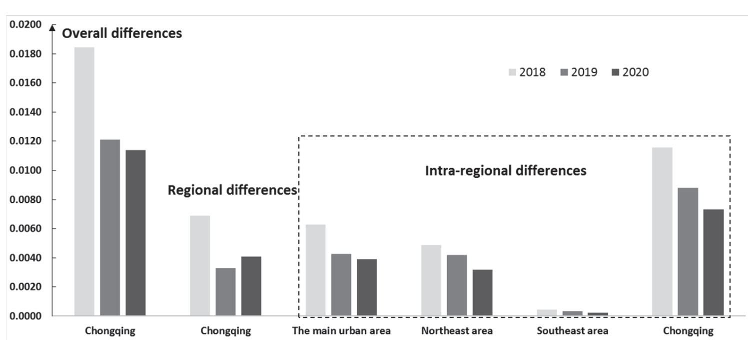

Figure 3. Evolution of differences in the rural green development levels.

3.3. Trends of Rural Green Development

The trends of rural green development in each district and county of Chongqing City are shown in Figure 4. An overall increasing trend was found in the studied areas. During 2018 to 2019, only Chengkou and Youyang experienced a decrease in the development level. A decrease in production dimension level was the main reason for the overall decrease in Chengkou, while decreases in ecological dimension and living dimension levels could explain the decrease in Youyang County. High-speed growth development was observed in 11 districts and counties including Hechuan, Changshou, etc., low-speed growth was observed in only Kaizhou, and medium-speed was observed in 24 districts/counties including Banan, Fuling, etc. During 2019 and 2020, decreased development level was only found in Shizhu, Shapingba, and Jiulongpo, which was caused by the decrease of living dimension levels in Shizhu, the decrease in ecological dimension and severe decrease in living dimension level in Jiulongpo, and the decrease in living dimension level in Shapingba. During 2018 and 2020, the city was on an upward trend of development level, with the proportions of low-speed growth, medium-speed growth, and high-speed growth districts and counties of 5.26%, 81.58%, and 13.16%, respectively. The low-speed growths in Shizhu and Jiulongpo were both due to the fall back after a significant increase during 2018 to 2019.

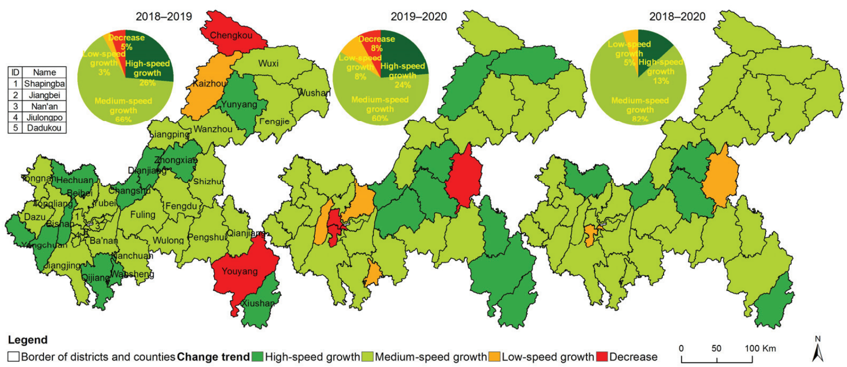

Figure 4. Distribution of the change trend of rural green development level in Chongqing.

Factor Analysis of Rural Green Development

We have calculated the level of green development in rural areas as mentioned above, but the level of green development is not only influenced by indicators related to "production–living–ecological", but also by urban development, aging, asset status, and government regulation. Therefore, further in-depth research is needed for the factors that affect the level of rural green development, which has a reference value for the government to formulate rural green development policies. We select urbanization level, aging level, contribution level of total assets, education expenditure level of government finance, health expenditure level of government finance, social security and employment expenditure level of government finance as influencing factor indicators.

The optimal scale regression model was used to assess the factors affecting rural green development. The R^2 of the model was 0.183, and the p value was <0.01, which also passed the F test, indicating the statistical significance of the model. As shown in Table 3, most indexes passed the significant test at the 1% level, with the exception of the urbanization level and aging level. Tolerance, defined as the proportion of the impact of the factor on rural green development that cannot be explained by other factors, reflected the collinearity between factors (the higher the better). The results of the tolerance indicated that the tolerance of the education expenditure level of government finance were relatively low. However, the overall tolerance was acceptable, indicating that the collinearity situation was limited, and the optimal scale regression effect was great.

Table 3. Optimal scale regression analysis of the influencing factors of rural green development.

Variable	p-Value	Importance Coefficient	Tolerance
Urbanization level	0.272	−0.034	0.494
Aging level	0.190	0.122	0.534
Contribution level of total assets	0.003	0.161	0.911
Education expenditure level of government finance	0.007	0.088	0.709
Health expenditure level of government finance	0.002	0.260	0.589
Social security and employment expenditure level of government finance	0.008	0.403	0.939

The importance coefficient results showed that the factors affecting rural green development were, from the most to least important, social security and employment expenditure level of government finance > health expenditure level of government finance > contribution level of total assets > education expenditure level of government finance. This indicated that social security and employment expenditure level of government finance and health expenditure level of government finance had the greatest impact on rural green development, with their contributions being 40.3% and 26%, respectively.

4. Discussion

4.1. Construction of an Evaluation Model for Rural Green Development Level Should Be in Line with Regional Reality Characteristics

Compared with existing research, the construction of an evaluation model for rural green development level incorporates aspects such as regional ecological environment, living standards, and production structure into the evaluation index system, which is more in line with the practical characteristics of rural areas in Chongqing. We have also fully incorporated reasonable indicators that have been used by scholars in non-rural areas. For example, Han considered economic, social, and environmental indicators in the assessment of green development level in the ASEAN region [30]. Jiang used indicators such as energy consumption per unit of GDP and pollution status in the study of green development level in the Shandong Peninsula urban agglomeration [31]. Wang used indicators such as environmental pollution and ecological space in the comprehensive evaluation of green development in the Dongliao River Basin [32]. Yue used indicators such as personnel efficiency, economy, and environmental impact in the evaluation of green development efficiency in resource-based cities in the Yellow River Basin [33]. Therefore, the rural green development level assessment model proposed in this study was based on the summary of existing research results, constructing an evaluation model from the ecological dimension, living dimension, and production dimension, and combining statistical and geographical methods to conduct temporal and spatial feature analysis, trend analysis, and influencing factor analysis for development levels. This model could have great academic and practical application value for the construction of rural green development research methods and the improvement of the rural green development level in Chongqing City. However, in order to make the model more universally applicable, more geographical and spatial data should be incorporated to optimize the model.

4.2. Rural Development Should Pay Attention to Balancing the Relationship between Ecology, Life, and Production

To analyze the differences in rural green development among different districts, counties, or regions, we introduced the Thiel index and achieved good results. We have found that there is a certain imbalance in the relationship between ecological protection, people's lives, and economic development in various districts, counties, or regions. For example, Dadukou and Nanan belonged to areas with high economic levels, but the green coverage index, medical development index, and agricultural material consumption index in the region were relatively low. At the same time, we believe that environmental quality, education level, and economic energy consumption are the key factors that affect the level of rural green development. This is consistent with Cui's research on green development in cities along the Yangtze River Economic Belt, which believes that economy and environment are key factors [34]. Han's research in the ASEAN region also believes that slow economic growth and environmental protection pressures have a significant impact on the level of green development [30]. Xue found in his research on green development in Belt and Road that Europe has the highest level of green development in terms of balanced natural, economic, and social dimensions, while Africa has the lowest level of green development due to imbalanced development [35]. Currently, China is accelerating the construction of a beautiful country, and Chongqing City, as a mountainous city in the western region, has a more complex internal situation.

4.3. Pandemic Infectious Diseases Such as COVID-19 Have Little Impact on Rural Green Level

The outbreak of COVID-19 in 2020 has had a negative impact on the global and Chinese economy. We expect it to have a certain impact on economic indicators in rural green development, such as the consumption capacity index, overall efficiency index, and economic energy consumption index. We analyzed the research results and found that the proportion of areas where the consumption capacity index and overall efficiency index decreased in 2020 was 15.79% and 18.42%, respectively. However, the proportion of areas where the economic energy consumption index increased was as high as 78.95%. This may be related to the prevention and control policies of COVID-19 implemented by China. The economic energy consumption index is mainly controlled by the economy of urban areas, and the other two indexes are mainly controlled by the economy of rural areas. In general, the population density of cities is high, the prevention and control policy of COVID-19 is very strict, and many enterprises and stores have been closed for a long time, so its economic impact on urban areas is greater than that on rural areas. This is consistent with the research results conducted by Janssens et al. in rural areas of Kenya. They believe that although the work income of people in rural areas is reduced due to COVID-19, gifts and borrowing are also reduced, and household consumption such as food expenditure is still at the level before the COVID-19 outbreak [36]. Zhao and Rasoulinezhad found that COVID-19 poses a serious challenge to economic poverty in different regions of Asia, but has little impact on poverty in larger or developed economies [37]. This is consistent with the actual situation in China, where due to strong government regulation, significant achievements have been made in poverty alleviation in rural areas. Therefore, pandemic infectious diseases such as COVID-19 will affect some indicators of rural green development, but will not affect the overall level of rural green development.

4.4. Suggestions and Prospects

From this study, the overall level of green development in rural areas in the city was good, but attention should be paid to the following aspects: (1) during the development process, the balance between ecological protection, people's living, and economic development should be emphasized. (2) The reasons for the degradation phenomenon that appeared during the development process in some districts and counties should be further analyzed for continuous improvement. For example, the living dimension level in Shizhu and the ecological dimension level in Jiulongpo both declined during the period of 2019–2020. (3) The green development of different rural areas in the city should stabilize the advantages in other aspects while highlighting their local advantages. For example, the ecological advantages of the Yudongnan urban agglomeration and the Yudongbei urban agglomeration were obvious and should be further strengthened in terms of improving the living and production dimensions.

Although we have proposed evaluation indicators and methods for rural green development, further research is needed on the grading standards for each indicator in the future, such as determining the grading values of high, correlated high, correlated low, and low levels for different indicators. Meanwhile, due to data limitations in the Yearbook and Bulletin, we have only evaluated the evolution trend of rural green development level from 2018 to 2020. In the future, we will conduct long-term series research to more clearly identify the evolution laws and trends of rural green development level. We will also evaluate the impact of the implementation of major national strategies over a longer period of time.

5. Conclusions

This study constructed a model for evaluating the level of rural green development in a region based on ecological, living, and production dimensions, with Chongqing as the research area. The spatiotemporal characteristics, trends, and influencing factors of the rural green development level in the region from 2018 to 2020 were analyzed using an entropy weight method, Theil index, optimal scale regression model, and GIS method. The following conclusions were drawn:

1. The overall trend of the ecological dimension, living dimension, production dimension, and comprehensive result of the rural green development level in the city shows continuous improvement. Based on the comprehensive index, the proportion of counties with high-level and relatively high-level grades has increased from 5.26% and 18.42% to 47.37% and 34.21%, respectively, from 2018 to 2020;
2. The Theil index results showed that the difference in the rural green development level among counties in the city has decreased with the improvement of the development level. The Theil index in the city was 0.0185, 0.0121, and 0.0114 in 2018, 2019, and 2020, respectively;
3. The trend in rural green development level change showed an overall upwards trend in the city. All counties showed an upwards trend from 2018 to 2020, with the proportion of counties with slow growth, medium growth, and high growth being 5.26%, 81.58%, and 13.16%, respectively;
4. The results of the optimal scale regression model showed that the factors that had the greatest impact on the rural green development level are social security and employment expenditure level of government finance and health expenditure level of government finance, with their contributions being 40.3% and 26%, respectively.

Author Contributions: Conceptualization, K.Z., D.S., Y.L., and L.Z.; methodology, K.Z., L.Z., and X.T.; software, K.Z., L.Z., Y.H., and Y.L.; formal analysis, K.Z. and S.Z.; resources, K.Z. and L.Z.; data curation, K.Z. and D.S.; writing—original draft preparation, K.Z. and X.T.; writing—review and editing, K.Z., D.S., Y.L. and X.T.; visualization, K.Z. and L.Z.; funding acquisition, K.Z., D.S. and X.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported and funded by Chongqing Municipal Bureau of Science and Technology (No.CSTB2022TIAD-KPX0120; No.CSTB2022NSCQ-MSX0538), Chongqing Municipal Education Commission (No.22SKGH569), Chongqing Academe of Eco-environmental Science (No.Cqhky2021jxjl00001). The work was supported by the Innovation Center for Green Intelligent Environmental Protection Technology and Equipment Technology in Chongqing.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The meaning of 39 initial indicators selected from the perspective of "production–living–ecological".

Primary Index	Order Number	Indicators	Explanation	Expert Suggested Indicators	Reason for Exclusion	Properties
Ecological Dimension	1	Forest coverage rate	Reflect the ecological environmental of the region.	Yes		Positive
	2	Comprehensive environmental air quality index	Reflect the air environmental of the region.	Yes		Negative
	3	Production water coefficient	Reflect the water resource of the region.	Yes		Positive
	4	Production water modulus	Reflect the water resource of the region.	Yes		Positive
	5	Soil erosion area ratio	Reflect the situation of soil erosion in the region.	Yes		Negative
	6	Area of rocky desertification	Reflect the distribution of rocky desertification in the region.	No	The differences between different regions are significant and not representative.	Negative
	7	Area of ecological restoration	Reflect the ecological restoration status of the region.	No	The differences between different regions are significant and not representative.	Positive
Living Dimension	1	The proportion of water bodies with surface water reaching or better than Class III	Reflect the water safety situation of residents.	No	The proportion of each district has approached 100%, which is meaningless.	Positive
	2	Proportion of water bodies with surface water quality inferior to Class V	Reflect the water safety situation of residents.	No	The proportion of each district has approached 100%, which is meaningless.	Negative
	3	The compliance rate of water quality in water functional areas	Reflect the water safety situation of residents.	No	The proportion of each district has approached 100%, which is meaningless.	Positive
	4	The proportion of centralized drinking water sources with water quality reaching or surpassing Class III	Reflect the water safety situation of residents.	No	The proportion of each district has approached 100%, which is meaningless.	Positive
	5	Growth rate of per capita GDP	Reflect the economic situation of residents.	No	This indicator is duplicated with the per capita GDP indicator.	Positive
	6	Per capita GDP	Reflect the economic situation of residents.	Yes		Positive
	7	Per capita disposable income of rural residents	Reflect the economic situation of residents.	Yes		Positive
	8	Per capita consumption expenditure of rural residents	Reflect the economic situation of residents.	No	This indicator overlaps with the per capita disposable income indicator of rural permanent residents.	Positive
	9	Permanent population	Reflect the economic situation of residents.	Yes		-
	10	Number of hospital beds	Reflect the status of residents' medical resources.	Yes		Positive
	11	Number of students in ordinary middle schools	Reflect the status of residents' educational resources.	Yes		Positive
	12	Number of students in primary schools	Reflect the status of residents' educational resources.	Yes		Positive
	13	Number of teachers in ordinary middle schools	Reflect the status of residents' educational resources.	Yes		Positive
	14	Number of teachers in primary schools	Reflect the status of residents' educational resources.	Yes		Positive
	15	Length of highways	Reflect the convenient transportation conditions of residents.	Yes		Positive
	16	Area of the region	Represents the territorial area of a region.	Yes		-

Table A1. *Cont.*

Primary Index	Order Number	Indicators	Explanation	Expert Suggested Indicators	Reason for Exclusion	Properties
Production Dimension	1	Overall labor productivity	Reflect the level of productivity in the region.	Yes		Positive
	2	Output value of the secondary industry	Reflect the status of industries in the region.	Yes		Positive
	3	The proportion of the output value of the tertiary industry to GDP	Reflect the status of industries in the region.	No	The correlation between this indicator and rural areas is low.	Positive
	4	The proportion of employees in the tertiary industry among the workforce	Reflect the composition of industrial personnel in the region.	No	The correlation between this indicator and rural areas is low.	Positive
	5	Energy consumption of industrial enterprises with annual revenue over a certain amount	Reflect the status of industrial energy consumption in the region.	Yes		Negative
	6	Water consumption per CNY 10,000 of GDP	Reflect the status of industrial water consumption in the region.	Yes		Negative
	7	Water consumption per unit of industrial added value	Reflect the status of industrial water consumption in the region.	No	This indicator is duplicated with the water consumption per CNY 10,000 of GDP.	Negative
	8	Utilization rate of hazardous waste disposal	Reflect the status of industrial chain in the region.	No	The correlation between this indicator and rural areas is low.	Positive
	9	Comprehensive utilization rate of industrial solid waste	Reflect the status of industrial chain in the region.	No	The correlation between this indicator and rural areas is low.	Positive
	10	Effective utilization coefficient of irrigation water in farmland	Reflect the status of agricultural water use in the region.	Yes		Positive
	11	Comprehensive utilization rate of crop straw	Reflect the status of agricultural waste utilization in the region.	No	The difference in this indicator among different regions is too small and meaningless.	Positive
	12	Comprehensive utilization rate of livestock and poultry manure	Reflect the status of agricultural waste utilization in the region.	No	The difference in this indicator among different regions is too small and meaningless.	Positive
	13	Safe utilization rate of contaminated farmland	Reflect the safe utilization of agricultural land in the region.	No	The difference in this indicator among different regions is too small and meaningless.	Positive
	14	Sown area of crops	Reflect the scale of agricultural land in the region.	Yes		-
	15	Amount of fertilizer applied	Reflect the status of agricultural fertilizer use in the region.	Yes		Negative
	16	Amount of pesticides used	Reflect the status of agricultural pesticide use in the region.	Yes		Negative

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Article

Spatial–Temporal Evolution Characteristics and Driving Factors of Rural Development in Northeast China

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Abstract: An assessment of rural development and its driving factors can effectively reflect the characteristics and transformation of rural areas and provide important information for the formulation and implementation of rural development strategies. Taking Northeast China as study area, a rural development index framework was constructed from three dimensions, i.e., basic rural conditions, the state of agricultural development, and farmers' living standards, based on which the rural development level of each city in Northeast China for the years 2000, 2005, 2010, 2015 and 2020 was assessed. Then, an exploratory spatial data analysis was used to explore the spatial and temporal variations in the rural development level in Northeast China during the period 2000–2020. The driving factors were also analyzed using a geographically and temporally weighted regression model. The results showed that the rural development level showed an increasing trend overall, with a spatial pattern of "high in the central, low in the east and west" in most periods. The degree of spatial agglomeration of the rural development level also showed a strengthening trend overall. The hots spots of rural development were mainly distributed in the Southern and Northern regions, while the cold spots were mostly concentrated in the central, eastern and western regions. Urbanization processes, elevation, annual precipitation and other natural factors have weakened the level of rural development to a certain extent, while agricultural production upgrading, an increase in the general public budget expenditure per capita and the sound financial situation of the government can promote rural development in Northeast China. The effects of the natural environment and local economic conditions on rural development were different in different regions. To improve rural development in the future, we should scientifically grasp the basic conditions, such as rural resource endowment, location conditions, agricultural technology, policies, investment and other external conditions, and formulate regional rural development strategies according to local conditions and in light of local rural characteristics.

Keywords: rural development; spatial–temporal divergence; driving factors; Northeast China

Citation: Zhang, X.; Wu, H.; Li, Z.; Li, X. Spatial–Temporal Evolution Characteristics and Driving Factors of Rural Development in Northeast China. *Land* **2023**, *12*, 1407. https://doi.org/10.3390/land12071407

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 7 June 2023
Revised: 9 July 2023
Accepted: 11 July 2023
Published: 13 July 2023

1. Introduction

Sustainable development is a common goal of all countries in society [1,2]. However, most studies currently focus on the sustainable development of countries as a whole or on urban areas as the main areas of socio-economic activity [3]. As an important part of the country, especially in developing countries, the sustainable development of rural areas is often neglected [4,5]. Rural decline, rural population reduction and outflow, land loss, rural ecological environment pollution, backwards infrastructure and other problems are becoming increasingly serious and significantly hinder the sustainable development of rural areas [6]. As a typical developing and agricultural country, China's three rural issues (agriculture, rural areas and farmers) have been some of the major social issues concerning the government and all sectors of society [7]. These issues constitute the major contradictions in China's economic and social development. In recent years, China's rapid economic development has led to a rapid urbanization process [8]. However, this has also led to an imbalance in the development of rural and urban areas [9,10]. The sustainable development of rural areas is further constrained by the shift of arable land to other types of land [11,12], the loss of rural labor [13,14], the increasing aging of the rural population [15,16] and the loss of rural culture [17]. The imbalance between urban and rural areas must be addressed urgently, and rural revitalization is an important part of future socio-economic development [18].

A quantitative evaluation of rural development is a prerequisite for recognizing the current state of rural development and for gaining insight into the weaknesses of rural development [19]. Research on rural areas mainly focuses on rurality evaluation [20], the spatial differentiation of rural settlements [21], rural reconstruction and rural multi-functions [22,23]. In addition, the evaluation of rural development should not be limited to a single aspect but should be based on the actual situation and a reasonable choice of evaluation angles [24]. Rural revitalization covers several areas, including ecological viability [25,26], industrial development [27], harmonious human governance [28,29] and cultural prosperity [30]. Therefore, scholars generally adopt the construction of rural indicators, field surveys and grouping to evaluate the level and characteristics of rural development [31]. The evaluation system changes with different research areas and data dimensions [32]. The evaluation indicators mainly include employment structure, traffic patterns, population density and structure, resident satisfaction, distance from the city center and other socio-economic and geospatial patterns and subjective survey indicators [33]. Conventional indicators can be applied in most research areas, but the selection of micro-indicators and more detailed and targeted indicators can be adapted to local conditions to carry out unique analyses of the actual situations in rural areas [34,35]. For example, rural areas endowed with tourism resources need to incorporate more tourism-related factors such as the number of hostel beds, the number of tourists and the number of scenic spots into the evaluation system [36]. In rural areas dominated by the planting industry, more consideration should be given to industry-related indicators such as the yield of agricultural products and input of agricultural capital [37].

After the quantitative evaluation of rural development, the factors influencing rural development must be identified [38]. Based on this identification, the weaknesses in rural development analyzed in the quantitative evaluation are targeted for improvement and management. Rural development can be driven by both external factors and internal factors [39]. A variety of models and methods are applied to identify and analyze the driving factors of rural development [40–42]. Ma et al. quantitatively analyzed the urban–rural transition in Gansu Province by constructing a comprehensive evaluation index system for county population and land industrial systems and a quantitative model of the degree of urban–rural transition and explored its spatiotemporal changes and driving forces through the use of hotspot identification and a geographic detector model [43]. Yang et al. used the entropy weight-TOPSIS method to measure the rural resilience level in 31 regions in China and analyzed the configuration of influencing factors using a fuzzy-set qualitative comparative analysis (fsQCA) [44]. Yuan et al. used a spatial regression model to determine the core influencing factors and main driving mechanisms extracted at different stages [45]. Nie et al. used an intensity index of rural spatial reconstruction and the contribution rate of rural spatial reconstruction to quantitatively evaluate the spatial development levels of tourist villages on a microscale, investigating the stage characteristics of their spatial reconstructions [39]. Clarifying the relationship between the influencing factors and sustainable rural development and exploring the specific mechanisms of influencing factors can provide theoretical guidance and policy suggestions for the implementation of a rural revitalization strategy and provide a reference for rural development research [46].

In view of the above research background and deficiencies, this paper aims to carry out a comprehensive and quantitative empirical study on the spatiotemporal patterns and driving mechanisms of rural development in Northeast China. The contribution of this study is mainly reflected in the following three aspects. Firstly, from the perspective of a rural revitalization strategy, the study is set in Northeast China, an important grain base in China. Moreover, there is a great difference between urban and rural development in Northeast China. The study spans a long period of time, from 2000 to 2020, with time intervals of five years. This makes the research results more representative. Secondly, representative indicators are selected from the perspectives of the state of agricultural development (“agriculture”), basic rural conditions (“rural areas”) and farmers’ living standards (“farmer”) to explore the development of rural areas in Northeast China and to derive the characteristics of the spatial and temporal differences in sustainable rural development in different dimensions so as to provide a reference for the realization of sustainable rural development models. Third, for the analysis of the driving factors, the results of ordinary least squares regression (OLS), geographically weighted regression (GWR) and geographically and temporally weighted regression (GTWR) models are compared, and the GTWR model with the best fit is chosen to make the results more convincing.

2. Materials and Methods

2.1. Study Area

Northeast China covers 36 prefectures in three provinces, i.e., Liaoning, Jilin and Heilongjiang (Figure 1). Straddling the mid-temperate and cold temperate zones from south to north, it has a temperate monsoon climate with four distinct seasons, warm–rainy summers and cold–dry winters. Northeast China is rich in water resources and diverse in topography. It is surrounded by the Yellow and Bohai Seas to the south, the Yalu River, Tumen River, Ussuri River and Heilongjiang River to the east and north, and the land boundary to the west. The inner part of Northeast China contains the high mountains, middle mountains, low mountains and hills of the Greater Khingan Mountains, Lesser Khingan Mountains and Changbai Mountains, and the central part contains the vast Songliao great plain and Bohai sunken area. The complex and diverse geographical environment provides abundant agricultural resources such as arable land, natural vegetation and fresh water, constituting the foundation of regional rural development. Northeast China vigorously developed a heavy industry for the economic construction of China during the early period of its founding. Since China’s reform and opening up, due to environmental pollution, as well as the old industrial bases in Northeast China and other problems, the development of urban and rural areas in Northeast China is unbalanced, relatively slow, and some remote areas even remain backwards, with a lack of living facilities, poor traffic conditions and other problems. In this paper, 36 prefecture-level cities in Northeast China were taken as the research object to evaluate spatial–temporal evolution characteristics and the driving factors of rural development in Northeast China during the period 2000–2020.

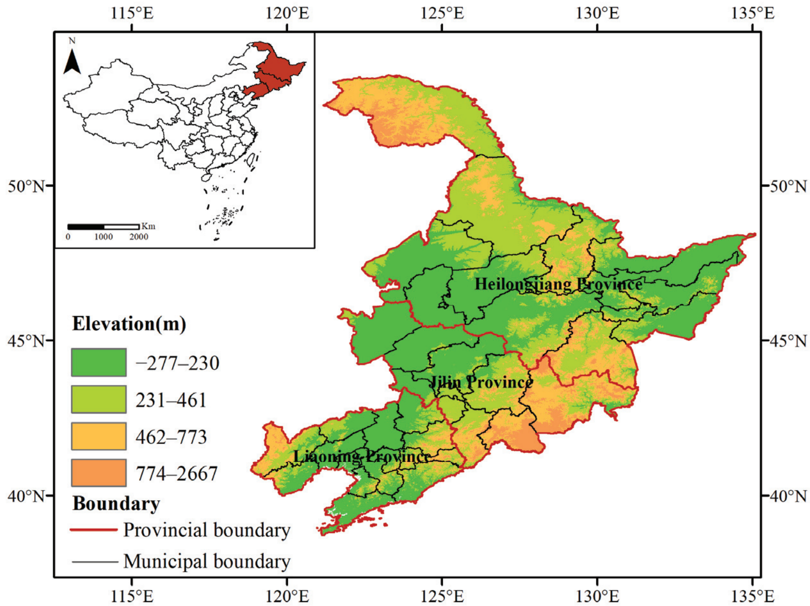

Figure 1. Geographical location of Northeast China.

2.2. Data Sources

In order to explore the level of rural development and driving factors in Northeast China in the context of rural revitalization and urban–rural integration, considering the time of rural development and the desirability of the research data, five time nodes of 2000, 2005, 2010, 2015 and 2020 were selected for analysis. The data sources for this paper were divided into two categories. One category comprises attribute data, which mainly reflect the socio-economic indicators of rural development and its influencing factors in Northeast China and were obtained directly from the *China County Statistical Yearbook*, *China Rural Statistical Yearbook*, *China Regional Economic Statistical Yearbook* and the statistical yearbooks of the provinces and cities in Northeast China for the period 2000–2020. The other category comprises basic geographic information data, which mainly reflect the ecological indicators, topographic factors, vegetation coverage and location variables of rural development in Northeast China. The relevant data were derived from remote sensing image interpretation, digital elevation model data (DEM) and map vector data, respectively, and were processed and extracted using ArcGIS.

2.3. Methods

2.3.1. Index System Construction

Based on the relevant literature and combined with the regional development situation in Northeast China and the availability of data at the prefecture city-level, this paper concludes that the rural development level can be characterized via three dimensions, i.e., "rural areas", "agriculture" and "farmer", and establishes an index system, as shown in Table 1. The ratio of population in the current year to the population in 2000, the per capita electricity consumption of the rural population, the number of beds in welfare homes, the number of hospital beds per capita and the amount of fertilizer applied per hectare of crop area sown were selected to represent the basic rural conditions. In addition to the amount of fertilizer applied per hectare of crop area sown, the higher the values of other indicators, the better the rural development situation. Agricultural development is represented by the production of grain per hectare of grain sown area, agricultural machinery power per hectare of grain sown area, meat production per capita, rural grain production per capita, agricultural output value per hectare of grain sown area and the added value of the primary industry. The greater the values of these indicators, the better the agricultural development situation. The per capita disposable income of rural households, the per capita savings balance of urban and rural residents, the Engel coefficient of farmers and the per capita housing area in rural areas were selected to represent the living standards of farmers. In addition to the Engel coefficient of farmers, the larger the index value, the better the living standards of farmers, and the smaller the Engel coefficient of farmers, the higher the living standards of farmers. Apart from the Gini coefficient, the higher the other indicators, the better the farmers' living standards. The weights of the indicators were determined using the principal component analysis method.

Table 1. Evaluation index system for the rural development at city level in Northeast China.

Dimension	Indicator	Weight	Calculation Method	Property
Rural basic conditions	Attractiveness	0.05	Rural population of current year/rural population in 2000	+
	Rural vitality	0.02	Rural electricity consumption/rural population	+
	Level of social welfare	0.07	Number of beds in welfare homes/total population of regional household registration	+
	Medical and health conditions	0.05	Number of hospital beds/total population of regional household registration	+
Agricultural development state	Agricultural environmental pressure	0.08	Fertilizer application/crop sown area	−
	Production efficiency	0.01	Total grain production/grain sown area	+
	Mechanization level	0.02	Total agricultural machinery power/grain sown area	+
	Meat production per capita	0.1	Total meat production/total population of regional household registration	+
	Grain production per farmer	0.07	Total grain production/rural population	+
	Production benefits	0.01	Total agricultural output value/grain sown area	+
	Agricultural scale	0.1	Primary sector value added	+
Farmers' living standards	Income level	0.12	Disposable income per rural household	+
	Savings deposits per capita	0.09	Urban and rural savings deposit balance/total population of regional household registration	+
	Living standards	0.1	Rural Engel coefficient	−
	Housing	0.09	Housing area per capita in rural areas	−

In order to eliminate the influence of the difference in the scale of the indicators, the indicators were standardized using the polar difference method. Based on the standardized values and indicator weights obtained, the rural development index was calculated for each year. The standardized formula is as follows.

$$X'_{m,ij} = \frac{X_{m,ij} - X_{m,jmin}}{X_{m,jmax} - X_{m,jmin}} (positive\ indicator) \quad (1)$$

$$X'_{m,ij} = \frac{X_{m,jmax} - X_{m,ij}}{X_{m,jmax} - X_{m,jmin}} (negative\ indicator) \quad (2)$$

$$RI_{m,i} = \sum_{j=1}^{n} W_j X'_{m,ij} \quad (3)$$

where $X_{m,ij}$ is the value of the indicator j for a municipality i in the year m; $X'_{m,ij}$ is the standardized value of the indicator j for a municipality i in the year m; and $X_{m,jmax}$ and $X_{m,jmin}$ are the maximum and minimum values of the indicator j in the year m, respectively.

$RI_{m,i}$ is the rural development index for a municipality i in the year m. W_j is the weight of the jth indicator; and n is the number of indicators.

2.3.2. Exploratory Spatial Data Analysis

An exploratory spatial data analysis (ESDA) revealed similar agglomeration and differentiation characteristics via an exploration of intrinsic spatial correlations, which can be divided into global autocorrelation and local autocorrelation. Global autocorrelation generally explores the degree of aggregation or differentiation of the global space, and the research methods include Moran's I, global G statistic, etc. The global Moran's I is as follows:

$$Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})}{s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{4}$$

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \overline{x})}{n} \tag{5}$$

Local autocorrelation mainly reveals the characteristics of high and low concentrations in local areas, that is, the formation of "hot spots" and "cold spots". The local Moran's index can be utilized to further measure the degree of spatial association between region and the surrounding regions. The local Moran's I is calculated as follows:

$$I_i = \left[\frac{x_i - \overline{x}}{s^2}\right] \times \left[\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})\right] \tag{6}$$

2.3.3. Analysis of Driving Factors

(1) Selection of driving factors

Scholars generally believe that natural factors and economic factors will have an impact on rural development. By referring to the relevant research results, based on the research purpose and considering the availability of the data and other practical situations, 11 explanatory variables were selected to comprehensively reflect the driving factors of rural development. The natural factors include elevation, slope, precipitation, temperature and NDVI, and the socioeconomic factors include the proportion of primary industry added value to the GDP, the urbanization level, population density, general public budget expenditure per capita, public financial revenue and social fixed asset investment. The raw data were normalized to eliminate multicollinearity between variables.

(2) Geographically weighted regression

Ordinary least squares regression (OLS), as a full domain regression model, generally explores the linear influence relationships between multiple independent variables and the dependent variable. However, this method only reflects spatially consistent patterns of influence and has difficulty revealing differences in the influence of factors over space. An OLS model estimates the value of the dependent variable in each urban unit using the full range of independent variables, and the model equation is

$$Y_i = \beta_0 + \sum_{j=1}^{n} \beta_j X_{ij} + \varepsilon_i \tag{7}$$

where Y_i is the rural development index for a city i. X_{ij} is the value of the jth driving factor. ε_i is the random error term of the independent distribution of the model. β_j is the regression coefficient, which is assumed to be a deterministic constant.

Compared to OLS, geographically weighted regression (GWR) is an extension of the OLS model that captures spatial trends in the regression coefficients of variables as they move with geographical location. The GWR model is expressed as follows:

$$Y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{K} \beta_k(u_i, v_i) X_{ik} + \varepsilon_i,\ i = 1, 2, 3\cdots,\ n \tag{8}$$

where Y_i is the dependent variable, X_{ik} is the kth independent variable, $\beta_k(u_i, v_i)$ is the kth coefficient at location (u_i, v_i) and ε_i is the random error term. Unlike OLS, the parameters are allowed to vary by location (u_i, v_i).

Traditional GWR models have shortcomings in their specific uses due to the limited sample size of cross-sectional data, such as the fact that the stability of interpretation is limited by the sample size and thus cannot estimate the model parameters. Geographically and temporally weighted regression (GTWR), on the other hand, effectively breaks through this limitation by introducing the time dimension into the GWR model to solve the problem of spatial and temporal non-smoothness, making the estimation more effective [47,48]. Its general form is as follows:

$$Y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{K} \beta_k(u_i, v_i, t_i) X_{ik} + \varepsilon_i,\ i = 1, 2, 3\cdots,\ n \tag{9}$$

where t_i represents the observation time point. The problem here is to provide estimates of $\beta_k(u_i, v_i, t_i)$ for each variable k and each space–time location i. The estimation of $\beta_k(u_i, v_i, t_i)$ can be expressed as follows:

$$\hat{\beta}(u_i, v_i, t_i) = \left[X^T W(u_i, v_i, t_i) X\right]^{-1} X^T W(u_i, v_i, t_i) Y \tag{10}$$

where $W(u_i, v_i, t_i)$ is the spatial–temporal weight matrix, $W(u_i, v_i, t_i) = \mathrm{diag}(w_{i1}, w_{i2}, \cdots, w_{ij})$ and the element on the diagonal of Equation w_{ij} is the spatial–temporal distance decay function. In this paper, a Gaussian function was used to define the weight matrix, and the specific formula is as follows,

$$w_{ij} = \exp\left(-\left(\frac{d_{ij}}{h}\right)^2\right) \tag{11}$$

where d_{ij} is the spatial distance between the regions i and j; h denotes bandwidth and refers to the non-negative decay parameter of the functional relationship between weights and distance.

3. Results

3.1. Spatial–Temporal Analysis of Rural Development at the City Level in Northeast China

3.1.1. Spatial–Temporal Pattern of Rural Development in Northeast China

The rural development indices of 36 prefecture-level cities in Northeast China in 2000, 2005, 2010, 2015 and 2020 are visually presented in Figure 2. They were classified into five grades, including weak (RI $\leq$ 0.2), relatively weak (0.2 < RI $\leq$ 0.35), moderate (0.35 < RI $\leq$ 0.45), relatively strong (0.45 < RI $\leq$ 0.50) and strong (RI > 0.50), according to the Jenks natural breaks method.

From the perspective of different periods, the rural development level in Northeast China has been enhanced overall, but its spatial distribution in different stages is different. In 2000, the rural development level of Northeast China mainly consisted of weak-type areas and relatively weak-type areas. The relatively weaker type areas were mainly distributed in the north and south, such as in Dalian and Qiqihar. This is closely related to the rapid development of the level of mechanization since Dalian began to produce electric locomotives in 2000, which further promoted and developed the mechanization levels of local rural areas. In 2005, the scope of weak and relatively weak rural development level areas gradually expanded further, and this change was mainly concentrated in the central part of Northeast China. By 2010, the trend had intensified. During this period, there was no weak rural development level area in Northeast China, and most areas were relatively weak rural development level areas. Meanwhile, there were medium rural development level areas, mainly in Harbin, Dalian and Qiqihar. This may be related to the significant increase in agricultural and rural input, the improvement of the agricultural subsidy system, the increase in the minimum grain purchase price and the improvement of rural financial services around 2010. The local government's earnest implementation of national policies promoted the rapid development of the rural development level in Northeast China. In 2015, areas of medium-level rural development were further expanded. By 2020, due to the gap between urban and rural development, the development of Northeast China, as a traditional old industrial base, is slow. The "Rural revitalization Policy" and "Revitalization Policy of Northeast China" were put forward successively. The government attaches importance to and invests in the development of Northeast China, promotes the development of rural infrastructure construction and the improvement of agricultural technology in Northeast China, and the national subsidies for Northeast China improve the income and quality of life of farmers and promote rural development.

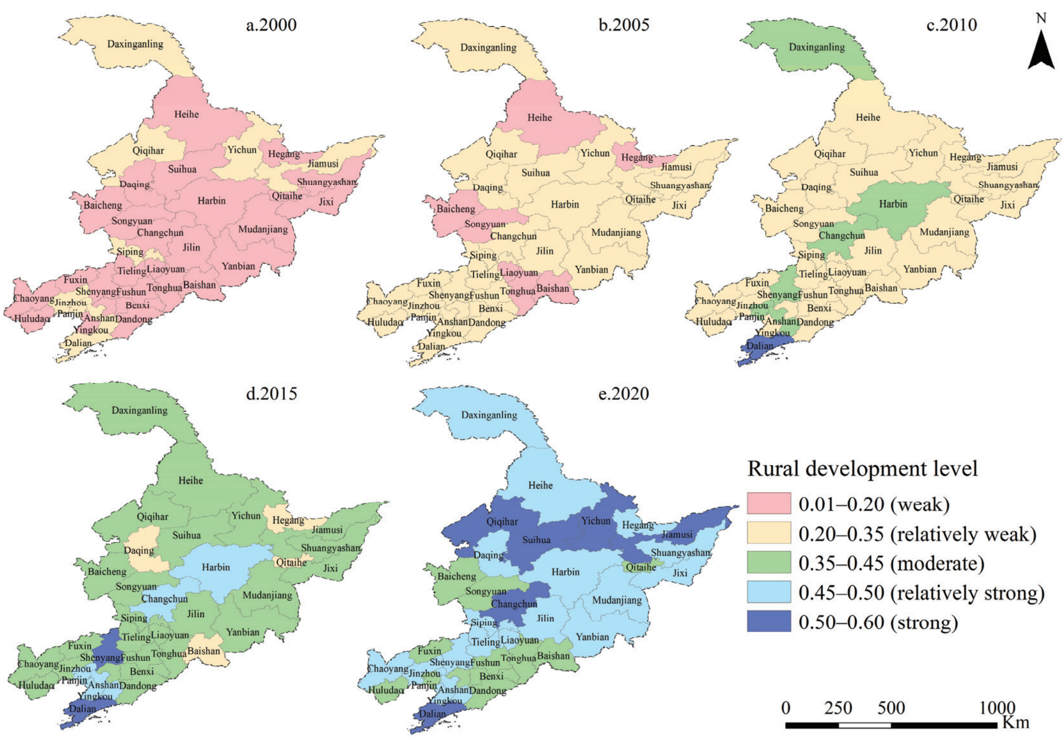

Figure 2. Spatial pattern of rural development at the city level in Northeast China from 2000 to 2020.

3.1.2. Spatial Autocorrelation Analysis of Rural Development at City Level in Northeast China

(1) Global autocorrelation analysis

In order to explore the spatial agglomeration and differentiation characteristics of the rural development levels of cities in Northeast China, Moran's I was further calculated (Table 2). The Moran's I values for the rural development level in Northeast China in 2000, 2005, 2010, 2015 and 2020 are all positive, and the Z(I) values are all greater than 2.58 at the

99% confidence level. This indicates a general tendency towards a spatial agglomeration of rural development in Northeast China. The year with the highest degree of agglomeration was 2015, and the year with the lowest degree of agglomeration was 2000. On the whole, the Moran's I values for the five time periods show an increasing trend, reflecting the gradual strengthening of the overall degree of spatial agglomeration.

Table 2. Global Moran's I value for the rural development level in Northeast China from 2000 to 2020.

Year	2000	2005	2010	2015	2020
Moran's I	0.154	0.219	0.309	0.322	0.194
Z(I)	3.337	4.461	6.129	6.308	4.106

According to the changes in Moran's I value over the years, the rural development level in Northeast China can be divided into two stages. The first stage was from 2000 to 2005, when the degree of aggregation of the rural development level in Northeast China showed an increasing trend. In this period, the rural development in Northeast China was relatively slow, and the degree of integration of urban and rural areas was low. The second stage was from 2010 to 2020, when the concentration of the rural development level in Northeast China showed a declining trend. This may be due to the development of industrialization and urbanization in this period, as well as the vigorous development of local characteristic tourism, which promoted rural development and drove the non-agricultural transformation of surrounding villages.

(2) Local autocorrelation analysis

The G_i^* index of rural development in Northeast China was analyzed, based on which the region was classified into five types, including a cold spot zone, sub-cold spot zone, mild zone, sub-hot spot zone and hot spot zone, according to the Jenks natural breaks method (Figure 3). Except for 2000 and 2020, most of the clusters with high rural development levels in Northeast China were concentrated in the southern region, while the clusters with low rural development levels were mostly concentrated in the northern and central regions. In 2000, hot spots and sub-hot spots were mainly distributed in the northern part of Northeast China and some central areas, such as Harbin, Qiqihar, Heihe and other cities (Figure 3a). In 2005, 2010 and 2015, mild areas decreased compared with the year 2000, and the decreased areas were replaced by cold spots and sub-cold spots (Figure 3c–d). Overall, cities with high and low rural development levels were clustered together. Revealing hot and cold areas helps the government formulate differentiated rural development strategies. For example, for hot spots, rural financial support should be strengthened, and local resources should be fully tapped to develop characteristic industries on the basis of guaranteeing traditional advantageous agriculture so as to enhance rural prosperity. For a cold spot area, we should support the development of diversified and new industries while consolidating rural modernization and encouraging farmers' entrepreneurship and technological innovation.

3.2. Effective Factor Analysis of Rural Development at the City Level in Northeast China

3.2.1. Comparison of Model Test Results

This paper quantitatively analyses the driving factors of rural development differentiation in Northeast China. The explanatory variables were screened using three models, i.e., the OLS model, the GWR model and the GTWR model, and the results of the three models were compared. As shown in Table 3, the coefficient of determination R^2 and the corrected coefficient of determination R^2 of the GTWR model were 0.954 and 0.951 respectively, which showed an overall enhanced explanatory power compared to the OLS and GWR models. The Akaike Information Criterion (AIC) value of the GTWR model was −186.257, which was smaller than that of the OLS and GWR models, indicating that the GTWR model was a better fit.

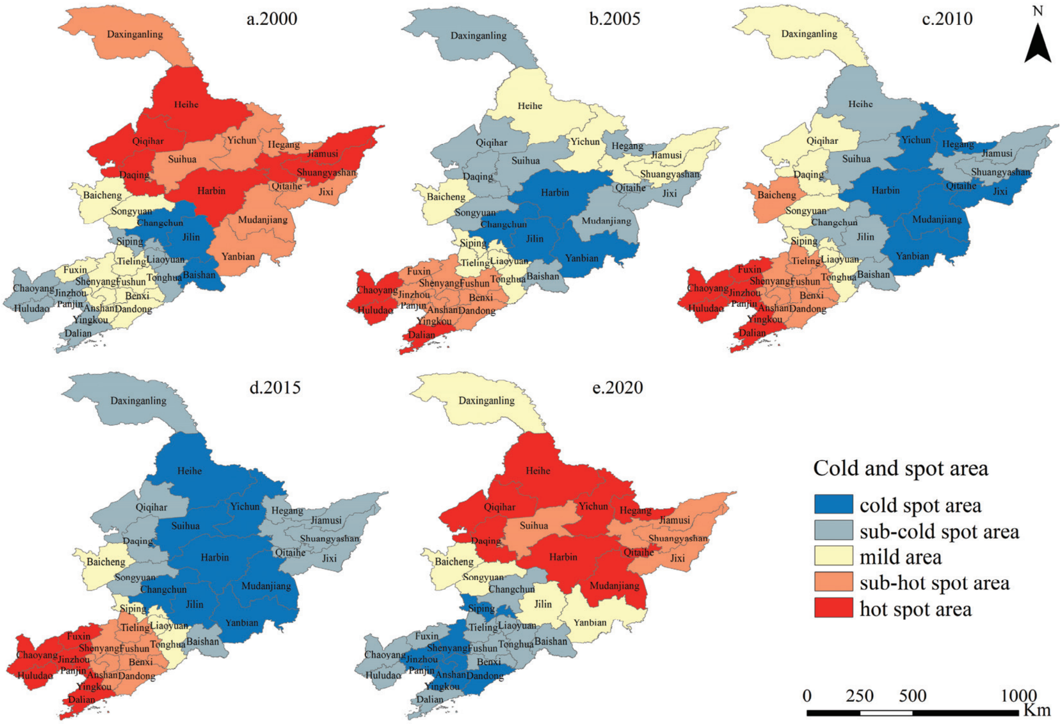

Figure 3. Spatial pattern of cold and hot spots of rural development at the city level in Northeast China from 2000 to 2020.

Table 3. Comparison of GWR model, GTWR model and OLS model fits.

Model Fitting Parameters	OLS Model	GWR Model	GTWR Model
R^2	0.842	0.911	0.954
Calibration R^2	0.813	0.905	0.951
Akaike Information Code (AICc)	−153.496	−177.007	−186.257

3.2.2. Driving Factor Analysis Based on the GTWR Model

(1) Analytical results of the GTWR model

Taking each factor in 2020 as an example, the average of the absolute value and the proportion of positive and negative values of the regression coefficients of each variable in the GTWR model were calculated, as shown in Table 4. The results showed that there were great differences in the degree of influence of each variable, which reflected the different influences of different factors on the rural development level. Among them, the proportion of primary industry added value to the GDP, the general public budget expenditure per capita, public finance revenue and population density had positive impacts on rural development for the whole region. This indicates that overall, the urbanization process and environmental protection had trade-off relationships with rural development. On the other hand, the more important the role of agriculture in economic production and the higher the government budget, the higher the level of rural development in Northeast China. This indicated that the region should coordinate the relationship between urban and rural development, upgrade the status of agricultural production and ensure a sound financial situation for the government. From the perspective of the positive and negative ratios of the regression coefficients, the natural environment (average elevation, average slope, annual precipitation, average temperature and average NDVI) and local economic conditions (urbanization level and social fixed asset investment) had both positive and negative effects, indicating that these factors both limited and promoted rural development and transformation in different regions; thus, the government needs to formulate strategies to promote rural development in accordance with local conditions.

Table 4. Regression coefficient statistics of the GTWR model for the driving factors analysis of rural development in Northeast China.

Driving Factors	Explanatory Variables	Average of Absolute Values	Positive %	Negative %
Natural factors	Average elevation	0.063	5.6	94.4
	Average slope	0.128	69.4	30.6
	Annual precipitation	0.043	36.1	63.9
	Average temperature	0.107	58.3	41.7
	Average NDVI	0.345	88.9	11.1
Socioeconomic factors	Proportion of primary industry added value to the GDP	0.105	100	0
	Urbanization level	0.028	16.7	83.3
	Population density	0.107	100	0
	General public budget expenditure per capita	0.231	100	0
	Public financial revenue	0.047	100	0
	Social fixed asset investment	0.022	69.4	30.6

(2) Spatial–temporal pattern of driving factors affecting rural development level at the city level in Northeast China

In order to observe the spatial distribution of the fitting coefficients of each driving factor more intuitively and reflect the spatial influence difference of each factor, taking the fitting results of each index in 2020 as an example, the regression coefficients of each variable in the GTWR model were visually expressed and analyzed (Figure 4).

The positive and negative effects of these natural environment indicators are different in space. Among them, the annual precipitation and average elevation have strong negative effects on most rural areas, while the average temperature, average NDVI and average slope have strong positive effects on most rural areas. From the perspective of spatial differences in influence, different regions play different roles. Relatively speaking, 94.4% of the rural development in the central, eastern and western regions of Northeast China is more susceptible to the negative impact of altitude. The central, eastern and western regions mainly include mountains, hills and large areas of plain. In the Songnen Plain in the west and Sanjiang Plain in the northeast, the main grain-producing areas, the per capita cultivated land area is five times that of the national per capita cultivated land area. The change in altitude may affect the local agricultural production situation to some extent. The average NDVI can promote the rural development levels of most villages in Northeast China. The increase in vegetation is conducive to increasing biodiversity. It can combine the construction of an ecological environment and the protection of rare animals and plants with eco-tourism agriculture to form a unique sightseeing agriculture, which is conducive to promoting the development of villages. An increase in annual precipitation caused a decline in rural development of 36.1% in the southern region, indicating that rural development in the southern region was more vulnerable to temperature constraints than in other regions.

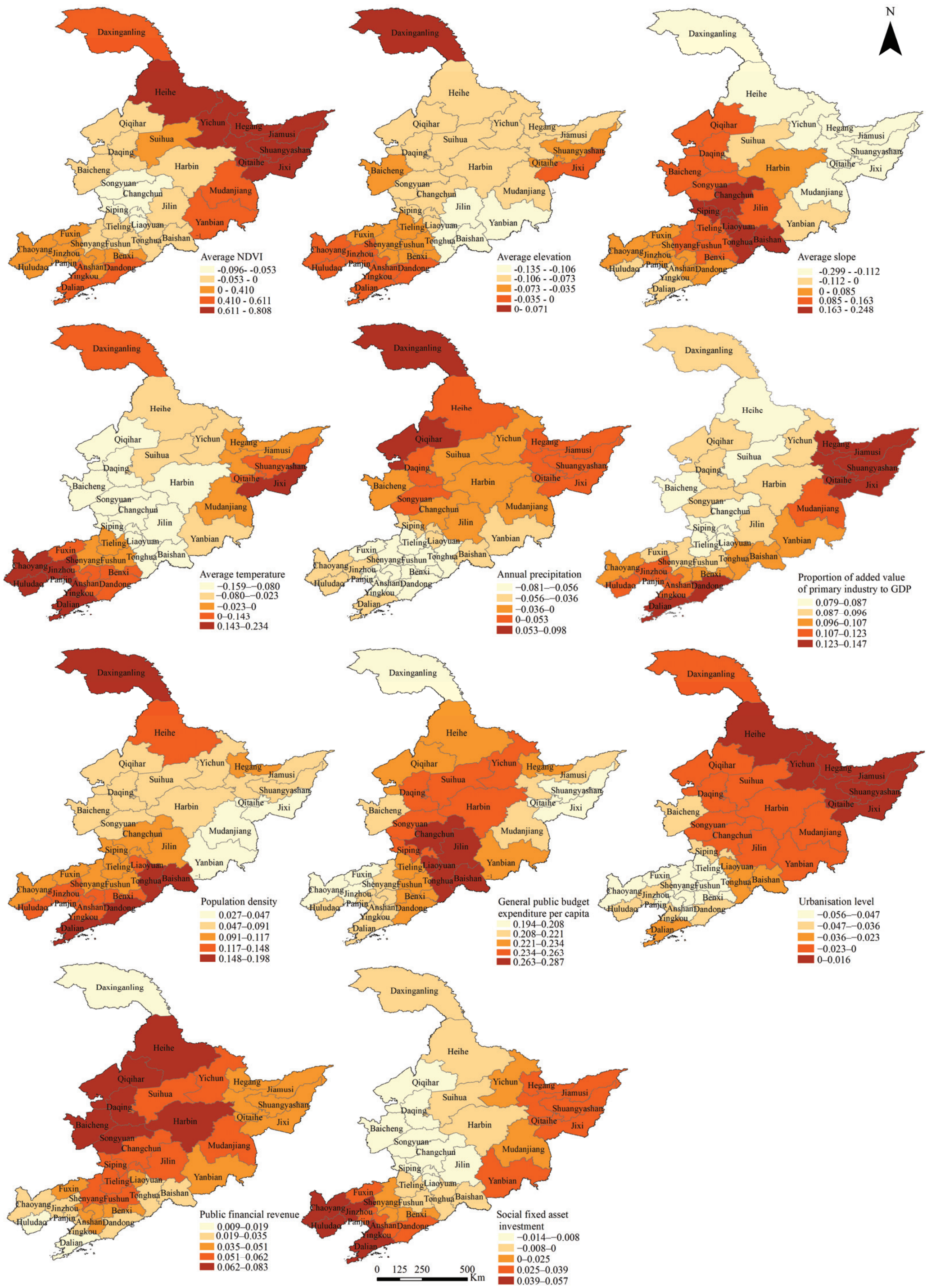

Figure 4. Spatial distribution of the coefficients of the driving factors of rural development in Northeast China, based on a GTWR model.

Slope has a negative effect on the level of rural development in 30.6% of the areas in Northeast China, reflecting the restricting effect of remote location conditions on rural development and transformation. Among them, the central and southern regions have the strongest restricting effects on local rural development and transformation, which gradually weaken to the north and show the lowest values in the eastern and northeastern regions. The central and southern regions have complex and diverse landforms with low hills, and the distribution of farmland is scattered and fragmented. These conditions are not conducive to large-scale and mechanized agricultural farming. In summary, the different effects of different natural factors on different regions highlight the regional differences in the impact of natural environment and also indicate that the natural conditions suitable for agricultural development vary from place to place.

Regarding the spatial–temporal heterogeneity of economic factors' influence on rural areas, it showed that the proportion of the primary industry added value to the GDP, population density, per capita expenditure of general public budget and public financial revenue all had positive effects on the level of rural development, reflecting the important roles of these indicators in promoting rural development and transformation. The level of urbanization has an inhibitory effect on the rural development of 83.3% of Northeast China. Liaoning Province's industrial development started early, and with the deepening of industrialization, the speed of urban outward expansion is increasing, which further increases the urban population. At the same time, Liaoning Province, as a large industrial province, provides more jobs, resulting in a loss of the rural population. There is a limiting effect on local rural development.

The influence of public finance revenue on rural development is strong in the central and eastern parts of Northeast China. This is related to the backward development of traditional agricultural areas in the east and west. This region has long suffered from problems such as weak infrastructure, backward agricultural technology, inefficient industrial management and a lack of talent. It is difficult to provide sufficient power support for local rural development and transformation. Compared with the abundant, high-quality resources in the south, its own development is more dependent on government support. Therefore, the government should continue to strengthen its financial tilt to the central, eastern and western regions in the future. The level of investment in fixed social assets has a promoting effect of 69.4% on the rural development level of Northeast China. It is mainly concentrated in the southern and eastern regions, perhaps because these areas have better basic conditions but lack human and technical resources. Increased social investment in these areas will contribute to rural development in these areas.

4. Conclusions and Discussion

4.1. Conclusions

Based on the theoretical analysis of the connotation, evolutionary logic and driving factors of the rural development level, this paper discusses the spatio-temporal characteristics of rural development in Northeast China in the years 2000, 2005, 2010, 2015 and 2020. In this study, the indicators were selected from three aspects, "agriculture", "rural" and "farmers", which makes the research more comprehensive and convincing. The research was set in Northeast China, which is an important grain base in China and has a large gap between urban and rural development. The findings of this study can provide important information for policy and planning decisions. Moreover, in the influencing factor analysis, an OLS model, GWR model and GTWR model were used for regression analyses. According to the analysis results from the three models, the model with the highest degree of fitting was selected to analyze the influencing factors. It showed that the spatial distribution of the level of rural development in different stages was different during 2000–2020. The rural development level in Northeast China had been enhanced overall and showed a spatial pattern of "high in the central, low in the east and west" in most periods. The level of rural development in Northeast China tended to demonstrate spatial agglomeration features. Overall, the Moran's I value for the five time periods showed an increasing trend, reflecting the gradual strengthening of the overall spatial agglomeration degree of rural development in Northeast China. The rural development agglomeration in Northeast China presented the spatial characteristics of "cold in the north and hot in the south", and it was relatively stable from 2005 to 2015. The theoretical driving mechanism of the rural development level and the empirical results of the GTWR model show that the urbanization process, elevation, annual precipitation and other natural factors have weakened the level of rural development to a certain extent, while agricultural production upgrading, an increase in general public budget expenditure per capita and the sound financial situation of the government can promote rural development in Northeast China. The effects of the natural environment and local economic conditions rural development were different in different regions.

In the future, to enhance sustainable rural development in Northeast China, the government should implement development strategies according to specific regional needs and potentials to address the unique challenges and opportunities of each region. Second, policies and initiatives that focus on sustainable resource management to mitigate the negative impacts of natural factors on rural development should be developed. This can include measures to protect water resources, improve soil quality, implement climate-smart agricultural practices and promote renewable energy. At the same time, local rural economies can be encouraged to diversify away from agriculture. It is also necessary to explore opportunities to support the development of other sectors such as tourism, eco-tourism, manufacturing and services. This can be achieved by providing infrastructure, market access and necessary support services. Cooperation between the public and private sectors can be promoted to accelerate rural development and construction. Finally, the government should also ensure effective governance and policy coordination at all levels of government to promote rural development. This includes streamlining administrative procedures, improving coordination among government departments, establishing a clear regulatory framework, and promoting transparency and accountability in resource allocation. Strengthening governance mechanisms will help ensure the effective implementation of rural development policies and programs.

4.2. Discussion

This paper explores the spatial–temporal patterns and driving mechanism of the level of rural development in Northeast China. Studying the rural development level can provide a comprehensive analysis of regional differences in local rural development. By identifying the areas with the greatest development gaps, researchers can advise on targeted interventions to reduce disparities and promote balanced rural development. Against the background of rural revitalization, rural development has a comprehensive scientific connotation. To promote rural development, it is not only necessary to accelerate the modernization of agriculture and rural areas but also to fully tap local characteristics and actively explore diversified rural functions and values. The most arduous and onerous task in building a modern socialist country in a well-rounded way still lies in the rural area. By addressing the challenges posed by natural factors and harnessing the potential of local economic conditions, the government and relevant departments have the potential to improve the livelihoods of rural residents, reduce regional disparities, promote sustainable development and contribute to the overall socio-economic growth of the region. In addition, a successful rural development strategy can provide important learning experiences and models for the rest of China, potentially boosting rural development across the country and creating a more balanced and inclusive development landscape. Research on the evaluation of the level of rural development =in Northeast China in this paper focuses on the discussion of the spatial–temporal differentiation characteristics and driving factors of the level of rural development, though there are still some limitations in revealing the differences in rural development levels in different rural development types in the region. In the future, this aspect of the research can be strengthened. In addition, rural development involves many aspects. As it is difficult to quantify rural planning, form, government restrictions and other factors, these factors must be abandoned in the construction of the index system. Future research will further improve the index system to promote rural development research.

Author Contributions: Conceptualization, Z.L. and X.L.; methodology, X.Z. and H.W.; formal analysis, Z.L. and X.Z.; data curation, X.Z. and H.W.; writing—original draft preparation, X.Z.; writing—review and editing, Z.L. and H.W.; visualization, X.Z.; supervision, Z.L. and X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA23070400).

Data Availability Statement: All data and materials are available upon request.

Acknowledgments: We would like to thank the reviewers for their thoughtful comments that helped improve the quality of this work.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Investigation and Comparison of Spatial–Temporal Characteristics of Farmland Fragmentation in the Beijing–Tianjin–Hebei Region, China, and Bavaria, Germany

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Abstract: Farmland fragmentation has emerged as the primary manifestation of global land use changes during the last century. Following the economic reform and opening up in China from the 1980s, the Beijing–Tianjin–Hebei (BTH) region has witnessed continuous farmland fragmentation. Understanding the spatial–temporal dynamics of farmland fragmentation is crucial for formulating sustainable land use management strategies. However, the specific causes and locations of farmland fragmentation remain unclear, as do potential significant differences or similarities across different countries. Given this quandary, this study empirically analyzes the spatial–temporal characteristics of farmland fragmentation in two different contexts: the BTH region in China and Bavaria in Germany. The study utilizes multiple theoretical models for temporal and spatial farmland fragmentation, applying the comprehensive index method, landscape pattern analysis, and the magic cube model. The results indicate that the farmland fragmentation index (FFI) value in BTH and Bavaria first increased or remained stable, but afterwards, both decreased and increased again. Moreover, the spatial analysis demonstrated high significance values for the FFI in the northern and western BTH region and in northern and southern Bavaria. There are, furthermore, significant differences in the FFI in different macro landforms. The FFI in the mountain regions is significantly higher than that of the plains. Finally, the results also demonstrate that a decreasing FFI relates to the overall low values within an FFI region. The theoretical framework in this study appears to align with empirical results, and thus provides a reference for future policy measures to protect farmland.

Keywords: farmland fragmentation; spatial–temporal characteristics; Beijing–Tianjin–Hebei region; Bavaria

Citation: Niu, L.; Xu, M.; Vries, W.T.d. Investigation and Comparison of Spatial–Temporal Characteristics of Farmland Fragmentation in the Beijing–Tianjin–Hebei Region, China, and Bavaria, Germany. *Land* **2023**, *12*, 1410. https://doi.org/10.3390/land12071410

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 21 June 2023
Revised: 7 July 2023
Accepted: 11 July 2023
Published: 14 July 2023

1. Introduction

Farmland is a fundamental resource for food production [1]. Its size, volume, and availability are critical factors in calculating a country or region's carrying and sustainable development capacity [2]. A mismatch between land supply and demand becomes increasingly acute with rapid socio-economic and spatial development (such as in China). The consequence of a growing population, decreasing arable land, degrading soil fertility, inefficient and fragmented arable land, and other problems in agricultural production threaten national food security [3,4]. Farmland fragmentation (FF) is a manifestation of these problems. While FF may have some benefits, such as enabling more households to engage in farming [5], it often leads to wastage of production materials and decreased agricultural productivity [6,7]. It further prevents the application of new farming technologies and hinders the large-scale development of agriculture [8]. As arable land resources become increasingly limited, there is a need to maximize the provision of products and services for the growing food demand [3].

Farmland fragmentation occurs in many transition economies and developing countries [1,9], yet it is the complex result of multiple factors [10]. The effect is, however, significant for food security and land resource sustainability in East Asia [4]. China's per capita arable land is only 0.09 hectares, far below the global average of 0.20 hectares per capita [11]. FF enriches the diversification of agricultural production and reduces the risk of agricultural production. However, it also causes many negative impacts, such as declining agricultural production efficiency and increased production costs [9], which have become an essential obstacle to China's agricultural modernization and large-scale development [12]. In order to reverse the negative impacts of FF, the Chinese government has been committed to controlling and managing farmland fragmentation in recent years. Among the land management methods, land consolidation effectively solves fragmentation problems and promotes agricultural modernization in many countries worldwide [13,14].

The practice of land consolidation contradicts, however, the theory behind it. Although land interventions, such as land consolidation, were implemented, FF has risen [15]. This calls for alternative methods to monitor FF's dynamics and create land policy interventions to minimize fragmentation [16]. This requires frameworks to detect spatial and temporal trends in the evolution of landscape fragmentation [17]. Recent empirical and methodological literature provides various spatial statistical methods to detect FF. However, relatively few studies still focus on the temporal and spatial dynamics of FF [15]. Given this, an in-depth analysis of farmland fragmentation's evolutionary characteristics can provide better theoretical insight into how and where land consolidation contributes to the development of modern agriculture and the implementation of rural revitalization strategies. As this phenomenon of fragmentation is occurring in different countries, it is furthermore relevant to rely on comparative studies in order to detect both generic and idiosyncratic aspects. For this reason, we compare two specific study areas, which differ in historical and institutional contexts, namely Germany and China. Such a comparison is relevant because one would expect several similarities and patterns that may determine how, where, when, and why FF occurs.

As the capital city group of China, the Beijing–Tianjin–Hebei (BTH) region has an important national and regional development strategic position. It connects the poor mountainous areas of Yanshan–Taihang to the more developed socio-economy of the Beijing–Tianjin area. The BTH region is a flat region of plains, hills, and mountains. The terrain is undulating and uneven. It is not easy to concentrate and contiguously distribute farmland. The varying topography in this area is the main reason why FF continues to exist. At the same time, FF is being addressed by national policies. China is in a period of rapid economic development, with the accelerated expansion of urban construction land and the rapid development of road transportation networks. While much farmland has been converted into construction land, the degree of FF has surprisingly increased [18]. Especially in the BTH region, there is still a severe degree of fragmentation of regional farmland [19]. Additionally, farmland located in the urban fringes has begun to show fragmentation characteristics [20]. The expansion of urban construction land occupying farmland is serious [21]. At present, FF is one of the main problems in the BTH region. Resource integration and cross-regional governance are prerequisites for the coordinated development of the BTH region. As one of the most critical resources in this region, the research on FF can provide scientific support for the optimal layout of regional land use and contribute to the realization of regional coordinated development and rural revitalization strategies.

In order to make a comparison, the Bavaria region in Germany (referred to as "Bavaria") was selected. The region has urban and rural areas, and land consolidation is an instrument to reduce farmland fragmentation and stimulate rural development. The Bavarian government has made a point of diminishing the spatial inequities between the rural and urban areas and increasingly uses land consolidation to stimulate effective land use. A comparison between the rate and trends of fragmentation describes different choices and spatio-temporal changes within local regions and can reveal specific endogenous trends and the influence of external factors in fragmentation. Hence, comparing the two can explore the similarities and differences in FF's dynamics between developed and developing countries and guide the development of FF in the BTH region.

The structure of this paper is as follows: The next section presents the theoretical models and introduces the study areas, data, and methods used in the research. Section 3 describes the results and the temporal–spatial analysis of FF variation in the case areas. These results enable a comparison of the two study areas in terms of FF values and variations. Section 4 discusses the findings in order to derive generic and idiosyncratic characteristics. Finally, Section 5 concludes and presents recommendations for further research.

2. Materials and Methods

2.1. Theoretical Models and Hypotheses

Land serves both as a physical resource and a basis for various concepts and definitions of property and ownership. Given the multi-dimensionality of land, scholars categorize fragmentation into three types: physical fragmentation, ownership fragmentation, and operational fragmentation [22,23]. In contrast to tenure or other social perspectives, physical land use fragmentation can reveal the compliance of physical land cover dynamics with some land use planning systems [15]. Therefore, we chose physical farmland fragmentation at the regional level to capture landscape configuration and study the distribution of FF [24].

From the regional or spatial perspective, the concept of physical farmland fragmentation manifests itself as the existence of many spatially separated (discontinuous) patches of farmland within a region, typically scattered across a broad area [25,26]. Small scales, irregular shapes, and discontinuous distribution dominate land fragmentation [27,28]. It is more difficult—or impossible—for agricultural machines to work on small-scale parcels and at low efficiency on more parcels than expected, especially in corners and along boundaries [29]. Moreover, irregular shapes prevent the proper cultivation of some crops that need to be cultivated in rows or series [27]. Furthermore, discontinuous distribution involves a complicated boundary network among parcels; hence, parts of a holding (especially the tiny parcels) will remain uncultivated at the margins of the parcels [25].

In stage I, society is primarily agricultural, transportation is limited, and the level of agricultural machinery production is low. The evolution of FF is often influenced by individual farmer behavior. Different plots have varying soil quality and slope, so farmers use FF as an environmental risk management strategy. By selecting suitable plots and planting different crops under varying conditions, they can mitigate the risk of crop failure and protect against total harvest loss due to various natural disasters [30]. As farming experience accumulates in this stage, farmers gradually recognize the positive impacts of FF, leading to a slow but steady increase in the degree of FF.

In stage II, society begins transforming from an agricultural to an industrial society. As industrialization develops, the degree of FF increases due to land abandonment for artificial uses such as infrastructure construction and rural industrial land [31,32]. During this stage, urbanization-induced farmland loss contributes to an increase in the degree of FF [33,34].

In stage III, due to urban expansion and sprawl, more farmland is consumed at urban fringes to meet housing demands [35]. The principal objectives of land consolidation projects include maintaining the viability of farming [36]. They can result in significant changes to farmland parcel size, shape regularity, and distribution, and the degree of FF decreases.

In stage IV, with the effect of urban expansion and urban sprawl, more farmland is consumed at urban fringes because of the demands for land for housing [37,38]. Farmland fragmentation intensifies, particularly in metropolitan areas and cities experiencing urban development [15,39], leading to another increase in the degree of FF.

H1. *Generally, with the advancement of socio-economic factors and implementation of land policies, the degree of FF initially undergoes a gradual deepening, then a sharp increase, followed by a decrease, but with the potential to rise again.*

The rate of evolution and spatial distribution of FF differ across various landform areas [18]. Farmlands are easier to merge, swap, or consolidate in plain or flat areas, resulting in relatively low FF. Consequently, land management interventions tend to be more effective for farmlands in flat areas [3]. In mountainous areas, cultivated land is divided into irregularly shaped and generally smaller plots due to the topographic and geomorphological conditions and the intervening water system. The unevenness of these plots can lead to a higher FF and limit the feasibility of land leveling.

H2. *Observed FF values are typically lower in flat regions than their mountainous counterparts. Moreover, the decrease in these values, brought about by land management interventions, exhibits a faster rate in plain terrains than in mountainous ones.*

2.2. Study Area

Two study areas were selected: the BTH region and Bavaria. The BTH region includes China's capital city (Beijing), municipal city (Tianjin), and 11 cities in Hebei Province, which has an important strategic position in national and regional development as the capital circle of China. The terrain of the BTH region is characterized by "high in the northwest and low in the southeast" (Figure 1a). The BTH region belongs to the warm temperate, semi-humid monsoon climate region. The superior geographical location and suitable climatic conditions make this region one of China's primary agricultural product-producing areas. Most farmlands are allocated in the North China Plain, the central and southern areas of this region, with grain and cash crop production based in Hebei.

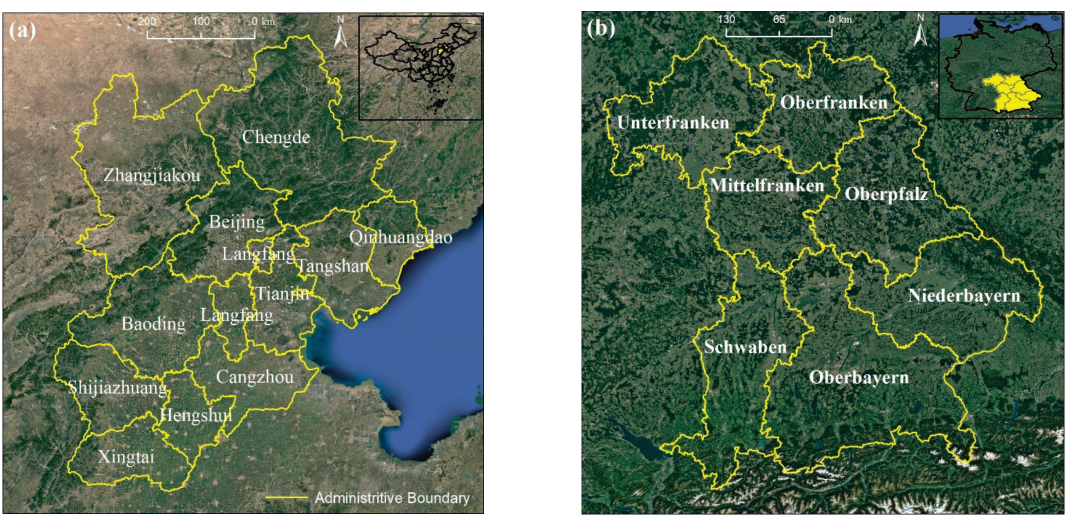

Figure 1. Study areas. (**a**): Beijing–Tianjin–Hebei region, China; (**b**) Bavaria, Germany.

The second study area is Bavaria, in Germany (Figure 1b). The Free State of Bavaria lies in the southeast of Germany. It has seven administrative regions, referred to as Regierungsbezirke. The southern part of Bavaria is hilly and mountainous (the Alps), and agricultural landscapes still dominate their surrounding areas. As a strong agricultural state, Bavaria has a nearly 500-year history of land consolidation [40], and after World War II, it launched several policies to improve and extend land consolidation beyond its agricultural optimization [41]. Similar policies were adopted in other parts of Europe, modeled after the German example.

The choice of BTH in China and Bavaria in Germany as the focus of this study, aiming to investigate and compare the spatio-temporal characteristics of FF, is based on two key considerations: Primarily, both regions are recognized as significant economic hubs within their respective countries, each undergoing accelerated urbanization processes over the previous decades. Consequently, assessing the intensity of FF in these regions enhances our comprehension of farmland spatial transformation patterns in the context of globally rapid urbanization. Secondly, considerable variations exist among these regions regarding policy environments, natural conditions, and agricultural paradigms. The diversity of these research contexts aids in verifying the external validity of the theoretical constructs with respect to FF, as outlined in this study.

2.3. Data

These spatial research units for the BTH region are the formal county-level administrative districts. The acquisition of farmland data at a resolution of 30 m in the BTH region in 1980, 1990, 2000, 2010, and 2020 relied on China's National Land Use and Cover Change (CNLUCC) dataset provided by the Resource and Environment Science Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 12 July 2020). This dataset has been validated to have high accuracy [42]. The digital elevation model employs the Shuttle Radar Topography Mission dataset [43].

The spatial research units for Bavaria are the municipal boundaries provided by the Bayern Atlas. The acquisition of farmland data in Bavaria relied on interpreting 1992, 1995, 2000, 2005, 2010, 2015, and 2020 land cover images [44] with a spatial resolution of 300 m derived from the European Space Agency (https://www.esa-landcover-cci.org/, accessed on 12 July 2020). This dataset contains a time series of annual global land cover classifications from 1992 to 2020, generated from multiple satellite images to gain a higher classification accuracy.

2.4. Methods

2.4.1. Multi-Dimensional Evaluation of FF

In contrast to current theoretical analyses of FF, our study proposes a new conceptual index system for FF assessment at the regional scale, with the following three dimensions: patch scale (PS), shape regularity (SR), and spatial distribution (SD). Referring to the existing literature [10,15,27], the definitions and quantitative methods of the selected indexes are shown in Table 1.

Table 1. Indicators for assessing farmland fragmentation.

Target Level	Standard Level	Index Level	Quantitative Method	Index Definition	Index Direction
Farmland Fragmentation	Patch scale (0.21)	Number of patches (0.667)	NP = N	The number of farmland patches in a certain area	+
		Largest patch index (0.333)	$\text{LPI} = \frac{max(LA_1, LA_2, \ldots, LA_i)}{A} \times 100\%$	The percentage of the maximum area patch in total farmland area in a certain area	−
	Shape regularity (0.24)	Landscape shape index (0.333)	$\text{LSI} = \frac{0.25P}{A}$	The complexity of the shape of farmland in a certain area	+
		Area–weight mean shape index (0.667)	$\text{AWMSI} = \sum_i^N \left[\left(\frac{0.25P_i}{\sqrt{LA_i}} \right) \times \left(\frac{LA_i}{LA} \right) \right]$	The regularity of patch shape of farmland in a certain area	+
	Spatial distribution (0.55)	Patch density (0.167)	PA = N/A	The number of farmland patches per unit area	+
		Aggregation index (0.833)	$\text{AI} = \left[1 + \sum_i^N \frac{P_i \ln(P_i)}{2\ln(N)} \right] \times 100$	The spatial aggregation degree of cultivated land in a certain area	−

Notes: A is the total area of farmland; N is the total number of patches; LA_i is the area of patch i; P_i is the circumference of patch i; P is the total circumferences of patches.

This study uses a farmland fragmentation index (FFI), which ranges between 0 and 1. The larger the value, the higher the farmland fragmentation degree. The formula for the FFI is as follows:

$$FFI = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} x_{ij} w_{ij} \right) w_i \tag{1}$$

In this expression, *FFI* is the farmland fragmentation index; n represents the number of dimensions—in this paper, n = 3; x_{ij} and w_{ij}, respectively, indicate the standardized value and weight of the j-th indicator in dimension i; and w_i and m denote the weight of dimension i and the number of indicators, respectively.

In order to compare the different sets of variables and improve data integrity, we standardized the data using the min–max method, one of the most widely used data standardization measures.

An analytic hierarchy process (AHP) was used to assign the FF indicators weights. Eight experts from related fields were invited to participate in the determination of the weights of each indicator.

2.4.2. Magic Cube Model

The magic cube model was used to qualify the multi-dimensional spatial characteristics of FF. More concretely, the three sides of the magic cube represent the patch scale (x), shape regularity (y), and spatial distribution (z) of farmland fragmentation, respectively. We further divide x, y, and z into two grades (i.e., lower and higher, with numbers 0, 1, respectively) by using "Mean $\pm$ 0.5 $\times$ Standard Deviation" [45]. On this basis, eight combinations are merged by consulting relevant experts to minimize within-group variability and maximize its homogeneity, and the study area can be divided into several categories (Figure 2 and Table 2).

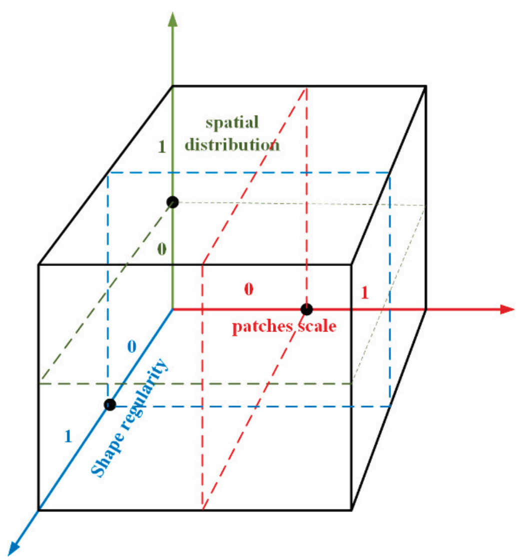

Figure 2. The magic cube model of farmland fragmentation.

Table 2. The classification standards and characteristics of farmland fragmentation based on spatial differences.

Zoning	Magic Cube Coordinate	Characteristics
Comprehensive improvement zone	(1,1,1)	Patch scale, shape regularity, and spatial distribution of farmland are poor. The phenomenon of FF is the most serious.
Key improvement zone	(0,1,1) (1,0,1) (1,1,0)	Two of the three dimensions are poor and need to be improved.
Target improvement zone	(1,0,0) (0,1,0) (0,0,1)	One of the three dimensions is poor and needs to be improved.
Comprehensive development zone	(0,0,0)	Modern agriculture development is endowed with superior patch scale, shape regularity, and spatial distribution of farmland.

3. Results

3.1. Characteristics and Patterns of FF in the Beijing–Tianjin–Hebei Region, China

3.1.1. Temporal–Spatial Patterns of FF in the BTH Region, China

At the regional level, the FFIs in different time nodes were calculated using Equation (1). When comparing the overall values displayed in Figure 3, FF in the BTH region displays patterns that are similar to the theoretical model, and thus confirms Hypothesis 1. The overall FFI in the Beijing–Tianjin–Hebei region decreased slightly from 0.292 in 1980 to 0.275 in 1990. In contrast, the FFI kept increasing from 1990 to 2000. From 2000 to 2005, the FFI decreased sharply, yet went up again after 2005.

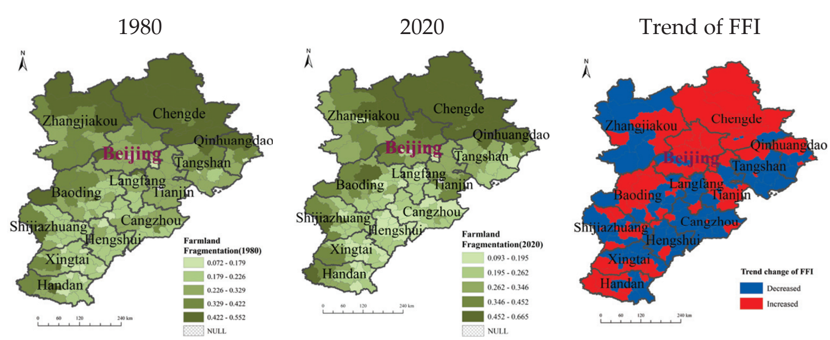

Figure 3. Spatial distribution maps of the farmland fragmentation index in the BTH region.

Regarding the three dimensions of FF, the SR and SD indicators exhibit trends that are similar to the FFI. The SR value remained the lowest, meaning that the shapes of farmland in the BTH region are relatively regular. The PS value remained stable from 1980 to 2020 and is the highest, implying that many parcels and smaller parcel areas in the BTH region are the main reason for the resulting FF.

Figure 3 shows the spatial distribution maps at the county level in the BTH region from 1980 to 2020. The high-value areas of FF in 1980 were distributed in strips along the Taihang mountains of Hebei and Zhangbei grassland (the vast grasslands in northern Zhang-jiakou), while the low-value areas were more geographically continuous, and mainly distributed in the southeastern BTH region. In 2020, the high-value areas of the FFI were still mainly distributed in the northern and western BTH region, while low-value areas were still similar to those from 1980. According to the trajectory change over the past 40 years, the districts and counties in the increased region are mainly distributed in the

Yanshan Mountains in northern Hebei, the Baishi Mountains in northern Baoding, and the Taihang Mountains in the southwestern Hebei region. The districts and counties in the decreased region are mainly distributed in the northwestern, northeastern, and middle of the southern BTH region. Moreover, the decreased regions are coupled with a low-value FFI, and the increased regions are coupled with a high-value FFI (Figure 3).

3.1.2. Spatial Differentiation and Characteristics of FF in the BTH Region

The spatial–temporal change results derived from the FF indicators in the BTH region are the basis for evaluating the differences between cities with different geomorphologies. The DEM data, accessed through the Geospatial Data Cloud, enabled the classification of macro geomorphological types under the basic geomorphological types (plains, terraces, hills, and mountains) in the BTH region for research purposes. Based on the study of Zhao et al., 2015, this paper adopts the division method of the proportion of plains and mountains in cities and divides cities in the BTH region into four macro landforms: plain region, plain–mountain region, mountain–plain region, and mountain region (Figure 4).

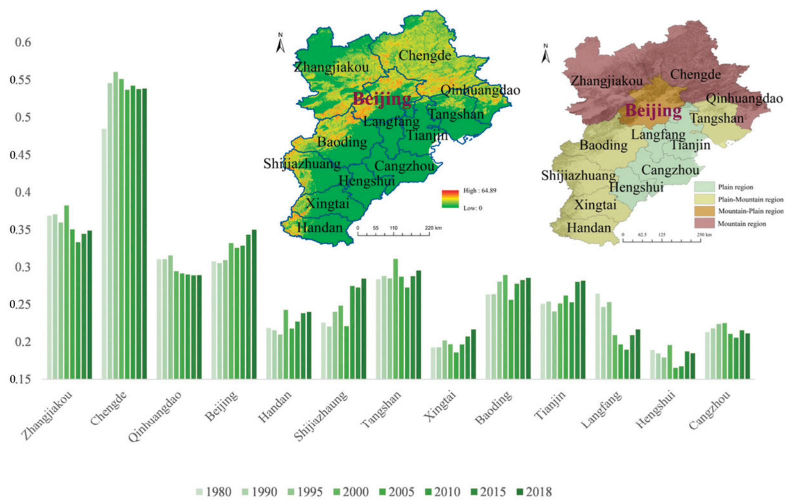

Figure 4. Spatial differentiation of farmland fragmentation under different macro landforms in the BTH region.

Almost all of the FFI trends in the BTH region's cities confirm both Hypothesis 1 and 2. As the proportion of mountains is higher in the spatial unit, the FFI is also higher. Cities in the mountain region (such as Zhangjiakou, Chengde, and Qinhuangdao), located in the northern BTH region, have a relatively high-value FFI. From 1980 to 1995, the FFI in Chengde and Qinhuangdao first rose and then went down from 1995 to 2000, while the FFI in Zhangjiakou rose until 2000. The FFI in these three cities was stable from 2005 to 2020, which suggests that they are still in stage III of the theoretical model. The FFI exhibits an increasing trend in the mountain–plain region, especially from 1995 to 2000. The FFI also decreased in Beijing from 2000 to 2005 because of the implementation of land consolidation policies [46]. It rose sharply again after 2005. The values of the FFI in the plain and plain–mountainous regions are lower than those in the mountainous and mountain–plain regions.

3.2. Characteristics and Patterns of FF in the Bavaria Region, Germany

3.2.1. Temporal–Spatial Patterns of FF in Bavaria, Germany

Compared to the BTH region, the FFI variation in Bavaria has different characteristics. The FFI was stable from 1992 to 1995 at around 0.320 and decreased to 0.293 in 2000. After

2000, the FFI rose slowly and reached 0.305 in 2020. The overall trend of the FFI in Bavaria showed how the FFI changed in stages III and IV, which is consistent with Hypothesis 1. The FF, PS, and SD dimensions showed a similar trend with the FFI.

Figure 5 displays the spatial distribution of FF from 1992 to 2020 for Bavaria. The high-value areas of FF in 1992 were distributed in strips along the Bavarian Alps, and in clusters in Oberfranken and Oberpfalz, where the Franconian Jura, Altmühl Valley Nature Park, and Bavarian Forest are located, while the low-value areas were more geographically continuous in central Bavaria, especially in the metropolitan regions. In 2020, the FFI showed a similar distribution to that in 1992. The change in the FFI over the past 30 years is relatively consistent and coherent. The FFI values in the rural districts consistently decreased, whereas the FFI in the metropolitan or nearby districts of the capital (such as Munich, Augsburg, Landshut, and Würzburg) increased. This pattern is in line with urban sprawl and rural–urban conversions. There are decreased FFI values in northern Bavaria and in the middle of southern Bavaria, in particular.

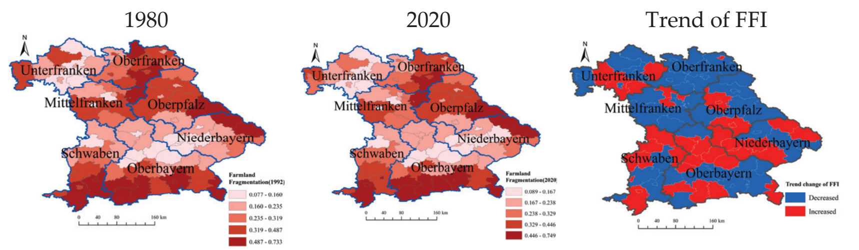

Figure 5. Spatial distribution maps of the farmland fragmentation index in Bavaria.

3.2.2. Spatial Differentiation and Characteristics of FF in the BTH Region

Almost all the trends of the FFI in Bavaria's administrative regions confirm Hypothesis 1 and 2 (Figure 6). The FFI in the mountainous region is much higher than in the mountain–plain region. The regions of Oberfranken, Oberpfalz, Oberbayern, and Scha-waben, located in northern and southern Bavaria, belong to the mountainous region. They exhibit relatively high FFI values. From 1992 to 2000, the FFI values in Oberpfalz, Schwaben, and Oberfranken declined sharply, while the FFI in Oberbayern gradually declined, in line with the transforming of natural areas into farmland [47]. The FFI in all these four regions slowly increased from 2000 to 2020, which means that they are in stage IV of the theoretical model and are affected by urban development. Afforestation and abandonment of farmland are prevalent in this stage.

3.3. Comparison of FF in the BTH Region and Bavaria

3.3.1. Time Evolution of FF in Two Study Areas

The overall FFI trends from 1992 to 2020, displayed in Figure 7, show that the FFI variation in Bavaria is similar to that of the BTH region from 2000 to 2020. In both areas, FFI values were stable, went down, and rose again. These trends are consistent with the theoretical model for temporal change with respect to FF, which suggests that Hypothesis 1 is valid. Meanwhile, the absolute FFI in Bavaria is higher than that of the BTH region. An explanation could be that Bavaria is a more mountainous region; i.e., the proportion of mountain and mountain–plain regions is much higher than that of the BTH region. Therefore, the FFI in Bavaria is also much higher than in the BTH region, which verifies Hypothesis 2.

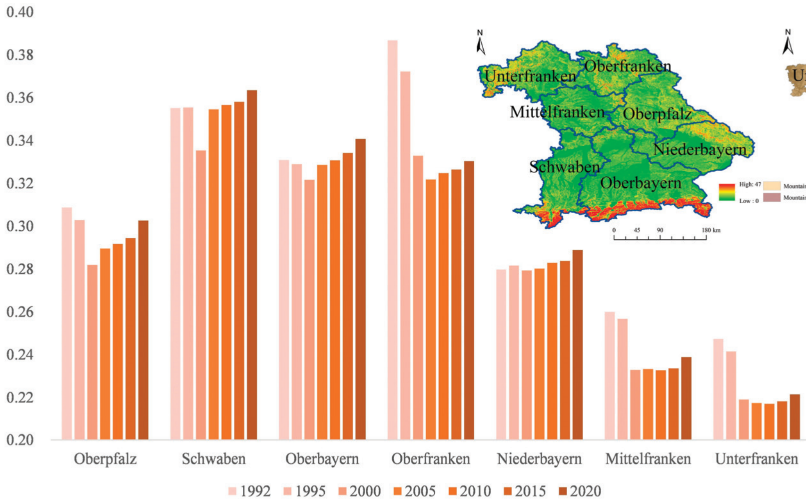

Figure 6. Spatial differentiation of farmland fragmentation under different macro landforms in Bavaria.

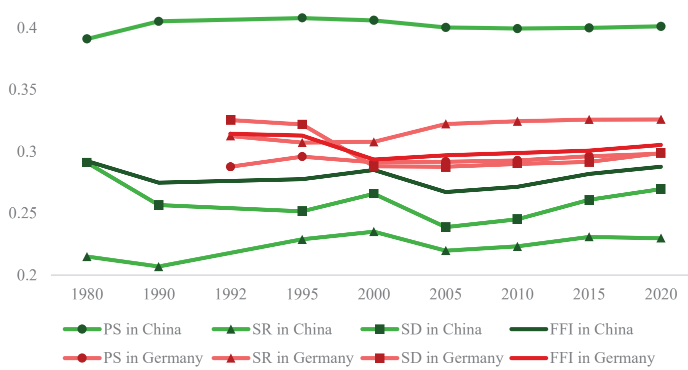

Figure 7. The trend of the farmland fragmentation index and its three dimensions in the two study areas.

In terms of the three dimensions of FF, the values of the three dimensions of FF in Bavaria are not very different from each other, and the trends of their changes are close to that of the overall FFI value, while the three values of the BTH region are significantly different, with only the trend of SD consistent with the overall FFI trend. Therefore, FF in the BTH region should be addressed comprehensively, especially concerning improving the patch scale.

3.3.2. Division of FF Zones and Implications for Future Land Consolidation

Based on the quantitative detection of temporal changes with respect to FF in the BTH region and Bavaria, we divided the study areas into four categories (Figure 8 and Table 3).

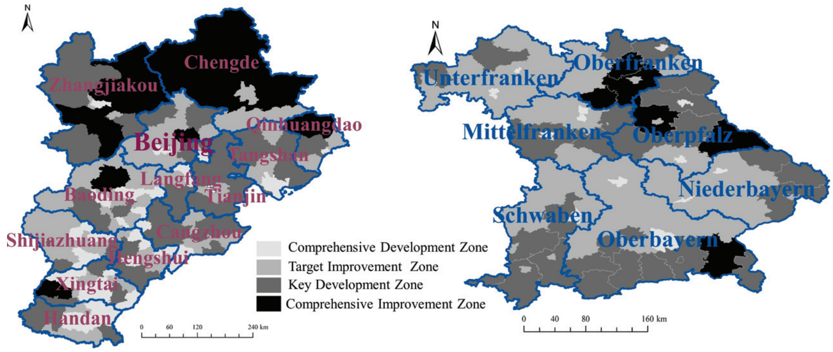

Figure 8. Division of farmland fragmentation zones in the two study areas.

Table 3. The percentage of each zone in the two study areas.

Zone		BTH Region	Bavaria
Comprehensive development zone		25.93%	13.68%
Target improvement zone	target for patch scale (PS)	5.29%	3.16%
	target for shape regularity (SR)	10.05%	36.84%
	target for spatial distribution (SD)	21.16%	10.53%
Key improvement zone	key improvement for PS and SR	20.63%	10.53%
	key improvement for PS and SD	2.65%	18.95%
	key improvement for SR and SD	5.82%	0.00%
Comprehensive improvement zone		8.47%	6.32%

Comprehensive development zone: The magic cube coordinate of this zone is (0, 0, 0), which means that the values of the three dimensions of FF are under average. Defragmentation is a critical phenomenon in this zone. The percentages for this zone in the BTH and Bavaria regions are 25.93% and 13.68%, respectively. The percentage for the BTH region is double that of Bavaria. This is because the BTH region has more plains, which provide better conditions for implementing land consolidation. This cluster is mainly concentrated in the core areas of capital cities with high socio-economic growth. Therefore, the consolidation of farmland in these areas is a priority of projects in order to make room for the expansion of construction land.

Target improvement zone: The magic cube coordinate of this zone is (1,0,0) or (0,1,0) or (0,0,1), which means that one of the values of FF's dimensions is over average and needs a targeted improvement to deal with fragmentation. This zone always surrounds a comprehensive development zone, which means that with the spillover effect of land consolidation in core capital areas, the surrounding areas can improve. Regarding the three target zones, the percentages of the targets in the patch scale zone in the two study areas are below 6%. As for the target in the shape regularity zone, the percentage in Bavaria is 36.84%, which is triple that of the BTH region (10.05%). Therefore, Bavaria should pay more attention to consolidating irregular shapes. As for the target in the spatial distribution zone, the percentage in the BTH region (21.16%) is double that of Bavaria (10.53%), which means that in the future, the BTH region should take more action to improve continuous farmland.

Key improvement zone: The magic cube coordinate of this zone is (1,1,0) or (0,1,1) or (1,0,1), which means that two of the values of FF's dimensions are over average and need fundamental improvement. These regions are far from core urban areas and receive little effort and attention from land consolidation. The BTH region should pay more attention to the critical improvement of PS and SR in some areas as the percentage reaches 20.63%, while some areas in Bavaria should focus on PS and SD (18.95%).

Comprehensive improvement zone: The magic cube coordinate of this zone is (1,1,1), which means that all the values of FF's three dimensions are over average and need comprehensive improvement. These areas are mainly mountainous, forest areas, and national parks. This zone is mainly in the northern BTH region, accounting for 8.47%, and in northern Bavaria, accounting for 6.32%. Both percentages in the study areas are relatively low, showing that land consolidation projects are successful in the two regions.

4. Discussion

Following the results of Section 4, one could question the extent to which these results are significant and generic beyond the single case areas. In other words, what is similar and different when comparing the two case areas, and to what extent can these differences and similarities be attributed to the landscape, institutional, and operational contexts only? Alternatively, are these a direct result of fragmentation trends and methods of fragmentation calculation? Although there are some common features, different areas show different patterns due to their different backgrounds and developmental stages [48].

4.1. Similarities between the Characteristics of FF in the BTH Region and Bavaria

The FFI in both case studies are in line with Hypothesis 1 and 2. Regarding the temporal pattern, with the reform and opening up in 1978, China has transformed from an agricultural society to an industrial society. At this stage, urban expansion is the most significant influencing factor for FF [49], which results in a gradual increase in the FFI between 1980 to 2000. This corresponds to existing studies on converting farmland to artificial land for urban use [32,50]. Land consolidation has effectively reduced the degree of FF in the 2000–2005 period, both in the BTH region and in Bavaria. Currently, urban sprawl continues to occur, which is the prime reason for the continuation of increasing FF [46] in both the BTH region after 2005 and in Bavaria after 2000. The results of the temporal changes thus support Hypothesis 1.

Regarding spatial distribution, Marraccini et al. [47] state that FF relates to the distance from core areas of capital cities. When applying a gradient analysis from urban to rural, Weng [51] found that landscape fragmentation correlates positively with the degree of urbanization, consistent with our results. For our case areas, we find lower FFI values are mainly distributed in the capital districts in the BTH region and in flat and flat–mountain regions, i.e., the central areas of Cangzhou, Hengshui, Langfang, Xingtai, Handan, Shijiazhuang, and Tangshan. In contrast, the degree of FF increases along the gradient from urban to rural. Bavaria has similar characteristics. Low FFI values exist in the regional capital cities, such as Munich, Landshut, Nuremberg, and Würzburg.

In terms of the FFI for the four landform categories, the results confirm Hypothesis 2. Natural condition plays a vital role in physical fragmentation distribution (Jiang et al., 2019). Topographic and landform features are essential [3,52]. The FFI values in the northern and western BTH region's mountain regions (such as the Yanshan Mountains and Taihang Mountains) are much higher than in the plain regions. Similarly, the FFI values in southern and northern Bavaria (where the Alps and the Bavarian Forest are located) are also higher. The terrain is undulating in mountainous areas, the farming conditions are harsh, and the farmland is often scattered. In grassland or forest areas, farmland development is often neglected and lags because of woodland conservation [53], resulting in a higher degree of FF.

4.2. Differences between the Characteristics of FF in the BTH Region and Bavaria

According to the theoretical model constructed in this study, from 1980 to 2020, the FFI in the BTH region experienced stage II–IV, while the FFI in Bavaria experienced stage III-IV, which shows that the development stage of FF in Germany is ahead of China. It entered stage III in 1992, while FF in China did not enter stage III until around 2000. Land use patterns are consistent with development stages [31]. As a developed country, Germany is in a higher stage of economic development, and the development stage of FF is also higher. In Bavaria, the FFI rose again in 2000, while it rose from 2005 in the BTH region. FF is affected by post-urbanization, especially with better social conditions. Therefore, FF in Germany is in an advanced stage.

As for spatial distribution, the FF patterns in Bavaria have formed concentric circles, with the capital cities in each administrative region as the center and the core areas of capital cities mostly low-value FFI and comprehensive development zones. With the gradient from capital cities to their surrounding cities in the district, the value of FF is increased, and the zone transforms into a comprehensive improvement zone. The results in Bavaria are consistent with the conclusion of other studies. Wadduwage et al. [54] used gradient analysis and landscape metrics and identified that the FFI decreased with the distance to core areas.

Analysis of socio-economic and natural condition variances between the two research areas enhances our understanding of FF transitions across diverse societal stages. In the BTH region, industrialization and urbanization have exacerbated FF, primarily driven by the competition between construction land and farmland. Conversely, Bavaria has mitigated FF by improving social conditions, potentially facilitated by advancements in agricultural technology and financial investments. This comparison illustrates that achieving intensive farmland during economic development is feasible yet remains a formidable challenge for developing countries. As a result, sustainable agricultural development targeting FF reduction requires extensive cross-sectoral and inter-regional collaboration for substantial progress. Moreover, we should extend our focus beyond topography to the effects of other natural conditions on farmland fragmentation. For instance, factors such as temperature and precipitation may impact crop ripening, subsequently altering farming patterns and FF.

4.3. Generic Aspects concerning Fragmentation Calculation Methods

4.3.1. Key Factors Affecting Spatio-Temporal Changes in FF

The temporal analysis in Sections 3.1.1 and 3.2.1 reveals visible differences in the temporal changes in FF between Germany and China. The results indicate that the FFI is inversely related to the development of society. With the development of society, under the influence of urbanization and industrialization, the contradiction between people and land is becoming increasingly severe, and the problem of low-efficiency utilization of farmland is becoming more and more prominent. In order to use farmland intensively and economically, the government has introduced a series of measures, such as land consolidation projects. One of the most important objectives of the consolidation projects is to decrease land parcel fragmentation and improve parcel shape to use the farmland more efficiently and make machine farming more comfortable [55]. After the implementation of the revised "land management law" in 1998, China launched the "national land development and consolidation plan (2001–2010)", which defined the core task of farmland consolidation regulation and explored the model of "merging small fields into large blocks" of farmland consolidation. Especially from 2000 to 2005, after the farmland consolidation, the FFI in the BTH region decreased significantly, the number of farmland patches decreased, the patch area increased, the patch boundary was smooth, and the spatial aggregation degree increased. From 2010 to 2020, the FFI of the BTH region rose again, among which the shape distribution (SD) index increased significantly. The patch density of farmland increased, and the aggregation degree decreased. This shows that the primary goal of farmland consolidation is to expand the amount of farmland and compensate for the farmland occupied by non-agricultural construction land, resulting in the segmentation and fragmentation of the farmland landscape [56].

The spatial analysis in Sections 3.1.2 and 3.2.2 suggests that landscape characteristics are driving factors with respect to the changes in FF. In particular, the spatial differentiation analysis of FF under different macro landforms in the BTH region varied widely. The FFI in the western mountainous area is significantly higher than in the eastern plain area of the BTH region, which implies that the FFI positively correlates with the proportion of the mountainous area. This indicates that FF has a synergistic relationship with the landscape. These findings are consistent with the work of Qian et al. [18], highlighting that the spatial distribution characteristics of FF matched the landforms. The enhanced areas are mainly distributed in the northwestern hilly area, while the weakened areas are mainly in the eastern plain area. Meanwhile, the research scale of this study area is also applicable to other regions, which encourages the use of county boundaries based on the landform characteristics of each city to help managers and decision-makers to manage farmland resources and implement differentiated measures to improve or utilize the farmland fragmentation in different landforms.

4.3.2. Contribution of the Analytical Framework and the Index of Farmland Fragmentation

Human activity is an essential factor affecting change with respect to farmland, and human intervention has a direct or indirect impact on the distribution of farmland [57]. With the development of industrialization and rapid urbanization, the scope of construction land continues to expand, resulting in an increased frequency of farmland conversion [58] and the FF problem becoming increasingly severe. Farmland fragmentation is caused by the long-term effects of socio-economic systems and the natural environment, and it must be assessed via a long time series and under different landforms [18,30,59]. Understanding the changing FF growth pattern in urbanization processes is vital in rural development planning and sustainable growth management. This requires stakeholders to have a sound knowledge of the characteristics of farmland in the multi-dimensional aspects of patch scale, shape regularity, and spatial distribution, and then make the most realistic decision-making for farmland utilization and agricultural development planning in different regions. Therefore, expanding the characteristics of FF under different landforms and exploring its long-term changes will be conducive to human well-being. However, improving the quality and efficiency of farmland has become an important part of farmland protection, but its ways and measures are still being explored. The analytical framework presented in this study has the potential to make an essential contribution to the existing literature as it enriches the spatio-temporal change model of FF to a certain extent and makes a comparison of FF in developed and developing countries. In terms of practical application, based on scientifically measuring the spatio-temporal characteristics of FF, this study brings forth the complex idea of considering patch scale, shape regularity, and spatial distribution of FF when guiding the practice, planning, and management of regional land consolidation projects, which is of great significance in terms of improving the utilization efficiency of farmland resources.

4.3.3. Policy Suggestions for Farmland Fragmentation Based on the Magic Cube Zone

Based on the spatial differentiation of farmland fragmentation, this paper proposes policies to optimize the farmland pattern in the BTH region.

(1) The comprehensive improvement zone mainly includes Zhangjiakou City and Chengde City, northwest of Hebei Province. The three-dimensional indexes of FF in this zone are higher than the average value. This zone belongs to the region with the highest degree of FF in the BTH region and needs to be comprehensively improved. This zone is a mountainous area with a poor environment. It should be combined with construction related to the "return of farmland to forest and grassland" and Three-North Shelterbelt. Policies such as strengthening the compensation of relevant policies and encouraging farmland consolidation should also be proposed.

(2) The critical improvement zone mainly includes some counties in the northwest mountainous and coastal areas. In this zone, two dimensions of the three-dimensional index are higher than the average value. Under the premise of protecting and improving the ecological environment, this zone should actively develop saline–alkali land and wasteland and supplement the effective farmland area.

(3) Only one aspect of FF in the target improvement zone needs targeted remediation. The construction of high-standard basic farmland should be strengthened in this area to

guide the centralized connection of farmland, regulate the shape of farmland plots, and improve the landscape value of farmland.

(4) The comprehensive development zone mainly includes counties in the central and southern plains of Hebei Province. The three-dimensional index of FF in this area is lower than the average value, which means the overall degree of fragmentation is low and the farmland is in relatively good condition. The zone should strengthen law enforcement of the ecological red line and permanent basic farmland, prevent further fragmentation of farmland, control land regulation standards, and take the green road of sustainable development.

5. Conclusions

Based on the proposed theoretical framework of farmland fragmentation, this study quantitatively measures the temporal–spatial variations of FF in the Beijing–Tianjin–Hebei region from 1980 to 2020 and in Bavaria from 1992 to 2020. The main conclusions are:

(1) The FF values in the BTH region are undulating, which is consistent with stages II–IV of the proposed theoretical framework. The FF values in Bavaria show a different and less consistent pattern, characterized by both stable and increasing and decreasing values. This pattern is more consistent with stages III–IV of the theoretical framework. Both results confirm Hypothesis 1 of this study.

(2) The FFI is mainly high in the mountain and the mountain–plain regions of the northern and western BTH regions and in northern and southern Bavaria. The FFI is mainly low in the flat regions of the southeastern BTH region, in the middle of Bavaria, and in the district capitals of both study areas.

(3) The decreased trend regions are mainly distributed in low-value FFI regions, while the increased trend regions are mainly distributed in high-value FFI regions.

(4) This study applied the magic cube model to describe and predict the variation in FF values. It turned out that the FF values within the three dimensions are not close to each other in the BTH region. The patch scale reached the highest, while shape regularity was the lowest among them. The values of the three dimensions of FF are close to each other in Bavaria. Among them, shape regularity was relatively high, whereas spatial distribution was relatively low.

These findings enhance our understanding of FF and aid in realizing sustainable agricultural development. Firstly, we underscore the importance of employing comprehensive approaches and long time series remote sensing data to assess FF thoroughly. Secondly, we advocate for tailoring land use policies to the specific circumstances of areas at different stages of farmland fragmentation to achieve improvements. As food security remains a globally pertinent issue, we still need to optimize the spatial layout of farmland, through means such as basic farmland protection, even in areas with lower degrees of FF.

This research constructed a comprehensive theoretical framework to identify and describe temporal and spatial variations in FF. A longitudinal empirical data collection and analysis of FF dynamics (spatially and temporally) confirmed the validity of the theoretical framework for this type of analysis. The applied model appeared to work for cases in both developing and developed countries, which suggests that it is valid for multiple locations. Therefore, the results of this research can support land management practitioners and spatial decision-makers using the FF analysis in their daily work.

Despite the results we have achieved, more analyses need to be conducted. Further research can focus on analyzing the FF variations for different distances to urban core areas. Additionally, one can test other methods to find the driving factors for FF variation in different regions or counties.

Author Contributions: L.N.: conceptualization, data curation, methodology, funding acquisition, visualization, writing—review and editing; M.X.: conceptualization, data curation, methodology, visualization, writing—original draft; W.T.d.V.: conceptualization, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the Outstanding Innovative Talents Cultivation Funded Programs 2021 of Renmin University of China.

Data Availability Statement: The data are freely available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Geographical Patterns and Influencing Mechanisms of Digital Rural Development Level at the County Scale in China

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Abstract: Digital rural development has become an emerging dynamic force for high-quality rural development in China. This paper constructs the "environmental-economic-social" analysis framework for digital rural development, analyzes the spatial variation of the digital rural development level (DRDL) in Chinese counties in 2020, and conducts the factor detection and interaction detection of its influencing factors. It is found that: (1) digital rural development has its own unique spatial differentiation mechanism, which can be analyzed from three dimensions: environmental system, economic system, and social system, which play a fundamental role, decisive role, and a magnifying effect on digital rural development, respectively. (2) The DRDL in China's counties has significant spatial distribution, spatial correlation, and spatial clustering characteristics. The DRDL in general shows a decreasing distribution trend from coastal to inland regions, and the overall differences in DRDL mainly come from intra-regional differences rather than inter-regional differences. The rural infrastructure digitalization dimension has stronger spatial correlation while the spatial correlation of the rural governance digitalization dimension is weaker. There are obvious hotspot and coldspot areas in the DRDL, with large differences between the coldspot and hotspot areas of different sub-dimensions. (3) The spatial divergence of the DRDL is closely related to geographical elements and is the result of the combined effect of several geographical factors. The factor detection results show that the dominant factors within the four regions are significant different. The interaction detection results show that the driving force of the two-factor interaction is stronger than that of the single-factor interaction and that the interaction among the factors further deepens the spatial differentiation of the DRDL.

Keywords: digital rural; digital divide; spatial differentiation; Geodetector; rural revitalization

Citation: Li, T.; Wang, S.; Chen, P.; Liu, X.; Kong, X. Geographical Patterns and Influencing Mechanisms of Digital Rural Development Level at the County Scale in China. *Land* **2023**, *12*, 1504. https://doi.org/10.3390/land12081504

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 2 July 2023
Revised: 25 July 2023
Accepted: 26 July 2023
Published: 28 July 2023

1. Introduction

With the continuous advancement of China's agricultural and rural informatization process, digital rural construction has become an important grasp of China's rural development. The application of digital technology in rural areas has greatly improved the digitalization level of rural regions and plays an important role in promoting rural transformation, implementing rural revitalization, and promoting urban–rural integration.

On the one hand, the development of the digital economy provides a power source for digital rural construction. With the rapid development of science and technology and the Internet, the digital economy has become an important engine to drive economic growth and an emerging way to drive industrial transformation and upgrading [1,2], which is an important grasp to promote high-quality economic development and common prosperity in China [3,4]. At the same time, along with the industrial upgrading and modernization transformation of the rural, the pace of integration between the digital economy and the rural economy and society has also accelerated significantly [1]. Some scholars point out that the integration of the digital economy and rural economy can promote the upgrading of agriculture, rural progress, and farmers' incomes in many aspects [5,6], which becomes an effective path to promote digital rural construction. In 2018, Document No. 1 of the Central Committee of the Communist Party of China first proposed "implementation of the digital rural strategy", which clarifies the general requirements for digital rural construction at the national level. In 2019, the General Office of the CPC Central Committee and the General Office of the State Council officially issued the *Outline of Digital Rural Development Strategy* (ODRDS), pointing out that digital rural development is both the process of the development and transformation of agricultural and rural modernization endogenous to the application of networking, informatization, and digitization in agricultural and rural economic and social development as well as the improvement of farmers' modern information skills [7]. The ODRDS takes digital rural construction as the strategic direction of rural revitalization and the construction of digital China. The ODRDS also puts forward specific construction tasks in terms of developing the rural digital economy, promoting the modernization of the rural governance capacity, and coordinating and promoting the integrated development of urban and rural informatization, which is a guiding platform for promoting the digital rural development of China. In 2020, the Cyberspace Administration of China and seven other departments jointly issued the *Notice on the National Rural Digital Pilot Work*, officially starting the deployment of a national digital rural pilot. Issued in 2021, the *Digital Rural Construction Guide 1.0* puts forward the general architecture design and typical application scenarios of digital rural construction, providing important references for local conditions and classification to explore digital rural development modes. Issued in January 2022, the *Digital Rural Development Action Plan (2022–2025)* clarifies the new stage of digital rural development goals, key tasks, and guarantee measures, promoting digital rural construction to a new stage [8].

On the other hand, the rural revitalization strategy provides new opportunities for digital rural construction. (2017) The 19th National Congress of the Communist Party of China put forward the rural revitalization strategy. It specifies the general requirements for prosperous industry, ecological livability, civilized rural effective governance, and affluent living. Among these, prosperous industry is the cornerstone of rural revitalization, ecological livability is the guarantee to improve the quality of rural development, civilized rural development is the soul of rural construction, effective governance is the core of good governance in rural areas, and affluent living is the goal of rural revitalization. Digital rural development provides powerful power and advanced means for the implementation of a rural revitalization strategy, is an important tool for implementing the general requirements of rural revitalization [9], and plays an active role in promoting rural revitalization. At the same time, the new generation of information and communication technology plays an important role in promoting regional economic growth and digital transformation. Information technology has become a new engine for rural development. This can help activate rural labor, land, capital, and other development elements, driving technology flow, capital flow, talent flow, and material flow to rural areas with information flow and enhancing the digital production capacities and governance abilities of rural areas. In addition, the improvement of the rural digitalization level can help promote the optimization of the allocation of resources in rural areas and the improvement of the total factor productivity of rural regions, which can effectively make up for the shortcomings of rural development and boost the development of the rural economy, society, culture, ecology, and other fields [9]. Thus, building digital rural is an important path to narrow the regional differences in rural development and an important measure to weaken the digital divide between urban and rural areas [10–12]. It has a positive effect on promoting the implementation of a rural revitalization strategy, promoting the construction of new urbanization, and coordinating regional coordinated development and urban–rural coordinated development.

Digital technology brings new opportunities for rural development [13–16]. Building digital rural is an urgent need to realize comprehensive rural revitalization and an effective way to promote the integrated development of urban and rural areas [17], and it is also an important means to narrow regional disparities and promote common development in the east, middle region, and west [18]. The experience of digital rural development in Europe and the United States is relatively mature. The digitalization of rural areas and the impact it brings to rural development has been widely explored. Relevant research has focused on the digital divide in the rural regions [19–23], the resilience of the digital rural [15,24,25], digital rural policy [26], digital economic development in the rural regions [27–29], and digital public services in the rural regions [30–32], etc. For example, Park (2017) points out that socio-demographic factors such as education level and employment status exacerbate the digital divide in the rural regions [33], and Salemink (2017) proposes that the development of the rural regions in the digital era should fully consider its connectivity and inclusiveness [34], which has made a positive contribution to the advancement of research on the digital rural. For China, studies on the digital rural have mostly been based on digital economy development and rural revitalization strategy, and they started relatively late. At present, most of the studies focus on the level measurement of digital rural development [35–37], digital rural governance [38–40], digital rural construction [8,17,41], digital rural public service [42], and the digital rural development model [43–45]. Related research shows that rural infrastructure construction and industrial development can help narrow the urban–rural digital divide [35,37] and boost the digital transformation of the rural regions to realize the modernization and intelligent development of the rural regions [46,47].

Through the literature, we can find that most of the existing studies have explored the theoretical and practical research on the digital rural from the perspectives of political science, economics, management, and other disciplines, but not enough attention has been paid to the research topic of digital rural development from the perspective of geography. The geographical pattern and spatial differentiation of digital rural development have not been clarified, and the influence factors and the strength of their spatial differentiation also need to be explored. In addition, the county scale is the basic unit of integrated urban–rural development [48], and it is also a suitable research scale for new urbanization and rural revitalization strategies [49], but few studies have paid attention to the issues related to digital rural development at this scale. Therefore, it is important to explore the digital rural development status at the county scale in order to effectively promote the rural revitalization strategy and dovetail with the development of county urbanization. Based on this, this paper explores the geographical pattern and spatial variation of digital rural development level (DRDL) at the county scale in China from the perspective of geography and probes and analyzes the influencing factors of their spatial divergence. In this paper, we aim to grasp the regional differences and variation characteristics of digital rural development in China and to provide some reference for the construction and development of the digital rural.

2. Theoretical Foundation and Analytical Framework

2.1. Rural Digital Transformation and Rural Regional System

As digital technology continues to penetrate into all aspects of rural production and living, a series of reconfigurations have taken place in the rural regions [50–52], focusing on spatial, economic, and social aspects [53–55], and concentrating on the digital transformation of the rural regions [56]. At the same time, rural digital empowerment provides new dynamic energy for rural society development [10], which promotes the digital revolution of the rural regions and triggers changes in production, living, and ecological and social governance in rural areas. As they constitute a complex regional system of human–land relations, the digital transformation of the rural regions is gradually changing the human–land relations in the rural regions, making the rural human–land relations emerge some new characteristics, which are concentrated in society, economy, and natural environment, and the three are interrelated and influence each other.

Integrity and regionalism are geography research characteristics [57–59], and understanding and analyzing the digital rural's heterogeneity from the perspective of geography is helpful to systematically understand the mechanism of interaction between the digital rural and geographical environment. The regional system of human–land relationship is the core of geography research [60]. As a significant sub-discipline of geography, rural geography's research core is the regional system of rural human–land relations [61]. The rural regional system in the context of digitalization is a complex system with certain functions and structures that is composed of the interaction of geographical location, ecological environment, resource endowment, economic development, policy system, public facilities, and other elements in a specific rural area (Figure 1). ① The environment system, which is composed of "land" as the core element, characterizes the influence of location conditions, topography, altitude difference, and other factors on digital rural development and reflects the relationship between digital rural development and the natural geographical environment. ② The economic system, with "industry" as the core element, portrays the role of economic development, the industrial base, and industry structure in digital rural development, and reflects the relationship between digital rural development and regional economic development. ③ The social system, with "human" as the core element, indicates the influence of the policy system, public services, and demographic characteristics on digital rural development and illustrates the relationship between digital rural development and policies/social services. Digital rural development is a concentrated expression of the coupling and coordination of the three core elements of "human", "land", and "industry" in the process of development and evolution of rural regional systems.

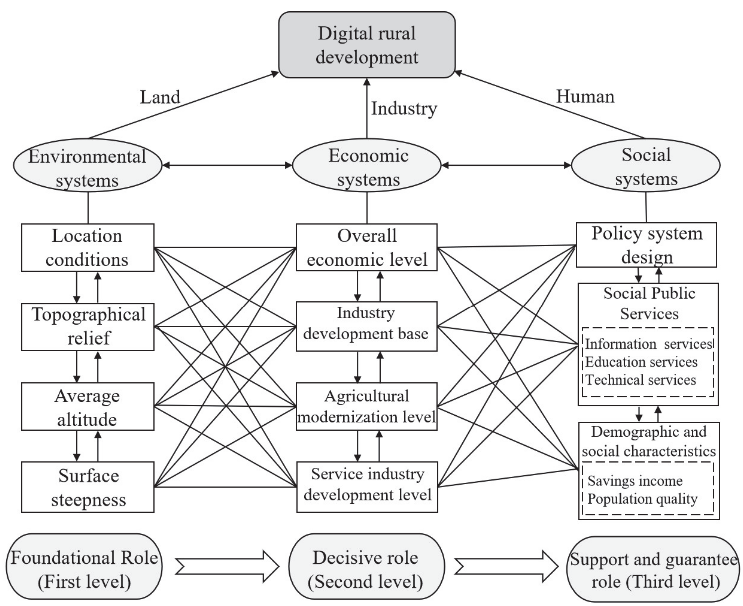

Figure 1. "Environmental-economic-social" analysis framework for digital rural development from the perspective of geography. Source: self-drawn by the authors via AutoCAD 2020 software.

2.2. "Environmental-Economic-Social" Analysis Framework for Digital Rural Development

Digitization's multidimensionality determines the complexity of digital rural development [62,63]. In terms of digital rural development and evolution, this complexity is manifested in the diversity of development elements. It is also manifested in the interactivity of action paths and the multidimensionality of digital rural representations. From the viewpoint of the elements of digital rural development, the geographical elements affecting digital rural development can be divided into two categories: natural geographical elements, including topography, climate, hydrology, biology, soil, etc., and human geographical elements, including population, location, transportation, industry, technology, capital, policy, social services, etc. [64]. From the viewpoint of the action path, digital rural development is not the result of the independent action of individual geographical elements within the rural regional system. Instead, it is the result of the joint action of multiple geographical elements between and within regions. Digital rural development representation includes three dimensions: the environmental, economic, and social dimensions (Figure 1).

(1) Digital rural development—the environmental system: The natural geographical environment of a specific region, which is innately present and inherent [65], is difficult to change and plays a fundamental role in digital rural development [66], and belongs to the first level. The influence of the environmental system on digital rural development is more stable and constant in the long run. This is mainly reflected in both the surface natural environmental conditions, such as topographic relief, surface steepness, and elevation difference, as well as the geographical location conditions in the rural regions. ① Topographic relief characterizes the general condition of a region's terrain. The greater the topographic relief, the more difficult it is to build transportation and communication facilities and the more difficult it is to promote the free flow and sharing of factors in the region, which restricts the development and modernization of rural areas and plays an innate restrictive role. ② The steepness of the ground surface indicates the difference in elevation within a region. The more gentle the surface is, the more conducive to the construction and use of public service facilities, and the more it can promote the popularization of information and communication, the Internet, and other technical facilities in rural areas, promoting the modernization and informatization process in rural areas. ③ Average altitude characterizes the altitude of an area, which directly affects temperature, precipitation, and other natural geographical factors in a region. The higher the altitude, the worse the natural environment is in terms of development conditions compared to the same region, and the more unfavorable the construction of infrastructure and public services becomes, thus affecting the digital development of the rural in the region. ④ Geographical location is crucial to a region's influence [67]. Areas far from economic, political, and cultural centers and transportation hubs have higher costs for the flow of goods, services, and various economic and social development factors between regions. These factors are less driven by the radiation of centers at all levels, and their development and driving effect on rural areas is even weaker.

(2) Digital rural development—the economic system: The economic system is the material basis and source of funds for digital rural development [68]. It plays a decisive role in digital rural development and belongs to the second level. The influence of economic system elements in the digital rural is mainly reflected in the general economic development level, industrial development base, agricultural modernization level, and service industry development level. ① In terms of overall economic development level, if the overall level of economic development of a region is better, the flow of economic and social development factors such as capital, technology, and information between urban and rural areas will be smoother, and high-quality development factors from urban areas such as networked, informatized, and digital development factors will flow into rural areas, which can have greater radiation-driven effect on rural areas. ② The industrial development base has a greater role in enhancing the economic growth capacity and digitalization level of a region. It will effectively promote the development of information technology, thus promoting the digital transformation of rural areas. ③ The use of agricultural science and technology and big data internet, etc. makes agricultural development gradually move from traditional agriculture to modern agriculture, and the use of new technology also makes agricultural production, management, and sales change, which facilitates the digital transformation of agricultural production in rural areas. ④ In addition, the rapid development of service industry, especially of transportation and communication and information networks, has led to the rapid development of service industry in rural areas, and a series of new rural service businesses such as rural tourism and rural e-commerce have flourished, greatly

promoting the change of service industry in rural areas and enhancing the digitalization of rural areas.

(3) Digital rural development—the social system: The social system has an amplifying effect on digital rural development. It plays a crucial role in supporting and guaranteeing the sustainable and solid development of the digital rural [69], and belongs to the third level. The influence of the social system on digital rural development is mainly reflected in policy guidance, social services, and individual residents. ① In terms of policy guidance, the government's guidance and support is a strong support for digital rural development. The government has strongly promoted digital rural construction by investing in digital infrastructure and placing resources such as information networks in rural areas. Reasonable and effective system design and institutional mechanism construction provide strong guarantees for digital rural development. ② In terms of social services, well-developed basic public services in rural regions play active roles in promoting digital rural construction. Digital rural development depends not only on the construction of digital infrastructure but also on the improvement of the quality of public services. For example, information and communication services provide strong guarantees for digital rural development, professional technical services provide professional technical talents for the digital transformation of rural regions, basic education services provide potential talent reserves for the continuous transformation and in-depth development of the digital rural, and the combined effect of social public services provides solid social security for the construction of digital rural. ③ In terms of individual residents, digital rural construction should adhere to the concept of people-oriented construction and development [17]. Improving rural residents' information literacy and skills are important parts of digital rural construction, and thus the personal characteristics of rural residents also play significant subjective roles in digital rural development. The higher the income level is, the stronger the ability to purchase digital facilities is; at the same time, the quality of the population determines, to a great extent, the use of digital equipment and facilities, and the higher the education level is, the stronger the ability to learn and use new technologies is, and the more conducive to the digital transformation of rural areas [70].

3. Data and Methods

3.1. Data Source and Processing

The digital rural index data used in this paper comes from the County Digital Rural Index (2020), jointly published by the Institute for New Rural Development of Peking University and the Ali Research Institute [71]. The index system of the county digital rural index includes 4 primary indicators and dimensions—the rural infrastructure digitalization index, rural economy digitalization index, rural governance digitalization index, and rural living digitalization index—and 12 secondary indicators: information infrastructure index, digital financial infrastructure index, digital production index, governance means index, etc. There are also 33 specific indicators, such as the number of mobile devices per 10,000 people, the breadth of digital financial infrastructure coverage, the depth of digital financial infrastructure usage, etc. Due to the length of the paper, the detailed index system and its calculation are not described here. Please refer to reference [71] for details. The index fully considers the new digital phenomenon in rural development and builds a digital rural index system that is more suitable for "agriculture, rural areas and farmers (the three rural issues)" in four aspects—rural digital infrastructure, rural economy, rural governance, and rural living—that can comprehensively reflect the digital development level of rural areas today [71]. The study area comprises 2481 county-level administrative units, including 699 municipal districts, 328 county-level cities, and 1454 counties. Some county units are treated as having "no data" in the following section because of missing statistics.

By considering factors such as scientificity, representativeness, and accessibility, and avoiding overlap with the county digital rural index, this paper constructs an index system that is based on the "environmental-economic-social" analysis framework for digital rural development. This index system is based on the three dimensions of the environmental system, economic system, and social system. Fourteen indicators such as average elevation, per capita GDP, and per capita public budget expenditure are selected to characterize the influencing factors of the digital rural development level (DRDL), and to comprehensively build a system of indicators to identify the spatial variation of the DRDL in Chinese counties (Table 1). The environmental system is the negative indicator, economic system is the positive indicator, and all indicators are discrete. The original data of the indicators are listed in Table 1; the base year is 2020. DEM data have been obtained from the geospatial data cloud (http://www.gscloud.cn/ (accessed on 30 May 2022)), the average elevation, average slope, and topographic relief of each county and city have been extracted through slope and neighborhood analysis, and the distance to the capital city of the province to which they belong has been obtained by calculating the distance from the administrative center of the county to the administrative center of the capital city. The rest of the socio-economic data have been obtained from the *2021 China Statistical Yearbook (County-level)*, *Tabulation On 2020 China Population Census By County*, and the statistical yearbooks and national economic and social development statistical bulletins of counties and cities of China; a few missing values have been supplemented by interpolation.

Table 1. Index system of factors influencing the spatial differentiation of county DRDL in China. Source: author's compilation based on relevant literature.

System Dimension	Specific Indicators	Representational Meaning	Calculation Method	Properties
Environmental Systems	X1: Average elevation (m)	Average surface elevation	Extracting the average elevation value of the county	–
	X2: Average slope (°)	Steepness of the ground surface	Extracting the average slope value of the county	–
	X3: Terrain undulation (m)	Surface elevation difference	Extracting the topographic relief of the county	–
	X4: Distance from the capital city of the province to which it belongs (km)	Geographical distance	Distance from the county administrative center to the provincial capital administrative center	–
Economic Systems	X5: GDP per capita (RMB 10,000)	Overall economic level	GDP/number of resident population	+
	X6: Value added of tertiary industry as a proportion of GDP (%)	Service industry development level	Value added of tertiary industry/GDP	+
	X7: Number of industrial enterprises above the scale per capita	Industrial economic base	Number of industrial enterprises above the scale/number of resident population	+
	X8: Percentage of facility agriculture area (%)	Agricultural modernization level	Area of facility agriculture/total area of administrative region	+
Social Systems	X9: Public budget expenditure per capita (RMB 10,000)	Government support	Government public budget expenditure/number of resident population	+
	X10: Number of fixed telephone subscribers (10,000 families)	Communication service level	Number of fixed telephone subscribers	+
	X11: Number of students in primary and secondary schools (persons)	Human capital reserve	The sum of the number of students enrolled in general secondary schools and primary school	+
	X12: Number of IT service industry personnel (persons)	Professional and technical talents	Total number of information technology services and related employees	+
	X13: Savings deposit balance per capita (RMB 10,000)	Resident savings income	Household savings deposit balance/number of resident population	+
	X14: Average education years for the population (years)	Regional population quality	Average years of education of residents	+

3.2. Research Methodology

3.2.1. Thiel Index and Its Decomposition

The Thiel index is an important indicator of income disparity between individuals or regions. In this paper, we use the Thiel index to analyze the differences between the DRDLs within and between regions in China and measure overall national differences, inter-regional differences, intra-regional differences, and related contribution rates. The specific formula is as follows [35]:

$$T = \frac{1}{k}\sum_{q=1}^{k}\left(\frac{S_q}{\overline{S}} \times \ln\frac{S_q}{\overline{S}}\right) \tag{1}$$

$$T_p = \frac{1}{k}\sum_{q=1}^{k_p}\left(\frac{S_{pq}}{\overline{S}_p} \times \ln\frac{S_{pq}}{\overline{S}_p}\right) \tag{2}$$

$$T = T_w + T_b = \sum_{p=1}^{4}\left(\frac{k_p}{k} \times \frac{\overline{S}_p}{\overline{S}} \times T_p\right) + \sum_{p=1}^{4}\left(\frac{k_p}{k} \times \frac{\overline{S}_p}{\overline{S}} \times \ln\frac{\overline{S}_p}{\overline{S}}\right) \tag{3}$$

In Equation (1), T denotes the Thiel index of the overall differences between the DRDLs, and its size is in [0, 1]; a smaller T indicates a smaller overall difference in the DRDLs, and the opposite indicates a larger overall difference. q denotes the county, k denotes the number of counties, S_q denotes the DRDL of county q, and S denotes the average of the national DRDLs. In Equation (2), T_p indicates the overall difference Thiel index of region p, k_p indicates the number of counties in region p, S_{pq} indicates the DRDL of county q in region p, and $\overline{S}_p$ indicates the average of the DRDL in region p. In Equation (3), the overall differences Thiel index of the DRDL is further decomposed into intra-regional differences Thiel index T_w and inter-regional differences Thiel index T_b. In addition, T_w/T and T_b/T are defined as the contribution of intra-regional differences and inter-regional differences to the overall differences, respectively, $(S_p/S) \times (T_p/T)$ is the contribution of each region to the overall differences within the region, S_p denotes the sum of the DRDL of each county in region p, and S denotes the sum of national DRDL.

3.2.2. Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is mainly applied to analyze spatial data interdependence, including two parts: global spatial autocorrelation and local spatial autocorrelation [72]. Moran's I is used to measure the global spatial association characteristics of the research object. Local spatial autocorrelation is mainly used to measure the local spatial association characteristics of the research object, expressed by the local Getis-Ord-Gi* index in this paper [73], which is used to identify the spatial distribution location of the similar clustering areas of the DRDL and classify them into coldspots and hotspots so as to facilitate the observation of the spatial difference degree of the DRDL between the studied county and the surrounding counties. The formula is shown below:

$$Moran's\ I = \frac{n\sum_i^n \sum_j^n w_{ij}(y_i - \overline{y})(y_j - \overline{y})}{\sum_i^n \sum_j^n w_{ij}\sum_i^n (y_j - \overline{y})^2} \tag{4}$$

$$G_i = \frac{\sum\limits_{j=1}^{n} w_{ij}x_j}{\sum\limits_{j=1}^{n} x_j} \quad (j \neq i) \tag{5}$$

In Equation (4), n is the total number of spatial units in the study area, Y_i and Y_j indicate the DRDL in spatial units i and j, $\overline{y}$ is the mean value of the DRDL, W_{ij} is the spatial weight matrix, and Z_i and Z_j are the normalized values of the observed values in spatial units i and j, respectively. In Equation (5), w_{ij} is the spatial weight, and $\Sigma_j = lnw_{ij} = 1$. If the G_i value is significantly positive, it indicates a high value agglomeration area around region *i*. If the G_i value is significantly negative, it indicates a low value agglomeration area around region *i*.

3.2.3. Geodetector Model

The Geodetector method is an innovative statistical method for detecting spatial heterogeneity and revealing the driving factors behind it. It includes four detectors: heterogeneity and factor detection, interaction detection, risk detection, and ecological detection [74]. In this paper, we draw on the factor detection and interaction detection functions in the Geodetector model. We explore the factors influencing the spatial differentiation of the DRDL and their interactions. The formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h {\sigma_h}^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \quad (h = 1, 2, \cdots, L) \tag{6}$$

In Equation (6), h is the stratification of variable Y or factor X; N_h and N are the number of units in square h and the whole region, respectively; ${\sigma_h}^2$ and σ^2 are the variances of Y values in square h and the whole region, respectively; SSW and SST are the Within Sum of Squares and the Total Sum of Squares, respectively; the value range of q is [0, 1], and a larger value of q indicates that the spatial heterogeneity of Y is more obvious. Interaction detection was also used to identify interactions between different levels of determinants. A comparison of q(X1), q(X2), and q(X1∩X2) was used to determine whether the deterministic effects of any two indicators of X1 and X2 on the DRDL were independent or whether they increased or decreased the explanatory power when acting together, and five types were classified according to the comparison [74] (Table 2).

Table 2. Expressions for interaction detection. Source: reference [74].

Expressions	Type of Action
q(X1∩X2) < Min(q(X1), q(X2))	Non-linear weakening
min(q(X1), q(X2)) < q(X1∩X2) < max(q(X1), q(X2))	Single-factor non-linear attenuation
q(X1∩X2) = q(X1) + q(X2)	The two factors are independent of each other
q(X1∩X2) > Max(q(X1), q(X2))	Two-factor enhancement
q(X1∩X2) > q(X1) + q(X2)	Non-linear enhancement

4. Spatial Divergence Characteristics of the DRDL in China's Counties

4.1. Overall Distribution Characteristics

With the help of the ArcGIS 10.2 software, the county DRDL data was divided into five categories according to the quantile classification method for visual expression (Figure 2), and the blue→red legends in the figure indicate the development stages of the low level, lower level, medium level, higher level, and high level respectively. According to Figure 2, the DRDL in general shows a decreasing distribution trend from the coast to the inland, showing a spatial distribution pattern of "high in the east and low in the west", and the middle- and high-level areas are mainly distributed in the area east of the Hu Huanyong population line (Hu line), but the distribution pattern of development levels in different dimensions reveals certain differences.

Specifically, in terms of the overall DRDL, the high-level and higher-level areas are mainly concentrated on the east side of Hu line, distributed in "clusters" in Hebei, Shandong, Zhejiang, Fujian, and other provinces, while the low-level and lower-level areas are primarily concentrated in the vast western region and northeastern region. In terms of rural infrastructure digitalization dimension, the high-level areas are also mainly located on the east side of the Hu line, such as Zhejiang, Anhui, Henan, and other provinces. However, it is worth noting that there are still more areas in the western region with high and higher levels of distribution, such as central, northern, and southeastern Tibet and northeastern Xinjiang. In the rural economy digitalization dimension, the "Hu line effect" is more obvious, with areas of medium level and above being mainly distributed to the east of the Hu line, while areas of higher level to the west of the Hu line are only "dotted" and most of them are low-level areas. In the rural governance digitalization dimension, besides Shandong, Zhejiang, and Hubei to the east of the Hu line, Ningxia, and Inner Mongolia to the west of the Hu line also show cluster-like distributions of high- and higher-level areas. In the rural living digitalization dimension, high-level areas are concentrated in Jiangxi, Fujian, Zhejiang, Shandong, and other provinces; in addition, the northern part of the northeast region and some parts of eastern Xinjiang also show cluster-like distributions.

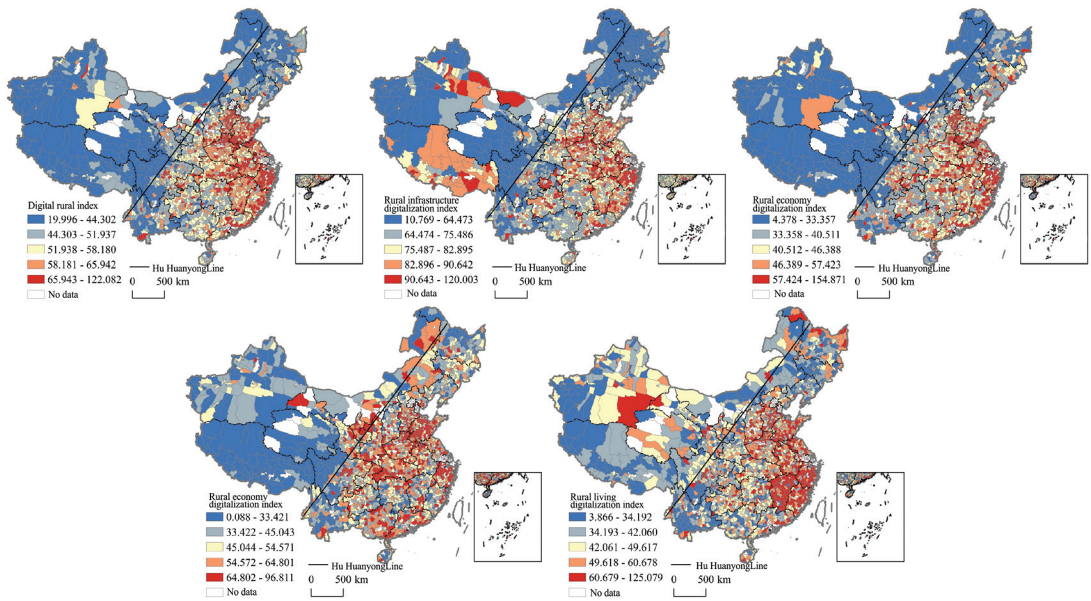

Figure 2. Spatial pattern of county DRDL in China. Source: self-drawn by the authors via the ArcGIS 10.2 software. Note: The map is based on the standard map with the review number GS(2020)4634 on the standard map service website of the Ministry of Natural Resources of China, with no modification made to the base map.

4.2. Characteristics of Regional Differences

Based on the Thiel index, the characteristics of regional differences in DRDL in Chinese counties were carved (Table 3). In terms of overall differences, the Thiel index of the digital rural overall level was 0.0315, which was relatively small compared with the rural economy digitalization dimension, rural governance digitalization dimension, and rural living digitalization dimension (Table 3). Among these, the Thiel index of the rural economy digitalization level, the rural governance digitalization level, and the rural living digitalization level were all higher than 0.6, indicating that the regional differences of these three types of index are larger and the regional development imbalances are more prominent. In contrast, the Thiel index of the rural digital infrastructure dimension was the smallest (0.0252), indicating that the regional differences in the development level of rural digital infrastructure are relatively small and that the level of regional development is more balanced.

Table 3. Thiel index and contribution rate of county DRDL in four major regions of China. Source: authors; values were derived by calculating the Thiel index.

Types	Thiel Index	Inter-Regional Differences and Contribution Rate (%)	Intra-Regional Differences and Contribution Rate (%)				
			Overall China	Eastern Region	Central Region	Western Region	Northeast Region
Digital rural index	0.0315	0.0122 (38.58%)	0.0194 (61.42%)	0.0206 (19.33%)	0.0103 (8.96%)	0.0260 (28.70%)	0.0170 (4.44%)
Rural infrastructure digitalization index	0.0252	0.0078 (30.84%)	0.0175 (69.16%)	0.0088 (9.60%)	0.0070 (7.67%)	0.0323 (46.85%)	0.0160 (5.03%)
Rural economy digitalization index	0.068	0.0204 (30.03%)	0.0476 (69.97%)	0.0621 (29.17%)	0.0306 (12.01%)	0.0526 (25.22%)	0.0280 (3.57%)
Rural governance digitalization index	0.0849	0.0082 (9.70%)	0.0766 (90.29%)	0.0433 (14.74%)	0.0567 (17.73%)	0.1134 (48.39%)	0.0959 (9.42%)
Rural living digitalization index	0.0625	0.0152 (24.35%)	0.0473 (75.65%)	0.0551 (26.19%)	0.0376 (16.96%)	0.0458 (25.07%)	0.0599 (7.45%)

Note: The eastern region includes Hebei, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan; the central region includes Shanxi, Henan, Hubei, Hunan, Anhui, and Jiangxi; the western region includes Inner Mongolia, Xinjiang, Tibet, Shaanxi, Ningxia, Gansu, Qinghai, Yunnan, Guizhou, Sichuan, Chongqing, and Guangxi; the northeast region includes Heilongjiang, Jilin, and Liaoning.

To explore the intra- and extra-regional differences in DRDL, the overall differences Thiel index is further decomposed into the intra-regional differences Thiel index and inter-regional differences Thiel index. From the decomposition results, the contribution rates of intra-regional differences in DRDL and its four sub-dimensions are all greater than 50%, i.e., the contribution rate of intra-regional differences is greater than that of inter-regional differences, indicating that the overall differences in DRDL in China's countries predominantly originate from intra-regional differences. From the overall level of the DRDL and its sub-dimensions, the highest contribution rates of intra-regional differences are mainly in the western and eastern regions while the contribution rates of intra-regional differences in the central and northeastern regions are relatively low, indicating that the intra-regional differences in DRDL in China are mainly in the western and eastern regions.

Specifically, in terms of the overall DRDL, intra-regional differences are mainly concentrated in the western and eastern regions, with relatively small differences within the northeastern and central regions, indicating that there are significant regional differences in the overall DRDL while large differences exist within the western and eastern regions. In the rural infrastructure digitalization dimension, the main difference originates from the western region, whose contribution rate is as high as 46.85%, indicating that there are large differences in the construction of rural digital infrastructure in the western region, while development within the eastern, central, and northeastern regions is relatively balanced. In the rural economy digitalization dimension, the higher contribution rate of intra-regional differences is the eastern and western regions and the sum of their contribution rates is more than 50%, indicating that there are large differences in rural economy digitalization development levels in the eastern and western regions. In the rural governance digitalization dimension, the contribution rate of intra-regional differences is as high as 90.29%, indicating that most of the regional differences in the rural governance digitalization level in China's counties are caused by intra-regional differences, among which intra-regional differences in the western region dominate (with a contribution rate of 48.39%). In the rural living digitalization dimension, intra-regional differences in the eastern region (contribution rate 26.19%) and intra-regional differences in the western region (contribution rate 25.07%) are relatively similar, and both are the main sources of intra-regional differences, mainly due to uneven development among the internal counties.

4.3. Spatial Correlation and Spatial Clustering Characteristics

The global spatial correlation characteristics of DRDL in Chinese counties were measured with the help of the Moran Index (Moran's I) and their spatial correlation was analyzed (Table 4). According to the results in Table 4, the Moran's I values of the DRDL and its sub-dimensions are all greater than 0, and the p-values all pass the significance test, showing strong spatial correlation. There are some differences in the spatial correlation of different dimensions, and the Moran's I values show that the rural infrastructure digitalization level > total level of the DRDL > rural economy digitization level > rural living digitization level > rural governance digitization level, indicating that the spatial correlation nature of the rural infrastructure digitalization level has a stronger spatial correlation compared with other sub-dimensions while the rural governance digitalization level has a weaker spatial correlation.

Table 4. Global Moran index of county DRDL in China. Source: authors; values were derived by calculating the Moran index.

Category	Moran's I	Z-Value	p-Value
Digital rural index	0.472	4.238	0.000
Rural infrastructure digitalization index	0.475	4.261	0.000
Rural economy digitalization index	0.435	3.910	0.000
Rural governance digitalization index	0.321	2.885	0.004
Rural living digitalization index	0.358	3.216	0.001

According to the Moran's I results, there is a strong spatial correlation between the DRDLs of Chinese counties. However, the specific correlation areas and clustering areas are unclear and need to be analyzed in more depth. Thus, with the help of the coldspot and hotspot analysis tool, we analyzed the DRDL of Chinese counties and identified the coldspot and hotspot distribution areas of the total DRDL and each of its dimensions so as to better understand the spatial clustering characteristics of DRDL (Figure 3). Through Figure 3, it can be found that there are obvious hotspot areas and coldspot areas in the DRDL and that there are differences in the coldspot and hotspot areas in different dimensions.

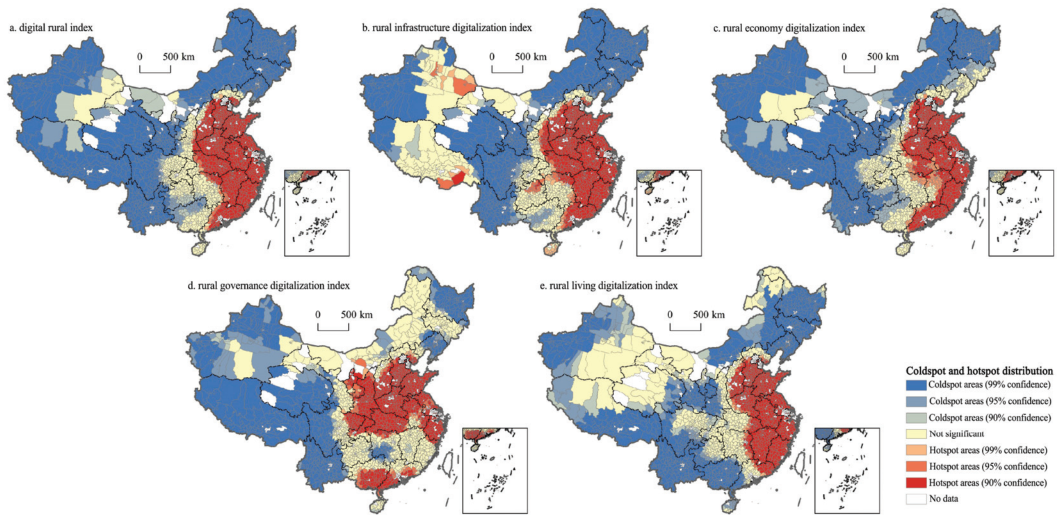

Figure 3. Coldspot and hotspot distribution of county DRDL in China. Source: self-drawn by the authors via the ArcGIS 10.2 software. Note: The map is based on the standard map with the review number GS(2020)4634 on the standard map service website of the Ministry of Natural Resources of China, with no modification made to the base map.

Specifically, in terms of the total level of DRDL, the hotspot areas are mainly distributed in the vast eastern region, with a gradual transition from the east to the west, and the hotspot significant areas are concentrated in the eastern provinces of Hebei, Shandong, Henan, Jiangsu, Zhejiang, Jiangxi, Fujian, and Guangdong; the insignificant areas are mostly concentrated in the central region, and also include parts of Xinjiang; the coldspot areas are mainly concentrated in both the vast western region as well as the northeast region. Regarding the rural infrastructure digitalization dimension, its hotspot areas are similar to the hotspot areas of the total level of the DRDL, being mainly distributed in the eastern provinces, but the coldspot areas are smaller in scope, being mainly concentrated in the northeast region, Yunnan, Qinghai, western Sichuan, western Xinjiang, etc. Regarding the rural economy digitalization dimension, the hotspot areas are distributed in a "piece" shape in Hebei, Shandong, Jiangsu, Zhejiang, Fujian, and other provinces, while the coldspot areas are concentrated in the vast western region, and the transition area between the coldspot areas and the hotspot areas is not significant. Regarding the rural governance digitalization dimension, the hotspot areas are mostly concentrated in the areas north of the Yangtze River, including Hebei, Shandong, Jiangsu, Henan, Hubei, and other provinces, and the areas south of the Yangtze River are mainly distributed in Zhejiang, southern Guangdong, and eastern Guangxi; the coldspot areas are mainly distributed in the vast southwestern region, while there are also local coldspot areas distributed in the northern and southern parts of northeast China and southern Hunan. Regarding the rural living digitalization dimension, the hotspot areas are still mainly concentrated in the eastern provinces, the coldspot areas are mainly distributed in the southwest region, northeast region, Shaanxi, and Gansu, and the rest of the areas are contiguous transition areas.

5. Detection of Influence Factors in the Spatial Divergence of County DRDL in China

5.1. Factor Detection and Dominant Factor Analysis

By geographically detecting the influencing factors for the spatial divergence of DRDL, we found that the intensities of the effects of different influencing factors on different scale spaces varied, showing certain scale differences and spatial differentiation characteristics, and so, they need to be discussed separately (Table 5).

Table 5. Factor detection results of geographical differentiation of county DRDL in China. Source: obtained by the authors using the Geodetector software.

	Overall China		Eastern Region		Central Region		Western Region		Northeast Region	
	q-Value	Contribution Rate	q-Value	Contribution Rate	q-Value	Contribution Rate	q-Value	Contribution Rate	q-Value	Contribution Rate
X1	0.3127	12.85%	0.0719	6.66%	0.1125	12.49%	0.2624	10.32%	0.1853	13.34%
X2	0.0956	3.93%	0.0230	2.13%	0.0626	6.95%	0.0514	2.02%	0.0136	0.98%
X3	0.2651	10.90%	0.0279	2.59%	0.0969	10.76%	0.2586	10.17%	0.1673	12.04%
X4	0.0362	1.49%	0.0151	1.40%	0.0634	7.04%	0.0897	3.53%	0.0018	0.13%
X5	0.0779	3.20%	0.0524	4.86%	0.0438	4.86%	0.0593	2.33%	0.0797	5.74%
X6	0.0198	0.81%	0.0285	2.64%	0.0130	1.44%	0.0113	0.44%	0.0574	4.13%
X7	0.2264	9.31%	0.1752	16.24%	0.0230	2.55%	0.1363	5.36%	0.1130	8.13%
X8	0.1269	5.22%	0.0704	6.52%	0.0312	3.46%	0.1117	4.39%	0.1592	11.46%
X9	0.2272	9.34%	0.0297	2.75%	0.0549	6.10%	0.3334	13.11%	0.0607	4.37%
X10	0.1869	7.68%	0.1652	15.31%	0.1121	12.45%	0.2371	9.32%	0.1020	7.34%
X11	0.2291	9.42%	0.1084	10.05%	0.0854	9.48%	0.2096	8.24%	0.1025	7.38%
X12	0.2948	12.12%	0.1854	17.18%	0.1265	14.05%	0.3407	13.39%	0.1753	12.62%
X13	0.1778	7.31%	0.0809	7.50%	0.0256	2.84%	0.2554	10.04%	0.0815	5.87%
X14	0.1563	6.42%	0.0451	4.18%	0.0497	5.52%	0.1869	7.35%	0.0900	6.48%

5.1.1. The National Scale

On a national scale, the factors influencing the spatial differentiation of DRDL in China's counties vary significantly. The intensities of effects presented by different factors vary greatly. Five factors—average elevation (X1), employees in the information service industry (X12), topographic relief (X3), number of students in primary and secondary schools (X11), and per capita public budget expenditure (X9)—have an explanatory power contribution of 54.63%, and are the main influencing factors of regional differences in DRDL.

Among them, in terms of natural environment, average altitude (X1) has the strongest effect, with a q-value of 0.3127, and terrain undulation (X3) also has a strong effect, with a q-value of 0.2651, indicating that on a national scale, spatial variation in DRDL is more restricted by natural factors and that the higher the average altitude is, and the greater the terrain undulation, the lower the DRDL will be. This is mainly because digital rural development requires certain digital infrastructure. However, with the increase of altitude and undulation, the construction of digital facilities such as information communication and mobile network becomes more difficult and the construction cost increases gradually, both of which make the construction of digital rural geographically restricted and further restrict the improvement of rural economy digitalization, living digitalization, and governance digitalization, and thus, to a greater extent, cause regional differences in DRDL.

Meanwhile, in terms of social environment, IT service industry practitioners (X12) and the number of school students in primary and secondary schools (X11) also influence digital rural construction to a greater extent. Digital-related professional and technical talents can provide the necessary human support and intellectual guarantee for digital rural construction. A certain number of school students provide a talent reserve for the cultivation of professional and technical talents, and are the reserve force of talent for digital rural construction. Therefore, specialized technical personnel and their reserve force can promote digital rural development to a greater extent, resulting in regional differences in

DRDL. In addition, the influence of per capita public budget expenditure (X9) on the DRDL is also high (with q-value of 0.2272 and contribution of 9.34%). The DRDL is closely related to digital infrastructure investment, which is mainly financed by the government's public financial expenditure. The more public financial expenditure is made, the more sufficient funds are available for digital rural construction, and the more conducive the situation to the improvement of the DRDL, thus resulting in the differences in its distribution patterns.

Compared with the above factors, the explanatory power of factors such as the proportion of the value added by tertiary industry to GDP (X6) and the distance from the capital city of the province to the place which it belongs (X4) is lower, probably because due to the development of digitalization and networking in the rural regions, digital technology has broken through the constraints of geographical space to a certain extent, and the role of geographical distance for digital rural development has been relatively weakened. At the same time, with the gradual promotion of industrial transformation and development in various places, the proportion of service industry output value in each region has gradually increased. Its effect on digital rural development has been relatively weakened.

5.1.2. Regional Scale

In the eastern region, the sum of the explanatory power of four factors, namely, the number of personnel in IT service industry (X12), the number of industrial enterprises above the scale per capita (X7), the number of fixed telephone subscribers (X10), and the number of students in primary and secondary schools (X11), reaches 58.77%, which is the main influencing factor for the regional variation of the DRDL in the eastern region. Compared with the overall situation in China, the number of IT service industry personnel plays a stronger role in the regional variation of the DRDL in the eastern region, and its influence contribution reaches 17.18%, indicating that professional and technical talents play an important role in the construction and development of the digital rural in the eastern region. The total number of information technology service personnel in eastern regions such as Zhejiang and Jiangsu is leading in China, and professional and technical talent can provide solid human support for digital rural construction and promote digital rural development, making the DRDLs in eastern coastal regions such as Zhejiang and Jiangsu relatively high. At the same time, the number of industrial enterprises above the scale per capita, as the basis of industrial economic development, also lays the economic foundation for digital rural development. Together with the developed communication services, this makes the rural infrastructure digitalization level, the rural economy digitalization level, and the rural governance digitalization level in the eastern region stay at a high level, making it a hotspot area of DRDL in China.

For the central region, the explanatory power of five factors on the DRDL reaches 59.23%, and these factors include the number of IT service industry personnel (X12), the average elevation (X1), the number of fixed-line telephone subscribers (X10), the topographic relief (X3), and the number of primary and secondary school students (X11). Similar to the eastern region, factors such as professional and technical personnel, communication service level, and human resource reserves also have strong explanatory power for the DRDL in the central region. However, unlike the eastern region, the two natural environmental factors of average elevation and terrain undulation are more prominent, mainly because some provinces in the central region straddle the second and third steps (e.g., Shanxi, Henan, Hubei, and Hunan provinces) and the differences in average elevation and terrain undulation within the provinces are relatively large, imposing different degrees of constraints on digital rural construction and thus affecting the development of the digital rural, resulting in spatial differences between their development levels.

In the western region, natural environment factors influence the DRDL more. Among them, the q-values of average elevation (X1) and topographic relief (X3) are 0.2624 and 0.2586, respectively, and the sum of their explanatory power occupies 20.48% of the contribution, indicating that the DRDL in the western region is influenced by the natural geographical environment to a greater extent. Meanwhile, the q-values of the number of personnel in the IT service industry (X12), per capita public budget expenditure (X9), and per capita savings deposit balance (X13) contribute 13.39%, 13.11%, and 10.04% of the explanatory power, respectively, indicating that professional and technical talent, government support, and people's income level play important roles in digital rural construction in the western region. Therefore, upgrading professional talent team construction, increasing government financial investment, and increasing people's income level are important ways to enhance the DRDL in the western region.

For the northeast region, the explanatory power of five factors—average elevation (X1), number of IT service industry personnel (X12), topographic relief (X3), percentage of facility agriculture area (X8), and number of industrial enterprises above the scale per capita (X7)—reaches 57.59%, making these the main factors influencing the DRDL in the northeast region. Notably, the contribution of agricultural modernization level to the DRDL in the northeast region (11.46%) is much higher than that at the national (5.22%) level and in the eastern (6.52%), central (3.46%), and western (4.39%) regions. The northeast region is an important commodity grain base in China, and its agricultural modernization and mechanization rate is in the leading position in China. The comprehensive mechanization degree in the northeast region has reached 95.05%, ranking first in China, and the comprehensive mechanization rate of agriculture in Heilongjiang Province is as high as 98% [75]. Moreover, the improvement of the agricultural modernization level can greatly promote the rural economy digitalization level, which becomes an important factor influencing the development of the digital rural in the northeast region.

5.2. Interaction Detection Analysis

Digital rural development is often the result of the combined effect of multiple factors, and the results of the combined effect of different factors may differ from the results of single factors. Therefore, this paper explores the interactions of factors influencing DRDL in Chinese counties on the basis of factor detection. For comparison, the top 10 factors in terms of the q-value of interactions were selected for analysis in the four major regions of China in order to explore the relationships among the influencing factors. The interaction detection results showed (Figure 4, Table 6) that the driving force of the two-factor interaction was stronger than that of the single-factor action and that the type of interaction showed either two-factor enhancement or non-linear enhancement. Compared with the single-factor effect, the q-values of each factor when acting together with other factors were all increased to different degrees, indicating that the explanatory power of the interactions among factors on the differences of the DRDL was always greater than that of the single-factor effect, thus further deepening the spatial differentiation of DRDL.

Table 6. Interaction detection results of the geographical divergence of county DRDL in the four regions of China. Source: Geodetector results collated by the authors.

Rank	Eastern Region		Central Region		Western Region		Northeast Region	
	Interaction	q-Value	Interaction	q-Value	Interaction	q-Value	Interaction	q-Value
1	X7∩X11	0.3656	X1∩X14	0.2250	X12∩X13	0.4915	X10∩X14	0.4378
2	X7∩X12	0.3446	X1∩X12	0.2118	X9∩X13	0.4899	X3∩X12	0.4315
3	X6∩X7	0.3050	X12∩X14	0.2036	X11∩X13	0.4789	X1∩X11	0.4262
4	X2∩X12	0.3010	X10∩X12	0.2031	X9∩X14	0.4575	X3∩X11	0.4141
5	X7∩X10	0.2982	X1∩X4	0.2001	X1∩X12	0.4425	X1∩X10	0.4057
6	X7⋂X9	0.2801	X9⋂X10	0.1981	X3⋂X12	0.4399	X12⋂X14	0.4001
7	X1⋂X7	0.2793	X1⋂X10	0.1973	X9⋂X12	0.4360	X1⋂X12	0.3890
8	X2⋂X7	0.2748	X11⋂X14	0.1969	X12⋂X14	0.4302	X11⋂X14	0.3693
9	X7⋂X8	0.2676	X10⋂X14	0.1934	X7⋂X9	0.4253	X1⋂X9	0.3675
10	X3⋂X7	0.2671	X4⋂X12	0.1919	X5⋂X9	0.4212	X11⋂X13	0.3672

Note: The light blue part indicates that the interaction type is non-linear enhancement and the light yellow part indicates that the interaction type is two-factor enhancement.

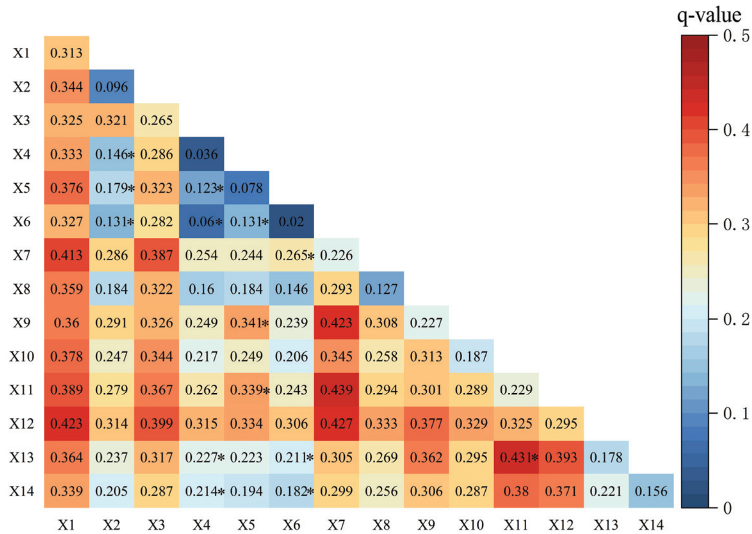

Figure 4. Interaction detection results of geographical differentiation of county DRDL in China. Source: Self-drawn by the authors via the Origin 2021 software. Note: * indicates non-linear enhancement, and the rest of the values are two-factor enhancement.

5.2.1. National Scale

Overall, nationally, the type of interaction is mainly two-factor enhanced, indicating that for most of the influencing factors, the interaction of a single factor with any other factor is greater than its own individual effect (Figure 4). Among them, the number of industrial enterprises above the scale per capita (X7) and the number of primary and secondary school students (X11) have the strongest interaction forces, indicating that the combined effect of industrial economic base and human capital reserve plays an important role in the regional differences in DRDL across the country. It is noteworthy that the q-values of the interactions between X7 and X11, X7 and X12, and X11 and X13 are significantly higher than the highest values of the q-values of the single-factor detection XI interacting with other factors, which indicates that in the case of interaction, the strength of the effect of natural environmental factors is less influential on the regional differences in DRDL while the interaction of socio-economic factors plays a dominant role in the regional differences in DRDL. It can be inferred that, on a national scale, although natural environmental factors have a greater constraint on the DRDL from a single-factor perspective, digital rural development is more of a socio-economic phenomenon and is more constrained by socio-economic conditions. Therefore, by improving the regional socio-economic conditions, it is still possible to compensate for the hindrance caused by natural environmental conditions and realize the catch-up development of the digital rural in areas with poor natural environments.

5.2.2. Regional Scale

From the eastern region, the type of interaction showed mainly non-linear enhancement (Table 6). The number of industrial enterprises above the scale per capita (X7) had a strong interaction with nine factors, including the number of students in primary and secondary schools (X11) and the number of workers in the information technology service industry (X12), and mainly showed a non-linear enhancement. It is shown that the economic development base, together with the vast majority of factors, has a greater influence than the sum of each factor individually. This indicates that economic development, as the material base of digital rural construction, plays a key role in digital rural development. It is noteworthy that the number of primary and secondary school students (X11) ranks 4th in influence in the single factor detection ($q = 0.1084$), but the q-value increases significantly after interacting with the number of industrial enterprises above the scale per capita (X7), which enhances the influence on digital rural development. This finding indicates that the influence degrees of individual factors of education service level on digital rural development is not significant. The rule of basic education lies in the long period, slow effect, and strong after-effects [76], which mainly shows an indirect influence on digital rural development. Therefore, when education service level is combined with other factors such as the economic development base, it can significantly promote digital rural development.

The types of factor interactions in the central region show both two-factor enhancement and non-linear enhancement, and the number of both interaction types is roughly equal, but the influence in the central region is weaker than in the east, west, northwest, and nation as a whole, and the maximum q-value of the interaction is only 0.2250. It is noteworthy that the single factor power of the average years of education of the population (X14) ranks relatively low, but the interactions with average elevation (X1), IT service industry personnel (X12), number of primary and secondary school students (X11), and number of fixed-line telephone subscribers (X10) result in significant increases in its q-value; in particular, the interaction with average elevation (X1) has its influence jumped to first place (q = 0.2250). This indicates that regional population quality has great potential for digital rural development in the central region and that its power can be fully realized when interacting with factors such as mean elevation, communication services, education services, and professional and technical services.

Western region interactions are mainly two-factor enhanced, indicating that they have a greater impact than each factor alone. The first-ranked single-factor interaction, IT service industry personnel (X12, q = 0.3407), continues its first-ranked influence in the interaction and has the strongest influence (q = 0.4915) in the interaction with per capita savings deposit balance (X13). Meanwhile, the influence of the interaction of IT service industry personnel (X12) with average elevation (X1), topographic relief (X3), public budget expenditure per capita (X9), and average years of education of the population (X14) is also strong. This indicates that for the western region, professional and technical personnel play a key role in digital rural development, either as a single factor or in interaction with other factors, and that this factor is more likely to influence regional variability in the DRDL when combined with socio-economic factors such as residents' savings and income, government support, regional population quality, and natural factors such as altitude and elevation.

The types of interactions in the northeast region were all non-linearly enhanced, indicating that the influence of the two-factor interaction in the northeast region was significantly greater than the sum of the two factors alone. It is noteworthy that the average elevation (X1) factor is the most influential factor (q = 0.1853) when acting as a single factor, but its influence decreases when interacting with other factors. The single-factor effects of the number of students in primary and secondary schools (X10) and the average years of education of the population (X14) were not significant. However, the interaction between the two factors increased significantly and the q-value jumped to first place (q = 0.4378). This indicates that the combined effect of the level of communication services and the regional population quality is significant, that the improvement of communication services combined with the improvement of population quality can significantly enhance people's awareness of digital technology and their ability to use digital devices, and that the superimposed effect of the two can effectively promote digital rural development and influence the regional differences in DRDL.

6. Discussion

6.1. Response to Previous Studies

Through its study of the DRDLs in Chinese counties, this paper has found that public services in rural regions constitute an important factor affecting DRDL. The improvement of public service in rural areas will contribute greatly to the digitalization of rural areas, which echoes the viewpoints of Real (2014) and other scholars [30]. At the same time, the digital divide is one of the key factors affecting the development of the digital rural and urban–rural integration and plays an important role in promoting the sustainable development of the digital rural, which is also the focus of scholars such as Rooksby (2002), Fong (2009), and Philip (2017) [11,19,21]. However, what needs to be highlighted is that this paper, based on the previous studies, further advances and improves the regional differences and influence mechanisms of digital rural development at the theoretical level, which has not been covered in the previous studies, and that this will help improve the theoretical studies on digital rural development. In addition, this paper focuses the study of the digital rural on the geographical perspective, which makes up for the lack of attention paid by previous studies to the regional differences in digital rural development under the geographical perspective, and at the same time identifies the influencing factors of the regional differences between the DRDL in different regions, thus providing references and guidance on the strategies and directions of the development of the digital rural in different regions, which have been lacking in the studies conducted by other disciplines.

6.2. Revelations and Recommendations

Nowadays, the organic combination and deep integration of digital economy strategy and rural revitalization strategy has provided an emerging dynamic energy for high-quality rural development, promoting the continuous optimization and enhancement of the functions of rural regional systems and bridging the digital divides both between urban and rural areas as well as between regions. On the one hand, the digital economy has penetrated into all aspects of socio-economic development and urban–rural integration, and the deep integration of digital economy and rural resources is an important way to realize rural revitalization, which has become an important force to promote the integration of rural spatial structure, industrial transformation and upgrading, governance innovation and optimization, and cultural inheritance and activation. On the other hand, promoting digital rural construction is an effective way to narrow the digital divide between urban and rural areas. The digital development of the rural regions can greatly improve rural informationization and intelligence level, accelerate the flow of elements between urban and rural areas, and promote the modernization process of the rural regions and the integration process involving urban and rural areas. At the same time, on the national level, promoting digital rural construction and enhancing DRDL is also an important way to narrow the imbalance of regional development in the rural regions and an effective path to realize rural development in the central and western regions to "catch up" with the rural development in the eastern regions. For example, the National Big Data Center established in Guizhou Province, through the empowerment of big data and digital technology, has greatly promoted the digital transformation and upgrading of rural governance in Guizhou Province, and is forming the "Guizhou experience" of rural digital governance in China, which has become a typical representative of rural development in the western region to catch up with the eastern region and achieve "overtaking" [77].

In addition, based on the interaction detection of the factors influencing the spatial differentiation of DRDL in Chinese counties, this paper has found that digital rural development in four major regions in China is not a single factor acting independently, but a factor, interacting with other factors, that can play a "1 + 1 > 2" superposition effect. Therefore, the results of this study can be used to further improve digital rural development in different regions by implementing different policy measures and human interventions to take advantage of their unique interactions. Specifically, for the western region, the factors of government support, professional and technical talent, and residents' savings and income show obvious two-factor enhancement effects when interacting with other factors. Therefore, in the western region, we should focus on increasing the government's investment in digital infrastructure in rural areas and providing technical support with corresponding professional and technical talents, and, more importantly, increasing residents' income levels to achieve the "catch-up" of digital rural development in the western region and narrow the digital divide of rural development between the eastern and western regions. For the central region, the two factors of professional and technical talents and regional population quality interact significantly with other factors, showing obvious superposition effects, and so, we should focus on improving the cultivation of digital technical talent, vigorously developing basic education, and improving the level of population quality. For the northeast region, the interactions of human capital reserve and communication service level with the remaining factors are significant. However, due to the severe outflow of population in the northeast region in recent years, its population has been shrinking extensively [78]. Based on this, while increasing the supply of communication services, a population development strategy should be formulated scientifically to curb the continuous shrinkage of population in the northeast region so as to ensure a sufficient population to support the construction and development of the digital rural. For the eastern region, the industrial and economic base is the most prominent factor in its interaction; thus, steady economic growth should be maintained in the eastern region while increasing industrial investment to provide solid and stable material support for digital rural development.

7. Conclusions

The research in this paper will help to deepen the theoretical knowledge of China's digital rural development and its regional heterogeneity, clarify the regional pattern and geographical differences between the DRDLs in Chinese counties, and identify the geographical factors affecting the differences in DRDL so as to provide scientific references for digital rural construction in China. The main research conclusions are as follows:

1. The DRDL is an important representation of digital technology to promote rural development and transformation and has its unique spatial differentiation mechanism. Digital rural development can be analyzed from two elements and three dimensions, namely the natural and human elements and the three dimensions of environmental system, economic system, and social system. Among these, the environmental system plays a fundamental role in the process of digital village development, which is mainly reflected in the natural environmental conditions of the earth's surface such as in topography topographic relief, surface steepness, altitude difference, and the geographical location conditions in which the rural regions are located. The economic system plays a decisive role in digital rural development, which is mainly reflected in the overall level of economic development, industrial development foundation, agricultural modernization level, and service industry development level. The social system plays an important role in guaranteeing and supporting the sustainable and solid development of the digital rural, mainly in terms of policy guidance, social services, and individual residents.
2. The DRDL data for China's counties has significant spatial distribution, spatial correlation, and spatial clustering characteristics. In terms of spatial distribution, the DRDL shows a decreasing distribution trend from the coastal to inland regions, with the high-value area generally distributed in the area east of the Hu Line, but the distribution pattern of different sub-dimensions shows certain differences. In terms of regional differences, the overall regional differences between the DRDLs are relatively small while the regional differences in each sub-dimension are relatively large, and the contribution rate of intra-regional differences is larger than that of inter-regional differences. In terms of spatial correlation, compared with other sub-dimensions, the rural infrastructure digitalization dimension has a stronger spatial correlation. In terms of spatial clustering, the hotspot regions are primarily concentrated in the eastern region, and the coldspot regions are mainly concentrated in the western region and the northeastern region, but there are large differences in the hotspot and coldspot regions of different sub-dimensions.
3. The spatial variation of DRDL is closely related to geographical factors and is the result of the combined effect of several geographical factors. The factor detection results show that average surface elevation, surface elevation difference, government support, human resource reserve, and professional and technical talent are the main influencing factors of the spatial variation of DRDL at the national level. The dominant

factors vary within the four regions. Among these factors, average surface elevation, communication service level, and residents' saving incomes have stronger influence on DRDL within the four regions in general. The interaction detection results show that the driving force of the two-factor interaction is stronger than that of the single-factor action, indicating that the explanatory power of the interaction among the factors on the DRDL is always greater than that of single-factor action, further deepening the regional differences between DRDLs.

It should be noted that due to the limitations of research scale and data acquisition, this paper has only analyzed the DRDLs of Chinese counties in 2020—a choice that has had certain limitations in terms of time scale and spatial scale. The following two directions can be explored and extended in the future. First, one may expand the time scale of the study. Based on the availability of data, one may do a long-time series study of ten years, or even of twenty years, to explore the spatial and temporal evolution characteristics of DRDL and to analyze the reasons for changes. The second direction for future research is to refine the spatial scale of the study. In the future, we can further focus the research scale on the village scale, select typical villages to do case studies, and combine qualitative research methods to conduct qualitative analyses to further deepen and supplement this study.

Author Contributions: Conceptualization, T.L. and S.W.; methodology, T.L. and S.W.; software, X.L.; validation, X.L.; formal analysis, T.L.; investigation, T.L.; resources, S.W.; data curation T.L.; writing—original draft preparation, T.L.; writing—review and editing, P.C.; supervision, P.C.; project administration, X.K.; funding acquisition, X.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research is financially supported by the National Natural Science Foundation of China (Grant No. 42130510, 41771156 and 42271244).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the first author.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Exploring the Coupling Coordination and Key Factors between Urban–Rural Integrated Development and Land-Use Efficiency in the Yellow River Basin

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Abstract: Exploring the complex dynamic relationship between urban–rural integrated development and land-use efficiency can contribute to most efficient urban–rural land-use and the rational promotion of urban–rural integrated development. This study established an evaluation model of urban–rural integrated development, adopted the super-efficiency SBM model to measure land-use efficiency, and studied the evolution of the spatial–temporal patterns of urban–rural integrated development and land-use efficiency coupling in the Yellow River Basin. We also examined the factors affecting them with the help of the coupling coordination degree model, non-parametric kernel density estimation, and geographic probes. The results indicate the following: (1) Within the study period, the coupled coordination of urban–rural integrated development and land-use efficiency was similar to the spatial distribution characteristics of land-use efficiency, both showing a "high at both ends and low in the middle" trend. (2) The coupled coordination increased over time; however, a lagging land-use efficiency was a crucial impediment to improving the coupling coordination degree. (3) Carbon emissions, urbanization rate, and per capita GDP were key drivers. The results of this study can provide a reference for local governments in the Yellow River Basin and other similar areas to propose paths to optimize the allocation of urban and rural land-use.

Keywords: urban–rural relationship; urban–rural integrated development; land-use efficiency; coupling coordination relationship; geographic detector

Citation: Shen, C.; Shi, L.; Wu, X.; Ding, J.; Wen, Q. Exploring the Coupling Coordination and Key Factors between Urban–Rural Integrated Development and Land-Use Efficiency in the Yellow River Basin. *Land* **2023**, *12*, 1583. https://doi.org/10.3390/land12081583

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 21 July 2023
Revised: 7 August 2023
Accepted: 8 August 2023
Published: 11 August 2023

1. Introduction

In the rapid global industrialization and urbanization process, urban–rural polarization is evident in many countries around the world. It is accompanied by problems such as "urban diseases" and "hollowing out of the countryside" [1,2]. The orderly integration and balanced development of cities and villages is not only a cornerstone of social stability but it is also closely related to the realization of SDG 10 (reduce inequality within and among countries) and SDG 11 (make cities and human settlements inclusive, safe, resilient, and sustainable) [3,4]. For a long time, China's dual system with an urban–rural division has resulted in an imbalance between urban and rural development and the allocation of land elements, and this imbalance has become a key issue in China's new era of high-quality development [5,6]. To facilitate the bi-directional mobility of resources between urban and rural regions in China, the Chinese government has proposed establishing a robust institutional framework and policy structure for urban–rural integration [7]. The land is the physical carrier of the two settlement spaces, urban and rural [8]. However, under the current non-market mechanism of China's land transaction model, many land-use issues such as severe wastage of land resources and low land-use efficiency (LUE), have already seriously constrained urban–rural integrated (URI) development [9,10]. To protect China's existing land resources and alleviate the contradiction between land supply and demand, China has proposed the conservation and intensive use of land resources. At the same time, it has further pointed out that promoting a fundamental change in how land resources are used is necessary [11]. Along with introducing China's pilot comprehensive reform policy on the market-based allocation of land transactions, URI development and LUE have become more closely linked. On the one hand, urban–rural integration improves the efficiency of land resource allocation through the smooth circulation of land resources between urban and rural areas, which, in turn, promotes efficient land-use; on the other hand, the economic and intensive use of land improves the comprehensive efficiency of land-use, which can effectively alleviate the contradiction between population growth and exceedance of the carrying capacity of the land, accelerate urban–rural population mobility, and effectively promote URI development [12,13].

The urban–rural relationship is the most fundamental economic and social relationship, and most countries in the world have been exploring the structure of the urban–urban relationship in urbanization as appropriate for their national conditions [2,14,15]. Research on urban–rural relationships has mainly resulted in the urban–rural dual structure theory represented by the Ranis–Fei model, the urban–rural coordination theory represented by the core–periphery model, and the urban–rural integration theory described by the Marxist theory of urban–rural relationships [16–18]. China is currently in a critical period of transforming the urban–rural ties, and the "urban–rural integrated development" plan proposed by the Chinese government in 2017 is an important initiative to solve a series of problems such as the division of urban and rural areas, the division of land, and the separation of people and land, and to create a new type of urban–rural relationship [19,20]. Currently, the research on urban–rural integration focuses on the theoretical connotation, the construction of an indicator system, the change in spatial and temporal patterns, and the influencing factors [21,22]. Jiang [21] constructed a multi-level urban–rural integration evaluation index system at the population, land, and economic levels. Based on the quality of life perspective, Ma [17] created an assessment system for urban–rural integration from economic, social, and environmental perspectives. Silva [23], using an integrated research methodology approach based on ecological and socio-economic factors in the Paraíba Valley (Brazil), found that rural–urban coupling enhances synergies between rural and urban areas and can promote the sustainability of arable land and improve ecological services. The study found that long-standing urban–rural development imbalances have widened the gap [16–18,24]. Sánchez-Zamora [25] studied the region of Andalusia (Spain) and found that the financial crisis has severely exacerbated regional and rural–urban inequalities, but that employment and entrepreneurship, economic diversification, and technological upgrading have helped to raise the level of rural development, thereby reducing the rural–urban gap. Furthermore, precise poverty alleviation, green growth, and the digital economy positively affected urban–rural integration [26–28].

Improving LUE can effectively promote integrated urban–rural development and is significant for achieving the global Sustainable Development Goals (SDGs) [3,29,30]. Much research has focused on this, mainly resulting in theories of the urban spatial structure, represented by concentric circles, sectors, and multiple nuclei, with the intelligent growth theory emphasizing the efficient use of existing land, and the theory of compact cities [31,32]. The research has mainly focused on defining the connotations of LUE, constructing an indicator system, analyzing the spatial and temporal patterns, and exploring the paths for improvement [33,34]. Some scholars have used the DEA model, super-efficiency SBM model, panel data regression model, and various hybrid models to measure LUE levels. Wang [35] constructed an LUE evaluation index system by taking industrial "three waste" emissions as "non-desired outputs" and found that urban LUE has different impacts on the optimization of industrial structure in various provinces and cities in China. Haller [36] studied urban–rural land change in the Central Peruvian Andes and found that urban expansion led to a reduction in arable land, which, in turn, lowered the incomes of farmers. Masini [37] analyzed the relationship between economic growth and LUE in 417 cities in 17 countries in Europe, and found that the higher the level of the economy, the more efficient the land-use. Song [3] studied LUE by constructing a ratio of land-consumption rate to population growth rates and found a coherent relationship between LUE and the Sustainable Development Goals (SDGs). By building a Tobit regression model, Yu [38] found that the economic level, economic structure, and government regulation positively impacted LUE.

At present, the research on urban–rural relationships and land-use focuses more on unilateral research URI development or LUE. The analysis of the relationship between the two focuses on URI development and land-use transformation, urban–rural spatial evolution and land-use changes, urbanization development and land-use transformation, and rural revitalization and arable land utilization [1,13,39,40]. There are fewer studies on the relationship between URI development and LUE. Niu [12] found that optimizing land-use, including improving LUE level, can restructure the urban–rural socio-economic pattern and promote integrated urban–rural development. By analyzing land-use in Spain, Serra [41] found that the rationalization of land-use can improve land-use efficiency, and thus reconstruct urban–rural relations. Taking Israel as the object of his study, Bittner [42] combined the intensive use of land with the spatial evolution of urban and rural spaces. He found that specialized and intensive land-use improves the efficiency of the land, and ultimately, the urban space interacts with the rural space in a new way. Yin [43] also discovered that LUE can be effectively enhanced through land consolidation and land-use transformation, promoting urbanization, rural revitalization, sustainable regional development, and integrated urban–rural development. Chen [13] used kernel density estimation, spatial autocorrelation analysis, and fixed-effects to study 372 samples from 31 province-level administrative regions in China. The study revealed that, under ideal conditions, land-use transformation can be achieved by enhancing the value of land elements and LUE, ultimately promoting integrated urban–rural development. Wu [44] found that land financing can effectively enhance integrated urban–rural development and thus improve the LUE level. Song [45] conducted a study using panel data from 30 province-level administrative regions in China, spanning the period from 2010 to 2019. The findings indicated that the overall degree of coupled coordination between URI development and LUE was not high, but it increased year by year. The existing studies have provided theoretical and empirical support for the association, interaction, and enhancement path between urban–rural relationships and land-use. However, the existing studies on URI development and LUE have provided few empirical studies on the dynamic relationship between the two. Moreover, there are fewer analyses on the factors affecting them.

The Yellow River Basin (YRB) is a substantial food production base and a significant supply base for energy resources in China. In 2019, the Chinese government pointed out the essential position of the YRB in China's economic and social development and ecological urban–rural integration. However, the YRB faces many problems, such as tightening constraints on land resources, the prominent imbalance between urban and rural development, and poor-quality of economic growth. In-depth exploration of the dynamic relationship between URI development and LUE in the YRB that can reveal the evolution of the spatial and temporal pattern of the coupled and coordinated development of these two aspects and the factors affecting them can provide a reference for optimizing the allocation of urban and rural land-use; at the same time, this study has significant reference value for promoting the cyclic flow of urban and rural resource elements, improving the efficiency of urban construction and arable land resources, and advancing the integrated development of urban and rural areas.

In this context, the study established an evaluation system of URI development indicators in the five dimensions of people, land, economy, society, and ecology. It was used to calculate the urban–rural integration level of 61 prefectures in the YRB using the linear weighting method. At the same time, the super-efficiency SBM model was used to measure the use efficiency of urban construction land and rural arable land, and the integrated LUE was obtained through weighting. In addition, the coupled coordination degree (CCD) model and non-parametric kernel density estimation method were used to explore the coordinated relationship and dynamic evolution of URI development and LUE in the YRB. Finally, the influencing factors of the coordinated development level of URI and LUE in the YRB were measured with the help of a geographic detector. This article aims to provide empirical and policy references for improving URI development and land resource utilization efficiency in regions similar to the YRB.

2. Study Area and Indicator System

2.1. Study Area and Data Sources

As one of China's most important economic growth areas, food production bases, and ecological barriers, the YRB faces multiple challenges including limited land resources, unbalanced regional development, and vulnerable environments. The Yellow River flows through 71 cities (including states and leagues) in 9 provinces, and the overall topography is characterized as high in the west and low in the east [46]. For this study, the YRB includes 61 geospatial units due to the missing data of some prefecture-level cities (Figure 1). The YRB was divided into three regions following the principle of "taking the natural Yellow River Basin as the basis and maintaining the integrity of the administrative units at the regional level as far as possible": the upstream region (including Qinghai, Gansu, and Ningxia, with a total of 14 cities), the middle reaches of the Basin (including Shanxi, Shaanxi, and Inner Mongolia, with a total of 26 cities), and the lower reaches of the Basin (including Henan and Shandong, with a total of 21 cities) [11,47,48].

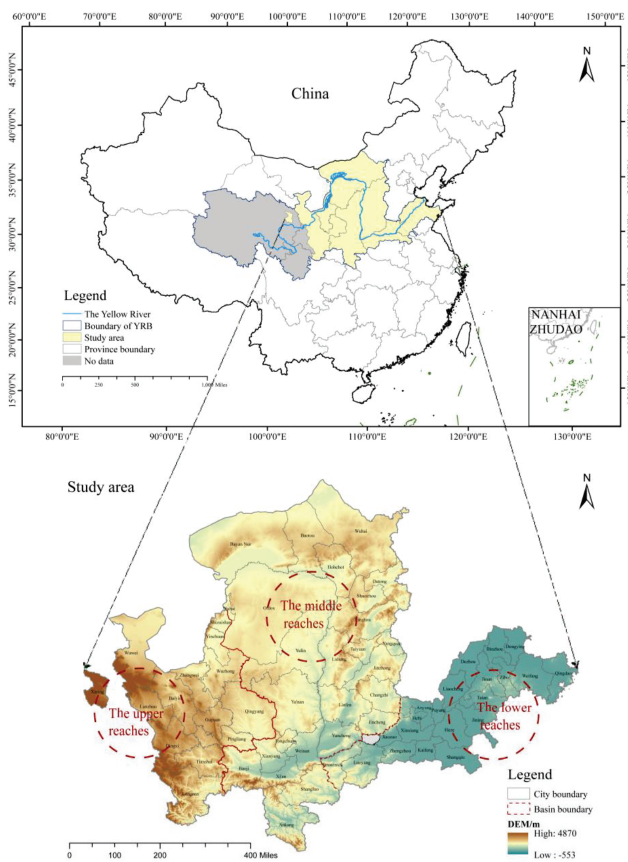

Figure 1. The spatial scope of the Yellow River Basin (YRB) in China.

In this study, there were two sources of data used in the paper (Table 1). The statistical data (including economic data, social data, land data, and ecological data) were from the official statistical website, and some of the missing data were filled in by interpolation. The raster data (climatic environmental data) were from the Institute of Resource and Environmental Science and the Data Center of the Chinese Academy of Sciences, and the raster data were all processed by ArcGIS. For all variables expressed in monetary terms, we deflated them using the Consumer Price Index (CPI) for each city with a base period of 1978. This study focused on the period from 2003 to 2021. Since Laiwu in Shandong Province was merged into Jinan in January 2019, and considering the consistency for higher data quality, this study also merged Laiwu into Jinan for calculations.

Table 1. Description of data types and sources.

Type	Date Presentation
Economic data	China Urban and Rural Construction Statistical Yearbook (2003–2021); Provincial Statistical Yearbook (2003–2021); EPSDATE (https://www.epsnet.com.cn), accessed on 30 April 2023.
Social data	Provincial Statistical Yearbook (2003–2021); EPSDATE (https://www.epsnet.com.cn), accessed on 30 April 2023.
Land data	China Urban Construction Statistical Yearbook (2003–2021); EPSDATE (https://www.epsnet.com.cn), accessed on 30 April 2023.
Ecological data	Carbon Emissions Accounts and Datasets, CEADs (https://www.ceads.net.cn); Multi-resolution Emission Inventory for China, MEIC (http://meicmodel.org.cn/); EPSDATE (https://www.epsnet.com.cn); accessed on 30 April 2023.
Climatic environmental data	Institute of Resource and Environmental Science and the Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), the resolution of elevation is 30 m, and the resolution of Precipitation is 1 km, accessed on 30 April 2023.

2.2. Design of the Evaluation Indicator System

The URI development is a process, a state, and a goal, determined by a combination of population, spatial, economic, social, and ecological factors. Thus, this study constructed a multidimensional evaluation index system for URI development from these five dimensions [16,27]. The LUE is determined by a combination of natural, economic, and social factors, and this study used the per capita input–output efficiency as the LUE, and the input and output indicators were selected with full consideration of the land's economic, social, and environmental benefits [49,50]. To reflect the overall land resource utilization efficiency, this study selected the input–output indicators of utilization efficiency of urban construction land and rural arable land as the input–output indicators, respectively [20,50].

Combined with the research on the structure of an indicator system for URI development and LUE in existing studies and considering the availability and reliability of the data, indicator systems for evaluating URI development (Table 2) and the LUE (Table 3) were developed.

Table 2. Indicator system for urban–rural integrated (URI) development.

Index Dimensions	Index & Properties	Basic Index	Calculation or Description of the Index & Unit	Interpretation of the Index
	X1 (+)	Population mobility rate	Urban population/total population (%)	Population mobility can positively impact the development of the rural economy, creating a beneficial urban–rural flow of people.

Table 2. *Cont.*

Index Dimensions	Index & Properties	Basic Index	Calculation or Description of the Index & Unit	Interpretation of the Index
People	X2 (−)	Coefficient of contrast between urban and rural employment	Employment of urban households/employment of rural households	Reducing the gap between the incomes and consumption of urban–rural residents, particularly in food, culture, education, recreation, and daily electricity bills, will promote balanced incomes and consumption between urban–rural households.
	X3 (−)	The ratio of per capita annual disposable income of urban to rural residents	Per capita annual disposable income of urban households/per capita annual net income of rural households	
	X4 (−)	The ratio of per capita income of urban to rural residents	Per capita consumption of urban households/per capita consumption of rural households	
	X5 (−)	Comparison coefficient of culture, education, and entertainment between urban and rural areas	Urban residents' household expenditure on culture, education, and entertainment/rural residents' household expenditure on culture, education, and entertainment	
	X6 (+)	The ratio of Engel's coefficients of urban to rural households	Engel's coefficient of urban households/Engel's coefficient of rural households	
	X7 (+)	The ratio of electricity consumption of urban to rural residents	Urban domestic electricity consumption/rural domestic consumer electricity consumption	
Land	X8 (+)	The ratio of urban to rural residential space	Urban residential space/rural residential space	Reflect the allocation and utilization of land resources between urban and rural areas
	X9 (+)	Urban spatial expansion	Built-up area/cropland area	
	X10 (+)	Land urbanization level	Built-up area/land area (%)	
	X11 (+)	Passenger turnover	Total passenger transportation (ten thousand people)	Reflect urban–rural accessibility, the greater the accessibility, the better the integration of urban–rural land.
	X12 (+)	Per capita postal and telecommunications services	Total postal and telecommunications services/total population (CNY/person)	
	X13 (+)	Regional economic operation condition	GDP per capita (CNY/person)	Under normal circumstances, regions with higher levels of economic development are more able to promote industry to feedback to agriculture and promote urban–rural integration development.

Table 2. *Cont.*

Index Dimensions	Index & Properties	Basic Index	Calculation or Description of the Index & Unit	Interpretation of the Index
Economy	X14 (+)	Agriculture finance	Public expenditure on agriculture, forestry and water resource projects/financial expenditure (%)	Reflects the central and local financial input to rural areas, the greater the input, the more conducive the area is to the URI development.
	X15 (−)	Ratio of fixed asset investment in urban–rural areas	Rural fixed asset investment/urban fixed asset investment	Reflects the strength of investments in fixed assets in urban–rural regions, especially in infrastructure improvement and optimization of livelihood projects.
	X16 (+)	Binary comparison coefficient	(Output value of primary industry/employees in the primary industry)/(Output value of secondary and tertiary industries/employees in secondary and tertiary industries)	Reflects the difference in economic structure between the traditional agricultural sector and the modern industrial and service sectors; the smaller the industrial gap between urban and rural areas, the more conducive the areas are to promoting URI.
	X17 (+)	Agricultural mechanization level	Total power of agricultural machinery/arable land area (Kilowatt/hectares)	Agricultural modernization has a positive impact on rural economic development and URI.
Society	X18 (+)	Internet penetration rate	Internet access in urban–rural areas/total number of urban–rural households (%)	Reflect urban–rural residents' access to public services.
	X19 (−)	The ratio of the level of medical protection for urban to rural residents	Hospital beds per 1000 population in urban healthcare institutions/hospital beds per 1000 population in rural healthcare institutions	
Ecology	X20 (+)	Harmless treatment rate of domestic waste	%	Reflect the level of the living environment for urban–rural residents, harmless treatment of domestic rubbish and sewage treatment can improve the living conditions of residents, and optimize the urban–rural ecological environment which can improve the URI.
	X21 (+)	Wastewater treatment	%	
	X22 (+)	Industrial sulfur dioxide emissions	Metric tons	Industrial pollution mainly affects the urban environment.
	X23 (+)	Industrial wastewater discharge	Metric tons	
	X24 (+)	Industrial solid waste emissions	Metric tons	
	X25 (+)	Ratio of investment in environmental pollution treatment	Investment in environmental pollution control/total output value (%)	Investment in pollution control represents the level of environmental pollution control, and a high level of control benefits URI.

Table 3. Input–output variables for land-use efficiency (LUE).

Goal Layer		Criterion Layer	Urban Indicators	Rural Indicators
Inputs		Land	Urban built-up area	Arable land area
		Labor force	Construction employees per unit area of building	Labor force per unit area of cultivated land
		Energy	Urban residential space	Rural residential space
			Capital investment per unit area of building	Agricultural machinery per unit area of cultivated land
Outputs	Expected outputs	Social benefit	Per capita annual disposable income of urban households	Per capita annual net income of rural households
		Economic benefit	The gross output value of the construction industry per unit area of building	Agricultural output per unit of cultivated area
	Non-expected Outputs	Emission reduction	Emissions of the "three wastes" (wastewater, waste gas, and industrial solid waste)	—

3. Methods

3.1. The Linear Weighting Method for Measuring the Level of Integrated Urban–Rural Development

The entropy weight method is one of the methods in the objective assignment method, which can decide the weight of indicators through the size of the information utility value of the indicators. In the study, the range method was used to process the positive index and negative index due to the differences in the dimensions and magnitudes of the indicators, respectively [1,16].

$$\begin{cases} {z_{ij}}^{+} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} + 0.0001 \\ {z_{ij}}^{-} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} + 0.0001 \end{cases} \tag{1}$$

In Equation (1), x_{ij} refers to the initial matrix, ${z_{ij}}^{+}$, ${z_{ij}}^{-}$ represent the normalized matrices for positive and negative indicators, respectively, and $\max(x_{ij})$ and $\min(x_{ij})$ reflect the maximum and minimum values of initial data, respectively.

The indicator j proportion is calculated as shown as Equation (2), and calculation the information entropy e_j by using the Equation (3); then, the weights w_{ij} for indicator j is calculated with Equation (4):

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \tag{2}$$

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{3}$$

$$w_{ij} = \frac{1 - e_j}{\sum_{j=1}^{m} 1 - e_j} \tag{4}$$

where p_{ij} refers to the data proportion, e_j refers to the information entropy, n is the number of the index i, m is the number of the indicator j, and w_{ij} is the weight matrix derived from the entropy weight method.

Finally, the study used the comprehensive score U to measure the URI level; the comprehensive score U is measured by the linear weighting method, as shown in Equation (5):

$$U = w_{ij} \times z_{ij} \tag{5}$$

3.2. The Super-Efficiency SBM Model for Measuring Land-Use Efficiency (LUE)

The LUE is the extent to which the value of inputs such as resources, labour, and capital is realized on the land. The paper measured the efficiency of land-use, using the super-efficiency SBM model containing the non-expected outputs is as follows [29,51]:

$$\rho = \min \frac{1 - \frac{1}{N}\sum\limits_{n=1}^{N} S_n^x / x'_{k'n}}{1 + \frac{1}{M+I}\left(\sum\limits_{m=1}^{M} S_m^y / y_{k'm}^t + \sum\limits_{i=1}^{I} S_i^b / b_{k'i}^t\right)}$$
$$\left\{\begin{array}{c} \sum\limits_{t=1}^{T}\sum\limits_{k=1}^{K} z_k^t x_{kn}^t + S_m^y = x_{k'n}^t, n = 1, \cdots, N \\ \sum\limits_{t=1}^{T}\sum\limits_{k=1}^{K} z_k^t y_{km}^t - S_m^y = y_{k'm}^t, m = 1, \cdots, M \\ \sum\limits_{t=1}^{T}\sum\limits_{k=1}^{K} z_k^t b_{ki}^t + S_i^b = b_{k'i}^t, i = 1, \cdots, N \\ z_k^t \geq 0, S_n^x \geq 0, S_m^y \geq 0, S_i^b \geq 0, k = 1, \cdots, K \end{array}\right\} \tag{6}$$

where ρ is the evaluation value of LUE; N, M, I refers to the number of corresponding input, expected factors, and non-expected output factors respectively; n, m, i are the corresponding indicator types; x, y, b are the types of slack variables; and S_n^x, S_m^y, S_i^b represent the slack vectors of the corresponding input, expected factors, and non-expected factors, respectively.

3.3. The Coupled Coordination Degree (CCD) Model for Evaluating the Coupling Coordination Level of Urban–Rural Integrated (URI) Development and LUE

The CCD model is widely used to study the interaction between multiple systems. In the study, the CCD model was used to evaluate the coupling coordination levels of the URI development and LUE, and the calculation formula is as follows [49,50]:

$$\left\{\begin{array}{l} C = \sqrt{(U \times \rho)\Big|((U + \rho)|2)^2} \\ T = \alpha \times U + \beta \times \rho \\ D = \sqrt{C \times T} \end{array}\right. \tag{7}$$

where C refer to the coupling levels, while U_1 and U_2 represent the level of URI development and LUE, respectively. T is the comprehensive evaluation value, and D is the coupling coordination levels. Generally, the subsystems are considered to be of equal importance and, therefore, $\alpha = \beta = 0.5$. Considering the current circumstances and other experts' research, the coupling coordination degree has been classified into six stages in this study (Table 4). Furthermore, the synchronous development model was implemented to separate the synchronous relationship between URI development and LUE and divided it into lagging URI $(H < -0.1)$, synchronous development $(|H| \leq 0.1)$, and lagging LUE $(H > 0.1)$, where $H = U_1 - U_2$ [52,53].

3.4. The Non-Parametric Kernel Density Estimation to Reflecting the Temporal Pattern of CCD

The kernel density estimation is a useful tool for analyzing changes in distributional dynamics, polarization trends, distributional extensibility of the coordinated development of urban and rural areas, and LUE in the YRB, etc. This article utilized a non-parametric kernel density estimation method, which is expressed as follows [21,50]:

$$f(q) = \frac{1}{mh}\sum\nolimits_{j=1}^{m} K\left(\frac{q_i - q}{h}\right) \tag{8}$$

where $f(q)$ is the kernel density function, q_i is the observation, q is the mean, h is the bandwidth, and K is the kernel function, and this study uses the Gaussian kernel function.

Table 4. Classification of the coupled coordination degree (CCD) level.

CCD Level	Coupling Coordination Stages	Coupled Coordination Features
$0.3 \leq D < 0.4$	Moderate disorder	Lagging URI Synchronous development Lagging LUE
$0.4 \leq D < 0.5$	Mild disorder	Lagging URI Synchronous development Lagging LUE
$0.5 \leq D < 0.6$	General coordination	Lagging URI Synchronous development Lagging LUE
$0.6 \leq D < 0.7$	Moderate coordination	Lagging URI Synchronous development Lagging LUE
$0.7 \leq D < 0.8$	Good coordination	Lagging URI Synchronous development Lagging LUE
$0.8 \leq D \leq 0.9$	Good quality coordination	Lagging URI Synchronous development Lagging LUE

3.5. The Geographic Detector for Identifying Key Factors

This study used the geographic model to investigate the factors that affect the coordination degree between URI level and LUE in the YRB. The geographic model has the advantages of a minor sample size limitation and is good at dealing with type volume. Furthermore, the article employed the detector's factor detection and interaction detection to uncover how various drivers and their interactions impact the coupling coordination degree. The specific announcement is as follows (Equation (9)) [1,54]:

$$q = 1 - \frac{1}{n\sigma^2} \sum_{h=1}^{L} n_h \sigma_h^2 \tag{9}$$

where L represents the variable stratification; n and n_h are the number of samples for the whole area and the layer h, respectively; and σ^2 and σ_h^2 are the sample variances of the entire area and the layer h, respectively. In particular, q is the degree of explanation of the detected factor, with a value range between 0 and 1, and q represents the degree of explanation for the detected factor.

4. Analysis of Results

4.1. Evolution of Spatial and Temporal Patterns of Integrated Urban–Rural Development

Taking the stages of urban–rural relationship adjustment (2003–2006), urban–rural relationship coordination (2007–2011), promotion of urban–rural unity (2012–2017), and the new stage of integrated development (2017-present) as a reference, the ArcGIS 10.2 software was used to determine the URI level in the YRB in 2003, 2007, 2012, 2018, and 2021 (Figure 2) [55]. During the study period, the spatial difference in URI development in the YRB was not apparent, with an average value of 0.379 for upstream prefectures, 0.408 for midstream prefectures, and 0.403 for downstream areas. There were 31 areas with higher than average values, with two regions located in the upstream areas, accounting for 14.29% of the upstream areas; 18 areas in the middle region, accounting for 65.38% of the midstream areas; and 11 downstream regions, accounting for 57.14% of the downstream areas. From the point of view of spatial distribution, from 2003 to 2021, the areas with higher levels of URI development in the YRB were mainly distributed in the following geographical areas: first, in a part of the middle reaches of the YRB consisting of the Baotou-Bayannur-Wuhai-Erdos-Taiyuan-Yuncheng area, which is the main coal resource-rich area, and second, in the lower reaches of the YRB, in the Dongying-Zibo-Weifang city cluster of the Shandong Peninsula.

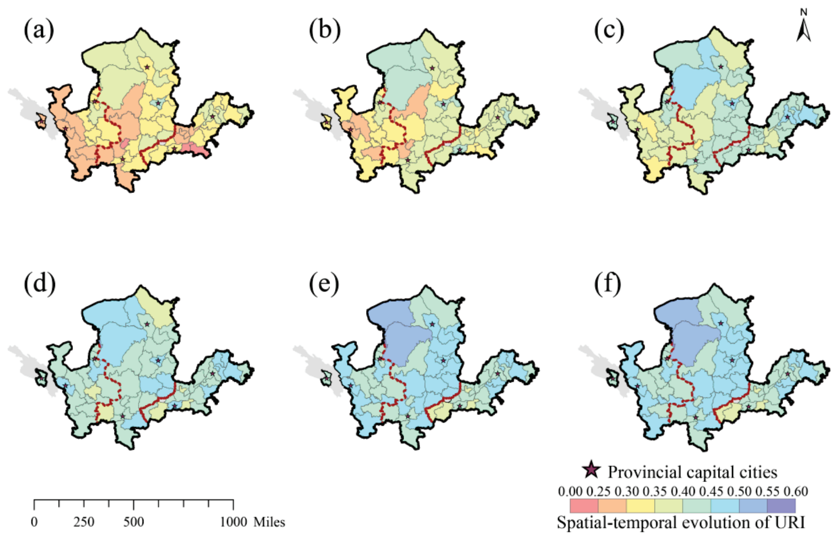

Figure 2. Spatial differentiation of the urban–rural integrated (URI) development. (**a**) The URI level in 2003; (**b**) the URI level in 2007; (**c**) the URI level in 2012; (**d**) the URI level in 2018; (**e**) the URI level in 2021; and (**f**) the average URI level.

From the time series evolution (Figure 3), the average value of the URI level in the YRB increased from 0.324 in 2003 to 0.446 in 2021, with an average annual growth rate of 1.91%; the highest annual growth rate was 4.45% in 2010, and the growth rate slowed down significantly in 2016 and 2021. Overall, the standard deviation of the URI level in the YRB decreased from 0.041 in 2003 to 0.032 in 2021, and the regional imbalance in the URI level improved. During the study period, the standard deviation of integrated development in the upstream areas of the YRB was flat, while that in the midstream areas decreased steadily, and in the downstream regions, it initially decreased and then increased. In summary, the mean of the URI levels in the YRB's upper, middle, and lower reaches all improved, and the uneven distribution in URI levels in the midstream areas was alleviated. However, the regional differences in the URI levels in the upstream and downstream areas still needed more attention.

4.2. Evolution of Spatial and Temporal Patterns of LUE

Regarding spatial patterns (Figure 4), there were apparent spatial differences in LUE in the YRB. During the study period, the average values of the upstream, middle, and downstream prefectures were 0.451, 0.508, and 0.301, respectively. In total, 29 areas had LUE values higher than the average, with 6 in the upper reaches, accounting for 42.86% of the upstream prefecture-level cities; 17 were in the midstream areas, accounting for 65.38% of the middle reaches; and 6 were in the downstream areas, accounting for 28.57% of the downstream areas. During the study period, the prefecture-level city with the highest LUE in the YRB was Guyuan City in Ningxia, with an LUE of 1.068 in 2021 and an average annual increase of 7.33%. In terms of spatial distribution, during the period of 2003–2021, the areas with a higher LUE value in the YRB were mainly concentrated in the following regions: in part of the midstream areas of the YRB, in the Guyuan-Qingyang-Tongchuan-Longnan-Xianyang-Xi'an area, the Great Guanzhong City Cluster, and Bayannur-Wuhai-Ordos-Hohhot-Yulin-Yanan area, in which are the resource-rich areas; the second is part of the downstream areas of the YRB, the Shandong Peninsula City Cluster, which is dominated by Jining and Jinan.

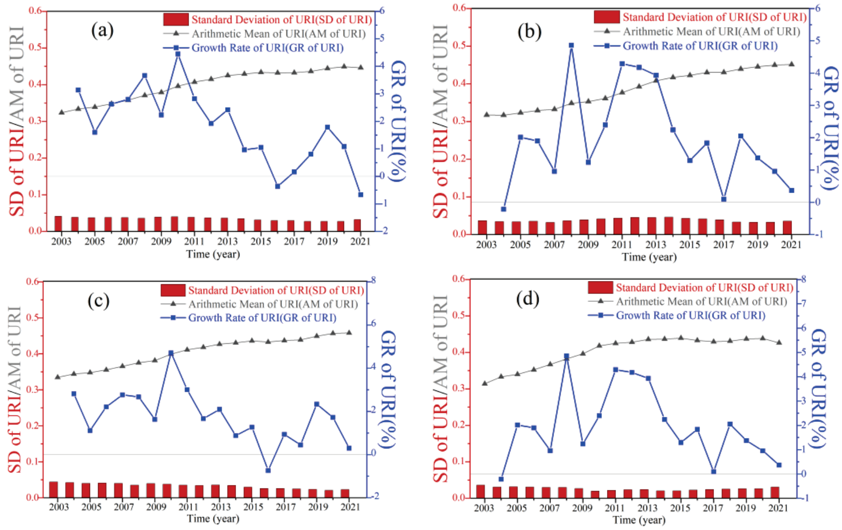

Figure 3. Temporal evolution of the URI development from 2003 to 2021. (**a**) The YRB; (**b**) the upstream areas; (**c**) the midstream areas; and (**d**) the downstream areas.

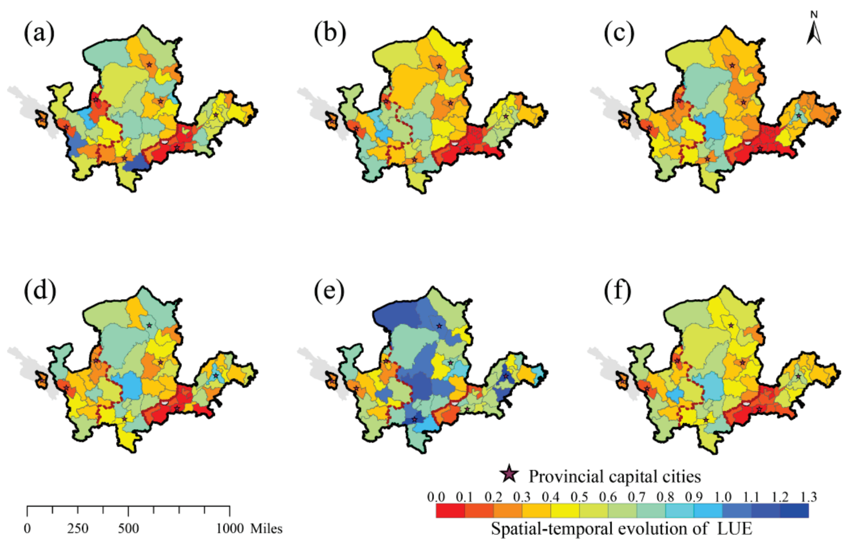

Figure 4. Spatial differentiation of the land-use efficiency (LUE). (**a**) The LUE in 2003; (**b**) the LUE in 2007; (**c**) the LUE in 2012; (**d**) the LUE in 2018; (**e**) the LUE in 2021; and (**f**) the average LUE level.

In terms of the time series evolution (Figure 5), the average value of LUE of prefecture-level cities in the YRB increased from 0.456 in 2003 to 0.677 in 2021, with an average annual growth rate of 2.10%, and the highest annual growth rate was 23.41% in 2021. Overall, the standard deviation of LUE in the YRB increased slightly from 0.250 in 2003 to 0.285 in 2021, and the imbalance in LUE among prefecture-level cities had yet to be effectively alleviated. During the study period, the standard deviation of LUE in the upstream, midstream, and downstream areas of the YRB decreased slightly, remained flat, and increased with a fluctuation, respectively. During the study period, the LUE of the upper, middle, and lower reaches of the YRB had improved, and the imbalance in LUE in the upstream areas had been mitigated. However, the regional differences in LUE in the midstream and downstream areas still needed more attention.

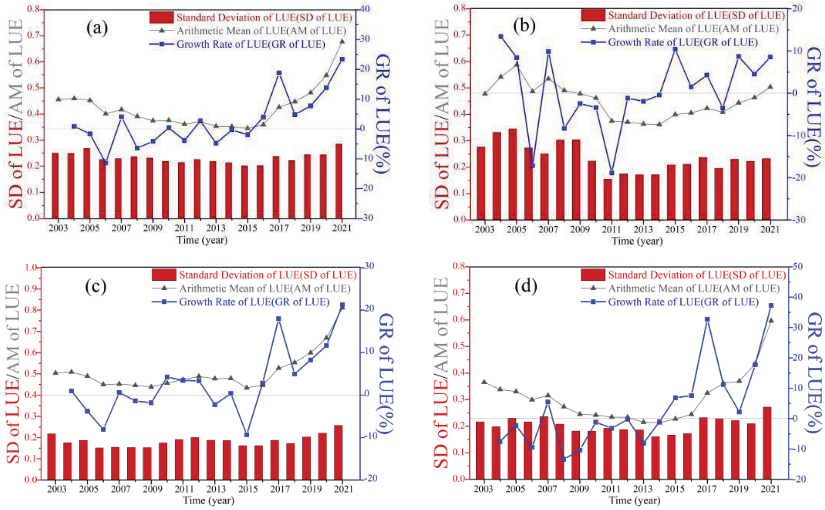

Figure 5. Temporal evolution of the LUE from 2003 to 2021. (**a**) The YRB; (**b**) the upstream areas; (**c**) the midstream areas; and (**d**) the downstream areas.

4.3. Evolution of Spatial and Temporal Patterns of Coupled Coordination

In terms of a spatial pattern (Figure 6), there were apparent spatial differences in the level of coupled coordination between URI development and LUE; the mean value of upstream, middle-reach, and downstream prefecture-level cities was 0.623, 0.662, and 0.552, respectively. During the study period, the prefecture-level city with the highest level of coupled coordination in the YRB was Wuhai City in Inner Mongolia, with a CCD level of 0.881 in 2021. From the viewpoint of spatial distribution, from 2003 to 2021, the areas with higher coupling coordination degrees were mainly concentrated in the following regions: first, in the midstream areas of the YRB, in the Wuhai-Erdos-Hohhot-Suozhou-Xinzhou-Yulin-Yanan area, which is the primary energy-resource-rich area of the Loess Plateau; and second, in the downstream regions of the YRB, in the Jinan-Dezhou-Jining central urban agglomeration of Shandong Peninsula. Jinan, Hohhot, and Xi'an had better-coordinated development among the provincial capital cities.

From the perspective of the time series evolution (Figure 7), the kernel density curve of coupling coordination degree in the YRB changed significantly. The kernel density curve peak moved to the right and changed from a double peak to a single peak. That is, the overall CCD fluctuated upward, and the bipolar differences gradually narrowed, which is a characteristic of dynamic convergence. At the same time, the main obstacle to improving the CCD in the YRB was the lagging LUE (Figure 8). In the upstream areas, the wave peak of the nuclear density curve moved to the left and then to the right. The peak value increased, decreased, and then increased again, which means that the CCD in the upstream areas showed a fluctuating upward trend. The regional imbalance still needs continuous attention, and the LUE lag dominated the coupling coordination characteristics. The peak of the nuclear density curve in the middle reaches moved to the right, and the right trailing was shortened. The CCD in the midstream areas showed a rising trend, and the inter-regional imbalance was eased, with the LUE mainly lagging behind the coupling coordination features. The kernel density curve in the downstream area changed from a double peak to a single peak, and the height of the wave peak rose gradually, i.e., the polarization phenomenon had been effectively alleviated, the regional disparity had been steadily reduced, and the lagging of the urban–rural integration and development level dominated the coupling and coordination features. At the same time, the scope of the balanced development area had been expanded.

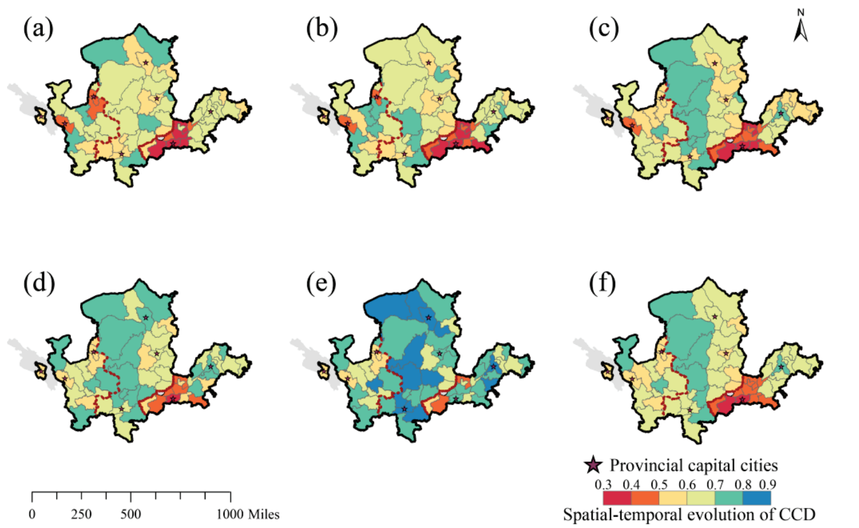

Figure 6. Spatial differentiation of coupling coordination degree (CCD) between URI development and LUE. (**a**) The CCD in 2003; (**b**) the CCD in 2007; (**c**) the CCD in 2012; (**d**) the CCD in 2018; (**e**) the CCD in 2021; and (**f**) the average CCD level.

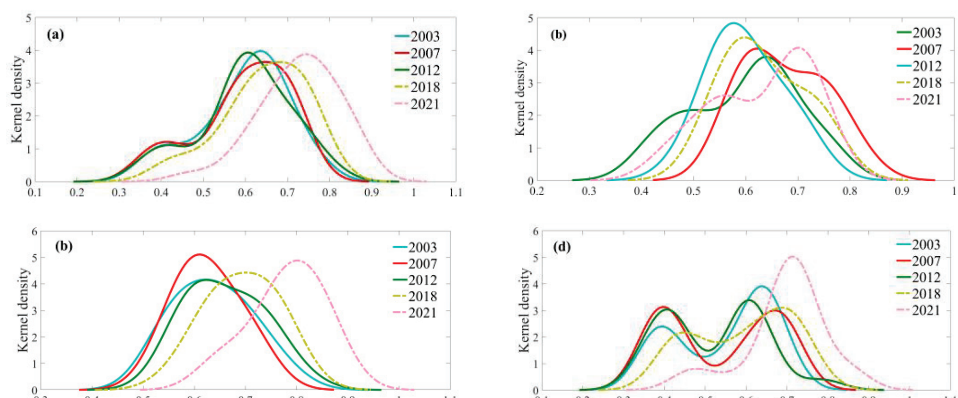

Figure 7. Temporal evolution of CCD between URI development and LUE. (**a**) The YRB; (**b**) the upstream areas; (**c**) the midstream areas; and (**d**) the downstream areas.

4.4. Analysis of Influencing Factors

A combination of factors affected the degree of coordinated development between the level of URI and LUE in the YRB. Combining the actual situation of the YRB with the research results of several experts and scholars, this study selected ten indicators to investigate from the four aspects of topography, economic level, natural environment, and industrial structure. These indicators were precipitation, elevation, slope, carbon emissions, GDP per capita, urbanization rate, population density, percentage of days with good air quality, per capita arable land area, and the proportion of non-agricultural industries [49,54]. Firstly, multiple linear regression analysis was used to screen the influencing factors, and it was found that six main indicators, with precipitation, altitude, carbon emissions, GDP per capita, urbanization rate, and population density passed the test at a significance level of 0.01 (Table 5).

Figure 8. Map of the distribution of the characteristics of CCD in the upstream, midstream, and downstream areas of the YRB.

Table 5. Statistical table of multiple regression results.

Variants	Regression Results	Standard Error	Values
Precipitation	21.222 ***	−7.111	1159
High-altitude	0.023 ***	−0.004	1159
Slope	0.001	−0.001	1159
Carbon emissions	−0.033 ***	−0.007	1159
GDP per capita	0.038 ***	−0.004	1159
Urbanization rate	−0.002 ***	0.000	1159
Population density	−0.049 ***	−0.003	1159
Percentage of days with good air quality	−0.000 *	0.000	1159
Per capita arable land area	0.001	−0.001	1159
The proportion of non-agricultural industries	0.005	−0.003	1159
Constant	0.791 ***	−0.077	

Note: * $p < 0.1$, *** $p < 0.01$.

This study selected the geodetector model to detect the six main driving factors affecting the coupled coordinated development level divergence between URI development and LUE in the YRB in different periods to determine the degree to which each indicator in different periods affects URI development and LUE. The six drivers were classified into five levels using the natural breakpoint method in ArcGIS. The geographic detector detects the factors affecting the spatial variability of the coupled coordinated development level. The contribution and interaction results of each driver are shown in Figures 9 and 10.

According to Figure 10, the q values of the six drivers were 0.131, 0.286, 0.229, 0.181, 0.179, and 0.104 (in this study, a degree of influence $q \geq 0.100$ indicates a highly significant factor). During the study period, the degree of influence of precipitation (X1) on the coordinated development between URI development and LUE in the YRB increased from 0.106 to 0.183, with a mean value of 0.131; the degree of influence of elevation (X2) remained unchanged, with a mean value of 0.286; the degree of impact of carbon emissions (X3) increased from 0.200 to 0.250; that of per capita GDP (X4) increased from 0.143 to 0.180; urbanization rate (X5) increased from 0.068 to 0.294; and population density (X6) decreased from 0.128 to 0.034.

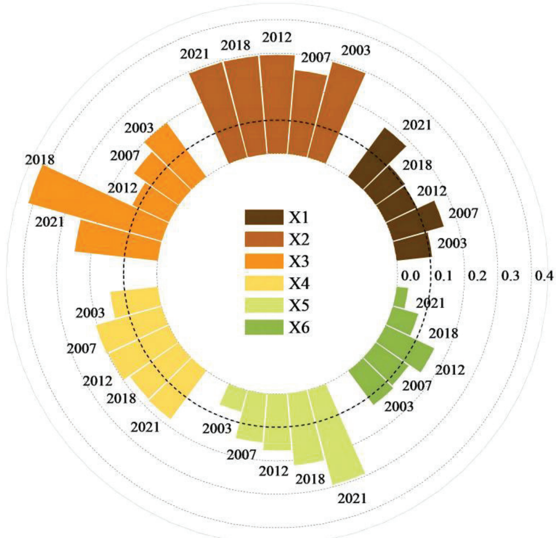

Figure 9. Temporal evolution of the degree of influence of CCD between URI and LUE in the YRB. Note: annual precipitation (X1), high-altitude (X2), carbon emissions (X3), per capita GDP (X4), urbanization rate (X5), and population density (X6).

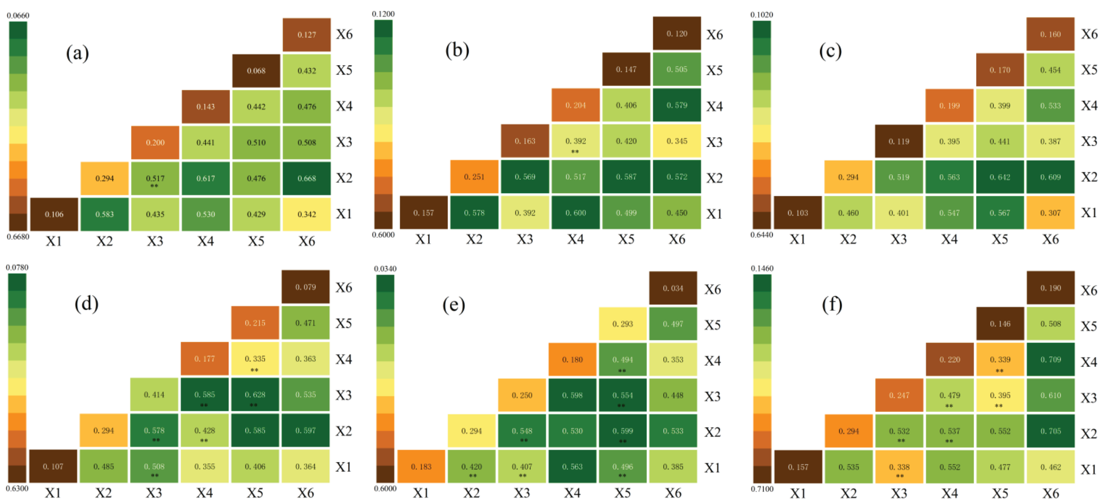

Figure 10. Heat map of factors influencing the CCD between URI and LUE in the YRB. The heat map in (**a**) 2003; (**b**) 2007; (**c**) 2012; (**d**) 2018; (**e**) 2021 (**f**) average level. Note: the heat map with ** represents bi-factor enhancement, the remaining are non-linear enhancement.

According to Figure 11, the different drivers have different degrees of influence on the level of coupled development between the level of URI and LUE in the YRB. At the same time, these drivers have a specific interaction relationship. Some had mostly a bi-linear or non-linear enhancement of the interaction during the study period. Based on the results of the interaction analysis of the six drivers and the factor effect strength values, the carbon emission rate (X3), the GDP per capita (X4), and the rate of urbanization (X5) were the three most influential drivers.

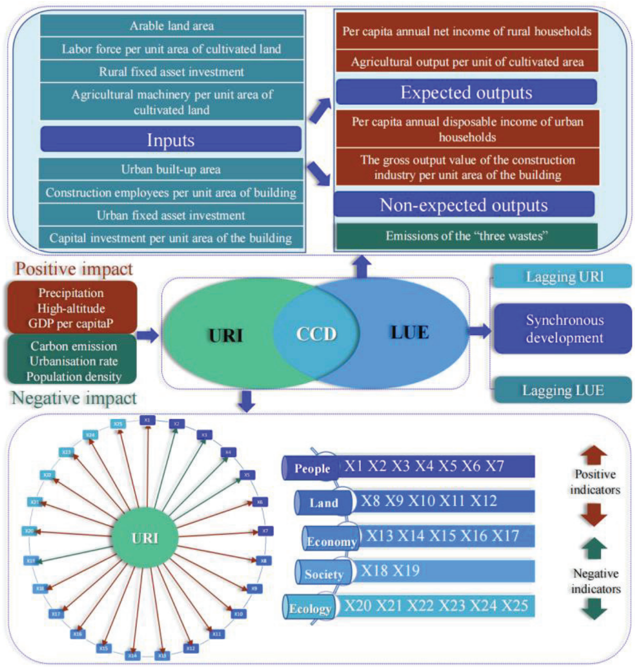

Figure 11. Mechanism of the CCD between URI and LUE in the Yellow River. Note: the specific meanings of X1-X25 are shown in Table 2.

5. Discussion

The URI development means treating cities and villages as a whole and addressing the imbalances in infrastructure, economic development, and basic public services, and the ecological environment in urban and rural development by promoting the equal exchange of urban and rural factors and reconfiguring the spatial structure of urban and rural areas [7,56]. The land is a critical element of urban and rural development and an essential spatial carrier to promote China's new urbanization construction, achieve comprehensive rural revitalization, and ensure China's URI development [19,57]. Along with China's urban–rural development transformation in the new era, China's urban–rural human–land relationships are undergoing a major restructuring, and the construction of new towns and cities, rural revitalization, and URI development can all be seen as a process of spatial expression of human–land relationships [58]. Focusing on the effective use of land resources, the Chinese government has adopted a variety of means to promote the rationalization of the adjustment of human–land relationships. The first is by promoting the mechanism of "pegging the link between increase and storage" to enhance the economical and intensive utilization of urban land, solve the constraints on urban land-use, accelerate the transformation and upgrading of urban industries, and promote the progress of new types of urbanization [58]. The second is to take the comprehensive improvement of land-use in the whole region as a handhold, improve the protection of arable land and the conservation and intensive use of land, and promote the comprehensive revitalization of the countryside [59]. The third method is to deepen the reform of the land market system, improve the unified urban and rural land-use market, and improve the level of integrated development of urban and rural areas [60]. In 2019, the Chinese government proposed to reshape the urban–rural relationship and solve many problems in land-use in urban–rural development by establishing and improving systems, mechanisms, and policy systems for integrated urban–rural development [13]. This paper studied the CCD and influencing factors of URI development and LUE in the YRB (Figure 11), which tried to make up for the lack of research on the coupling coordination relationship between URI development and LUE in prefecture-level cities in the YRB, and to deeply explore the internal reasons for the incoordination between URI development and LUE by studying the driving factors.

5.1. Strengthening Policy Support Is Conducive to Urban and Rural Areas' Comprehensive, Integrated Development and Improving LUE

Generally, during the study period, the time series evolution of URI level in the YRB showed a fluctuating upward trend [61,62]. The Chinese government has made active policy adjustments for the integrated development of urban and rural areas. In the new era, the Chinese government has changed the urban and rural development strategy from "cities leading rural areas" to "combining urban and rural areas". Strategic policies such as the "New Urbanization Strategy" proposed in 2014 and the "Rural Revitalization Strategy" presented in 2017 can effectively promote the level and quality of URI development [5,16]. During the study period, the regional imbalance in the level of the 61 prefecture-level cities in the YRB has improved. The YRB has seen the most rapid development of urban–rural population integration and urban–rural economic integration, in which the urbanization rate, urban–rural fixed-asset investment ratio, and the level of regional economic performance have improved considerably over the study period. Relatively speaking, prefecture-level cities with a high URI are concentrated in resource-rich areas, such as Shandong Peninsula. On the one hand, since resource-based regions tend to lead in economic development, a higher level of economic development is conducive to the spillover effect of cities on the countryside and to the promotion of integrated urban–rural development [61]. On the other hand, Shandong, as a coastal province with good economic development, has a good level of economic development that can promote the agglomeration and diffusion of resource factors, and the prefecture-level cities in the Shandong Peninsula region have flat terrain, a good agricultural base, and a high level of rural development. At the same time, Shandong Province is also a national-level comprehensive pilot area for the transformation of old and new kinetic energy, which provides a series of favorable conditions for integrated urban–rural development [1]. However, the growth rate of downstream prefecture-level cities was slower than that of the middle and upper reaches, mainly due to the excellent foundation of downstream prefecture-level cities' urban and rural development levels and the small space for progress [61,63]. On the other hand, during the study period, the LUE in the YRB showed an increasing trend with time, and there was spatial differentiation. The continuous improvement of LUE in prefecture-level cities in the YRB was mainly due to the growing attention given by the Chinese government to land resources; it proposed economizing and intensively using existing land resources, improving LUE, and alleviating the contradiction between land supply and demand. From the spatial distribution level perspective, prefecture-level cities with a high LUE are concentrated in resource-based areas, which have been towns seeking breakthroughs in urban transformation and industrial upgrading in recent years, and in medium-sized cities with a high proportion of land redevelopment. At the same time, these cities have better financial support policies for land-use [63,64].

5.2. The Economic and Intensive Use of Land Resources Is Conducive to the Simultaneous Development of Urban–Rural Integration and Land-Use

During the study period, the CCD of URI development and LUE in the YRB showed an upward trend over time, the inter-regional imbalance was alleviated, and the regional unevenness in the URI level improved. Lagging LUE was the main obstacle to improving the CCD of URI development and LUE [45,60]. During the study period, the prefecture-level city with the lowest mean value of CCD between URI development and LUE in the YRB was Zhengzhou, Henan Province, located in the midstream areas of the YRB, which also showed a decreasing trend over the study period. This is a result of the depletion of land resources, but the deeper reason is irrational urbanization and untimely policy adjustments [65,66]. During the study period, among the 61 prefecture-level cities in the YRB, the cities with high coordination levels of URI and LUE and relatively fast growth were concentrated in the resource-rich areas in the middle reaches of the YRB, the urban agglomeration of Shandong Peninsula in the lower reaches, and the provincial capital cities of Jinan, Hohhot, and Xi'an. As these prefecture-level cities are committed to eliminating backward production capacity, developing emerging industries, and optimizing economic structure, they have a relatively high level of URI and abundant financial support funds, which can provide strong support for balanced urban–rural development and land-use [1,48].

5.3. High-Quality Economic Development, Rational Urbanization Development, and High-End Green Transformation of Industries Increase the CCD between URI Development and LUE

The CCD of URI development and LUE in the YRB were affected by many factors. First, the increase in carbon emissions significantly negated urban and rural development. The critical elements in the increase in carbon emissions are rapid urbanization development, and a substantial increase in population and industrial production activities that need to be environmentally friendly. The YRB is also known as the "Energy Basin", and the long-term development of traditional high-pollution, high-water-consumption, and high-energy-consumption industries has led to a sharp rise in carbon emissions in the YRB, and studies have proved that excessive carbon emissions affect the efficiency of urban–rural integration and development, as well as ecological protection and high-quality development in the YRB [67]. In response to this, the Chinese government issued a policy in 2022 to achieve a low-carbon transition in energy consumption through green industrial development. Therefore, the Chinese government has proposed a "new urbanization strategy" and "high-end green transformation of industries" [68]. In addition, as the world's most significant carbon dioxide (CO_2) emitter, China needs to reduce carbon emissions to achieve "carbon neutrality" by 2050 [69,70]. Second, the increase in per capita GDP (X4) had a significant positive impact. Regions with higher per capita GDP have more fiscal revenue, which is conducive to improving the balance between urban and rural development, protecting land carbon storage, and improving LUE [13,71]. Third, the urbanization rate (X5) had a significant negative impact. As some prefecture-level cities in the YRB are located in ecologically sensitive areas such as the Loess Plateau, the existing studies have shown that unreasonable urbanization development will lead to low sustainability of land-use and unbalanced urban–rural development. At the same time, the urbanization of some cities is promoted by encroaching on wetlands and lakes, or even destroying pristine mountain ranges. Therefore, attention must be paid to sustainable new urbanization and rural revitalization in urbanization development [72–74]. The development of urbanization in the sensitive areas of the Loess Plateau can learn from the advanced experience of the large urban engineering, for example, the "Mountain Excavation and City Construction (MECC)" in China [75].

In conclusion, existing studies have largely advanced our comprehension of the spatio–temporal heterogeneities and changing dynamics of various aspects related to URI development, land-use efficiency, and institutional systems in the YRB. However, our findings may have the following limitations: First, this study analyzed the coupled and coordinated relationship and influencing factors between urban–rural integration and LUE, and concluded that there is an interactive correlation between urban–rural integration and LUE. Unfortunately, there are few theoretical discussions and empirical tests on the intrinsic mechanism of these two aspects in the existing literature, and this article only made a preliminary exploration of this topic. On the one hand, URI development can promote the intensive and economical use of land resources through optimizing and upgrading the industrial structure of urban and rural areas, enhance the economic benefits of land, and then effectively improve the efficiency of land-use. At the same time, URI development can induce the free flow of urban and rural factors, and optimize the allocation of land resources, so as to achieve the purpose of enhancing the efficiency of land-use. In addition, urban–rural integration can help strengthen the construction of transport and information networks and water and electricity infrastructure, enhance regional competitiveness, and ultimately effectively improve LUE. On the other hand, improving LUE can provide land factor security for urban–rural integration development by increasing the economic density of land, and then increasing the economic carrying capacity per unit of land. At the same time, LUE can help optimize the industrial spatial layout to achieve rational allocation of land and clustering of economic space, and thus promote the integrated development of urban and rural areas. In addition, the improvement in LUE can reasonably adjust the relationship between urban and rural populations and land, promote the two-way flow of urban and rural populations, enhance the employment level of urban and rural residents, and ultimately effectively enhance the level of URI development. However, this study failed to further deepen the research because the exploration of the inner mechanism of URI development and LUE requires more complex logical deduction on the basis of a solid theory, and needs to be tested and verified with the help of empirical data. This aspect is also the direction of future research on URI development and LUE in the YRB. Second, only ten influencing factors were selected for analysis in this study, which may not sufficiently represent the actual situation. Since the existing research focuses on the unilateral research on urban–rural integration or LUE, and there is less research on the influencing factors on the relationship between urban–rural integration and LUE, this study mainly referred to the indicators in the existing literature that have an impact on both relationships when selecting indicators. At the same time, we also considered the actual situation of the YRB to select the indicators. For example, foreign investment has an impact on LUE, but it is less related to URI development, so this indicator was not selected [76]. In addition, the research on URI development and LUE covers a wide range, and the influencing factors affecting their relationship are complex and diverse, but the selection of influencing factors needs to take into account the availability and accuracy of information and data. Generally speaking, authoritative data come from the data published by the statistical department, but the current statistical data have differences in the statistical calibre and scope, and the lack of temporal and comprehensive information data limits the selection of influencing factors. In future research, further field research and questionnaire surveys can be carried out to obtain first-hand research information through in-depth collection of basic data at the meso- and micro-levels, so as to better carry out the research on the factors influencing urban–rural integration development and LUE. Third, a significant positive effect of precipitation growth was found in the regression analysis, but the article does not provide extensive explanations on this matter. The main reason for this is that the exploitation and consumption rate of surface water in the YRB has far exceeded the carrying capacity of the Yellow River's water resources, and at the same time, most of the YRB is in an arid and semi-arid region, and the ecological environment relies on atmospheric precipitation to a high degree. Worse still, the annual precipitation and the number of annual rainfall days in the YRB have been on a declining trend in recent years, leading to an increasingly serious shortage of water resources in the YRB [77,78]. The shortage of water resources has become a major contention in the tensions between man and land, and has seriously constrained the high-quality development of urban and rural areas in the YRB [79]. However, the results of the regression analyses are only used as a preliminary screening of influencing factors, and the influence of precipitation will not be discussed in depth here.

6. Conclusions

Based on existing studies, this paper discussed the coupling and coordination relationship between URI development and LUE in the YRB. This study adopted the linear weighting method, super-efficiency SBM model based on non-expected output, CCD model, non-parametric kernel density estimation method, and geographical detector to explore the dynamic evolution characteristics and influencing factors of URI development and LUE in the YRB from 2003 to 2021.

The results showed that: (1) the spatial distribution of urban–rural integration in the YRB maintained a balanced level, showing the spatial distribution characteristics of "blurred difference boundaries, relatively high in the middle and lower reaches". During the study period, the regional imbalance of urban–rural integration in the YRB as a whole still needs continuous attention, and the regional imbalance of urban–rural integration in the middle reaches had been significantly alleviated. The overall LUE showed a spatial distribution characteristic of "high at both ends and low in the middle". The regional imbalance of LUE in the upstream region was somewhat alleviated during the study period. However, the regional inequality of LUE in the middle and downstream areas still needs continuous attention. (2) There were apparent spatial differences between the CCD of URI and LUE, similar to the distribution of LUE, showing the spatial distribution characteristics of "high at two ends and low in the middle". A high level of coupling coordination was mainly observed in the middle and lower reaches of the YRB. During the study period, the CCD of the YRB showed a fluctuating upward trend, and the regional imbalance was alleviated; in particular, the provincial inequalities in the middle and lower reaches were effectively alleviated. The main characteristic of CCD in the YRB were the lag in LUE. (3) According to the analysis of influencing factors, it can be concluded that carbon emissions, per capita GDP, and urbanization rate significantly impact the CCD of URI development and LUE. The increased carbon emissions and improved urbanization rate had a significant negative impact on URI development and LUE. The growth of per capita GDP had a significant positive impact on URI development and LUE, and a small number of the driving factors had a bilinear enhancement effect, although most of the driving factors had a nonlinear enhancement effect. In future research, on the one hand, we can evaluate districts and counties, carry out field research and questionnaire surveys, and study the URI development and LUE in a small region by collecting basic data at the meso- and micro-levels. This will help the local government to implement the optimal allocation strategy of land-use that is closer to the reality, to achieve more efficient land resource use, and promote the integrated development of urban and rural areas. On the other hand, with the deepening of the research on URI development and LUE, more and more related research will appear; on this basis, the internal mechanism of URI development and LUE can be explored in depth and tested and verified with the help of empirical data from the existing research.

Author Contributions: Conceptualization, C.S. and Q.W.; methodology, C.S.; validation, L.S. and X.W.; formal analysis, L.S. and X.W.; resources, X.W. and J.D.; data curation, C.S.; writing—original draft preparation, C.S.; writing—review and editing, C.S., L.S., X.W. and J.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant numbers: "42271221" "42061037".

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Research on Spatial Restructuring of Farmers' Homestead Based on the "Point-Line-Surface" Characteristics of Mountain Villages

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Abstract: The spatial restructuring of rural settlements is conducive to the realization of rural transition and development. This study constructed a "point-line-surface" framework for the spatial reconstruction of the homestead in a typical mountain village and used the weighted Voronoi diagram and buffer analysis method to analyze. The results are as follows. (1) The development capacity of rural homesteads in Longfeng Village was divided into three levels: high, medium, and low. Among them, the high-level homesteads clustered in the north and south of the village in the form of a "T" and a long strip, respectively; the medium-level homesteads are mostly aggregated in the middle of the village; the low-level homesteads are mainly distributed along the Fenghuang Mountain. (2) The layout of homesteads in Longfeng Village was axis-oriented, which is manifested by the number and scale being in a gradient-decreasing pattern with the main road axis as the centerline. (3) According to the principle of "maximum" development capacity of the homestead, nine reconstruction units are divided. By calculating the location entropy, it is found that the dominant functions of each reconstruction unit mainly include supporting life services, operational production, ecological agricultural production, and traditional agricultural production, and there are obvious differences in the development patterns of homesteads in different functional units. (4) Based on the "point-line-surface" characteristics of the homestead, four reconstruction modes, namely, modern community type, field and garden integration type, road-pointing type, and traditional residential type, are summarized, and the reconstruction strategies are proposed accordingly. The "point-line-surface" framework of rural settlements is of practical significance and theoretical value, which can provide a decision-making reference for the optimization and reorganization of residential land space in villages of the same type in mountain areas. Moreover, the integrated and innovative framework proposed in the paper has also international significance, thanks to the possibility of replicating the research strategy and methodological approach in other contexts.

Keywords: rural homestead consolidation; rural restructuring; "point-line-surface"; rural settlements; mountain area; agglomeration and upgrading village; rural revitalization

Citation: Feng, Y.; Li, J.; Feng, D. Research on Spatial Restructuring of Farmers' Homestead Based on the "Point-Line-Surface" Characteristics of Mountain Villages. *Land* **2023**, *12*, 1598. https://doi.org/10.3390/land12081598

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 20 July 2023
Revised: 8 August 2023
Accepted: 8 August 2023
Published: 14 August 2023

1. Introduction

Rural decline is becoming a global issue, and a rural revival is needed around the globe, especially for developing countries [1]. The connotation of rural revitalization is to stimulate internal motivation and absorb external resources through economic, political and cultural construction to cope with the loss and decline of internal factors in the countryside [2], so as to optimize the structure of factors, enhance regional functions, reshape rural forms, and realize the comprehensive rejuvenation of rural regional economy, society and ecology and the new pattern of urban–rural integration and development [3]. The core objective of rural vitalization is to systemically establish a coupling pattern of various rural development elements including population, land, and industry [4]. As one of the prerequisites, land resources are required to be optimally allocated via land consolidation [5]. Consequently, land consolidation contributes greatly to population agglomeration, industry development, and resource support under the context of combating rural decline [2–4]. As one of the most important types of land in rural space, the optimization of the spatial layout of rural settlements has always been a major difficulty in land consolidation.

Land issues can be harnessed to improve rural lives and economies [1,6], particularly through spatial planning and reconfiguration, land use restructuring, and community design. Similar to the Contemporary European Union (EU) and Pan-European policies stressing the importance of spatial planning for the long-term sustainability of regions [7], many countries and regions have carried out many theoretical and practical explorations on rural spatial planning and community renovation. Particularly, the common rural settlement pattern in many developing countries is dispersion [8], which tends to be one of the major contributing factors to rural disadvantage and under-development [9]. Therefore, concentrated residential planning as a rural development approach has been introduced around the world to reverse rural recession under urbanization and cope with rural settlement dispersion [10]. For example, as early as the 1960s, the Tanzanian government developed spatial plans for clustering several residential clusters or hamlets surrounding an area in which farms were to be established, with each cluster of houses accommodating about 60 families in plots of about half an acre each, making four clusters as a full-fledged settlement [11]. Moreover, the UK, the former Soviet Union, Japan, the USA, South Africa, Thailand, and other countries had also carried out key settlement construction or settlement rationalization projects, with ambitious schemes to reorganize the dispersed settlement pattern, modernize the infrastructures, diversify the economy, and slow the depopulation in rural areas [12–17], and these experiences have effectively demonstrated the above viewpoint.

In the vast traditional rural areas of China, the homestead is the place of production, life, and development of rural residents and the core of interaction between rural man-land relationships [18,19]. The optimization and reconstruction of its spatial layout is an important thrust to realize the fine management of land and improve the level of intensive use of rural land [3,20]. For a long time, the spatial layout of the homestead has been affected by natural environmental conditions, economic and social conditions, humanistic customs, and the absence of village planning [3,20,21], and caused many problems such as scattered and disorderly space, extensive utilization, backward facilities, and environmental pollution [22–24], which are still far from the overall requirements of building beautiful and livable villages in the new era [25]. The village area is the basic unit of rural social and economic activities in China, and the development of village areas requires scientific and comprehensive planning to make both spatial and temporal arrangements for the social and economic construction of villages [26]. The current academic community has mainly studied the process and influencing factors of rural restructuring in typical villages [27,28], the morphological characteristics of village settlements [29], the process of spatial evolution and its driving mechanism [30–32], and constructed the model of spatial reconstruction of village settlements based on the mutual attractiveness between settlements, the integration of the driving factors and the suitability evaluation [33–36], then proposed the strategies of spatial reconstruction for village settlements from the perspective of symbiosis [37]. The above research findings provide references for the practice and follow-up study of spatial governance of village settlements.

Under the background of the implementation of China's rural revitalization strategy, it is necessary to separately construct the method system of spatial reconstruction for settlements in the category of four types of villages: agglomeration and upgrading, suburban integration, characteristic protection, relocation and evacuation, to better realize the construction of an ecological and livable rural environment. At the village level, as a complex system with production, living, and ecological functions, the homestead is a "point-surface" complex intertwined with a single land use type and multiple system elements [38], and its spatial layout has obvious characteristics of point-shaped distribution and development along the axis. China has a vast territory and diverse geomorphic types. Among them, mountainous areas account for about 75% of the total area of the country, and the number of mountainous counties accounts for 43.21%. Affected by the special natural geographical and human environment, compared with the plain area, the spatial distribution and evolution of rural settlements in mountainous areas are characterized by low concentration, rapid decline, and complex types. Spatial reconstruction, as an important means to optimize rural spatial organization, promote rural sustainable development, and boost comprehensive revitalization, has become a hot topic of continuous attention in the field of rural geography in recent years [39]. China has a large mountainous area, a low level of economic and social development, and the phenomenon of empty and abandoned homesteads is serious [20]. It is urgent to promote the intensive and efficient use of residential space based on the spatial restructuring of rural residential land [40]. So, this paper established a "point-line-surface" analysis framework for the spatial optimization of homesteads at the village level and took Longfeng Village, Meitan County, Guizhou Province as an example. Based on the analysis of the development capacity, development axis, and dominant function of farmer's homesteads in the case village, the research formed the spatial restructuring technology system for farmer's homesteads in the agglomeration and upgrading village in mountainous regions from the two aspects of spatial restructuring direction and strategy selection for different reconstruction units, which is expected to provide references for improving the governance capacity for spatial optimization of rural residential land in the process of rural revitalization in the new era.

2. Research Framework and Methods

2.1. Theoretical Construction

"Point, line and surface" are the basic elements of plane space, and the distribution of regional spatial elements has obvious structural characteristics of "point-line-surface". Therefore, the "point-line-surface" analysis framework constructed based on these characteristics is of great significance to the in-depth understanding of comprehensive regional development. The framework of "point-line-surface" has multiple characteristics such as multi-scale, multi-content, multi-elements, and multi-function. At different spatial scales, the conceptual connotation, manifestation form, and value function of "point", "line", and "surface" are not only different but also collinear [41]. Generally, "surface" contains "line" and "point" of the same scale, "line" contains "point" of the same scale, and "point" is used as the "face" of the lower scale. With the transformation of scale and the change in elements and environments, the three can realize mutual transformation [42]. The process can be briefly described as follows. With the continuous increase in the number of scattered point elements derived from the progress of economy and society, the continuous strengthening of the degree of connection between "points" will inevitably give birth to axis elements such as roads. These "axes" will connect many scattered points into small-scale "point-line" complexes by giving full play to the exchange function of elements, and the expansion of multiple small-scale complexes will form a boundary blend in a larger scale space, and then evolve into a large-scale "surface" complex. In addition, the "point-line-surface" framework is not only limited to analyzing the evolution process of geographic elements on the time scale but also extends its application scenarios and scope of application due to its basic attributes of scale, systematicity, and dynamism. In other words, the framework is also applicable to analyzing the layout of regional elements at a certain time point on the spatial scale. It should be noted that when using the "point-line-surface" framework to analyze the spatial characteristics of regional elements in a specific year, it is necessary to control the connotation and scope of elements within the same scale (macro, meso, or micro) as a precondition. The framework of "point-line-surface" is applicable to analyze regional development at any scale, so the development according to the point-axis system model can achieve the optimal spatial combination between production layout and linear infrastructure, and achieve the optimal regional factor structure [43].

As far as the specific urban–rural settlement pattern is concerned, the "points" mainly refer to settlements and central cities at all levels, and the "lines" mainly refer to axis infrastructure such as transportation and waterways (for example, a large number of settlement patterns along waterways in the Pearl River Delta, China), and the "surfaces" mainly refer to integrated agglomeration areas developed dynamically from "point-line". The existing distribution pattern of rural settlements (at a certain point in time) is not suddenly formed, but evolved from a long history, and to a large extent with a "historical imprint". Correspondingly, the spatial evolution process of rural settlements affects the existing distribution pattern, while the existing distribution pattern effectively reflects the evolution process, and the two are interrelated and inseparable. Based on the above theory, it can be seen that the "point-line-surface" framework can be a theoretical basis for explaining the dynamic spatial evolution process of rural residential land, as well as the main features of the static distribution pattern of rural residential land at a certain time point. In other words, "point-line-surface" can simultaneously describe the vertical evolution process and horizontal plane characteristics of the spatial layout of rural residential land. However, since the conceptual connotation and change process of rural settlements have significant multi-scale complex relationships, the "point-line-surface" framework should be strictly differentiated according to the scale when analyzing the spatial structure characteristics of rural settlements at different scales, of which the micro-scale is suitable for analyzing the distribution pattern characteristics of rural residential land, whereas the medium- and macro-scales are suitable for staging the historical evolution of rural settlements. If the scale is further sunk to the micro-scale of the village, the "points" are mostly manifested as concrete residential land patches, the "axes" are manifested as roads or rivers, and the "surfaces" are shown as settlements or functional areas. From the existing studies, it is not difficult to find that the spatial layout of rural settlements in China (especially in mountainous areas) has obvious characteristics of point-shaped distribution and axis direction of transportation and water systems [44,45]. Most of them form planar agglomerations in intermontane valleys and have widespread problems such as scattered distribution and chaotic structure [46]. In summary, using the framework of "point-line-surface" to analyze the spatial characteristics of farmers' homesteads in mountainous regions and putting forward the reconstruction strategies had theoretical adaptability and realistic demand.

2.2. Main Research Thoughts

On this basis, this paper builds a spatial "point-line-surface" analysis framework of farmers' homesteads in mountainous areas at the microscopic scale (Figure 1). First, this paper selected 20 indicators such as "areas" to construct the measurement model of farmers' homestead development ability, described the development characteristics of the point-shaped homestead, and divided the spatial reconstruction unit of the homestead by using the principle of "taking the large" and the weighted Voronoi diagram. Second, the study interpreted the distribution characteristics of homesteads under different buffer distances from the road axis and analyzed the "surface" characteristics of the homesteads based on the dominant function of each reconstruction unit as assessed by the location entropy value. Finally, four types of spatial restructuring models and strategies for farmers' homesteads were proposed based on the "point-line-surface" characteristics to provide references for solving the problems of rural land use and promoting rural revitalization in mountainous areas.

2.3. Research Methods

2.3.1. Measurement of Development Capacity of "Point"

The spatial layout of farmers' homesteads is a projection of the results of long-term activities of rural man–land relationships in geographic space under the strong traction and restriction of various environmental factors [47]. The distribution of homesteads comprehensively reflects the development of agriculture, rural areas, and farmers [19,48]. In order to systematically express the congenital conditions of homestead space, this paper took the homestead plot as the basic unit, constructed a measurement index system from five aspects, including farmers' homestead endowment, location conditions, public service system, farmers' characteristics, and farmers' willingness (Table 1), and used the comprehensive evaluation method to calculate the value of development ability of each farmers' homestead plot (Formula (1)). When processing the raw data of the indexes, the min–max normalization method is used to standardize the indexes. In the process of calculating the index weights, this study used a combination of "the entropy weight method and the analytic hierarchy process (AHP)" to overcome the shortcomings of much subjectivity in the subjective empirical weighting method and the over-dependence of the objective quantification method on data quality. The entropy weight method and the analytic hierarchy process method were applied separately to determine the weight of each index, and then the weighted average method was used to calculate the comprehensive weight of the index (Table 2).

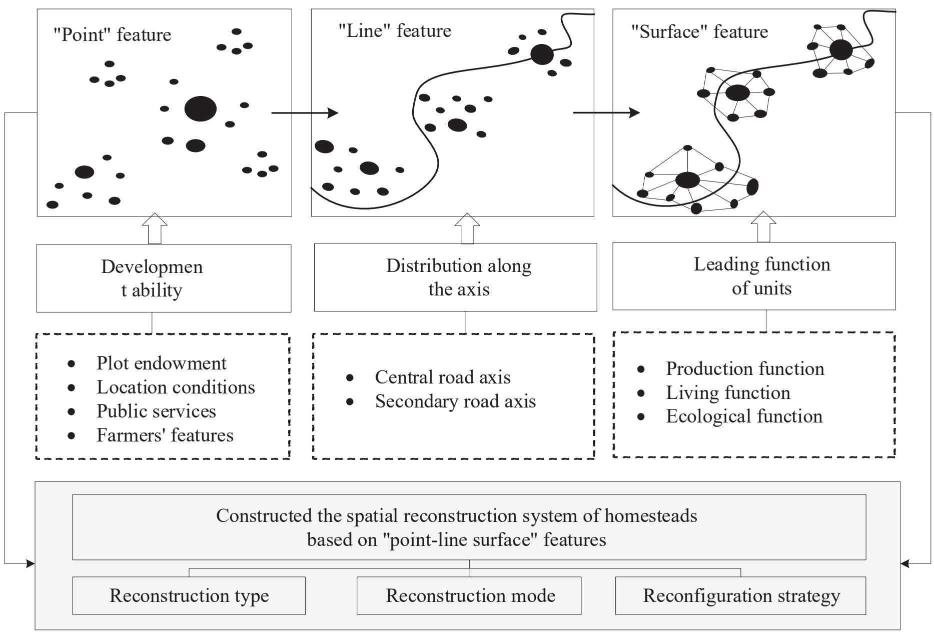

Figure 1. Research framework.

Table 1. Measurement indexes and description of farmers' homestead development capacity.

Goal Layer	Index Layer	Index Description	Action Direction
Homestead endowment	Homestead area (X1)	The area of farmers' homestead plot (m^2)	+
	Housing structure (X2)	Reflecting the building structure of the homestead: wood shingles = 1, brick and tile = 2, brick masonry = 3, steel-concrete = 4	+
	Building type (X3)	There are mainly three types of housing construction for farmers, assigned values respectively: houses with multi-layer and continuous arrangement = 1, houses with multi-layer or continuous arrangement = 2, single-family houses = 3	+
	Housing damage grade (X4)	The old and new degrees of homesteads were obtained according to arrange the farmers' oral statements during the survey	+

Table 1. *Cont.*

Goal Layer	Index Layer	Index Description	Action Direction
Location conditions	Elevation (X5)	Elevation of homestead plots (m)	−
	Slope (X6)	Slope of homestead plots (°)	−
	Average farming distance (X7)	Extracted by the nearest neighbor analysis tool of GIS software and processed by mean value (m)	−
	Distance from road (X8)	Extracted by the nearest neighbor analysis tool of GIS software (m)	−
	Distance from ditch (X9)	Extracted by the nearest neighbor analysis tool of GIS software (m)	−
Public service system	Electricity, water, and gas accessibility (X10)	Access to water, electricity, and gas: all three = 0, only one = 1, two = 2, all three = 3	+
	Perfection of public service facilities (X11)	Configuration of public service facilities for farmers' homesteads: complete = 1, relatively complete = 0.75, incomplete = 0.5, poor = 0.25	+
	Perfection of commercial facilities (X12)	Configuration of commercial facilities for farmers' homesteads: complete = 1, relatively complete = 0.75, incomplete = 0.5, poor = 0.25	+
	Satisfaction of health cleaning (X13)	Farmers' satisfaction with the health cleaning of their homesteads: poor = 1, general = 2, good = 3	+
Farmers' characteristics	Culture degree of the householder (X14)	Expressed using the year of education of the head of the household (years)	+
	Number of family members (X15)	Total number of farm household members (persons)	+
	Diversity of farmers' livelihoods (X16)	Farming, work, scale cultivation, self-employed business, others (each source of income is assigned a value of 1, cumulative calculation)	+
	Gross income (X17)	Annual total income of peasant households (ten thousand Yuan)	+
Farmers' willingness	Residential satisfaction (X18)	Reflecting farmers' residential satisfaction: dissatisfaction = 0, satisfaction = 1	+
	Willingness of living in village (X19)	Whether the farmers intend to stay in the village in the future: stay = 1, no stay = 0	+
	Willingness to support the spatial reconstruction of homesteads (X20)	When personal interests conflict with planning, whether will give way: will = 1, depending on the situation = 0.5, will not = 0	+

The formula for calculating the development capacity of farmers' homesteads is:

$$Z = \sum_{i=1}^{n} X_i W_i \tag{1}$$

where Z represents the development capacity value of the *No.i* sample unit, which reflects the development conditions of the farmers' homestead plot. X_i stands for the standardized processing value of the *No.i* index. W_i represents the comprehensive weight of the *No.i* index, n stands for the number of indexes.

An in-depth analysis of the index weight is conducive to clarifying the value, relative importance, and proportion of each specific index in the development process of farmers' homesteads. Specifically (Table 2), the comprehensive impact of public service system and farmers' characteristics on the spatial change in rural homesteads is as high as 40.03%, in which villagers are especially concerned about the degree of improvement of public utility services and commercial facilities in the vicinity of the housing (the cumulative proportion of the two indicators is 32.1%). In addition, the influence of the diversity of farmers' livelihood and household income on rural homesteads has continued to increase, and the willingness of farmers to renovate is the smallest influence on the change in homesteads. This is mainly because farmers' willingness is susceptible to fluctuations in income, livelihood, social values, and policy changes, among other factors. It can be found that, at the village scale, accelerating the construction of a sound network system of public service facilities, improving the rural human settlement environment system, promoting farmers' diversified livelihood methods, and ensuring farmers' income sources have become the key policy fulcrum to promote the spatial reconstruction of rural residential land.

Table 2. Weights of indexes for measuring the development capacity of farmers' homesteads.

Index	Weight of AHP Method	Weight of Entropy Weight Method	Comprehensive Weight
X1	0.0342	0.0632	0.0487
X2	0.0401	0.0418	0.0409
X3	0.0480	0.0052	0.0266
X4	0.0201	0.0441	0.0321
X5	0.0244	0.0160	0.0202
X6	0.0348	0.0074	0.0211
X7	0.0417	0.0031	0.0224
X8	0.1054	0.0042	0.0548
X9	0.0513	0.0185	0.0349
X10	0.0664	0.0114	0.0389
X11	0.1766	0.1780	0.1773
X12	0.0985	0.1889	0.1437
X13	0.0513	0.0220	0.0367
X14	0.0160	0.0250	0.0205
X15	0.0195	0.0394	0.0295
X16	0.0363	0.1851	0.1107
X17	0.0508	0.0902	0.0705
X18	0.0348	0.0204	0.0276
X19	0.0277	0.0113	0.0195
X20	0.0221	0.0247	0.0234

2.3.2. Selection of Spatial Reconstruction Axis "Lines"

The unique conditions of topography and resource endowment have created the basic spatial pattern characteristics of "large scattering and small concentration" of rural homesteads in mountainous areas, while roads lay the foundation for mountain settlements at all levels to cross geographical barriers and form spatial inter-coupling and linkages. The axis transportation network centered on roads has an overall impact on the spatial pattern evolution of homesteads in mountainous areas, which is mainly manifested as follows. (1) The road is the axis connecting the settlements in different locations in mountainous areas and the main channel for the transfer of material flow and information flow between each other, as well as the foundation of the high-intensity rural link network [49]. By giving full play to the carrier function of the road, it will effectively promote the correlation and mutual flow of multiple remote elements such as value concepts, production modes, material resources, and information technology, thus realizing the complementary supply and demand of spatial elements and the balanced development of the spatial pattern of mountain settlements. (2) The road has a profound impact on the changing process of spatial characteristics such as the scale structure, morphological layout, and utilization mode of specific homesteads in mountain settlements. The perfect road axis network system in the mountains can provide various conveniences for the outward expansion and development of homesteads. So in reality, the closer the buffer zone is to the road, the more dramatically the landscape pattern of the homesteads changed [50]. In general, mountain roads have strong cohesion and attraction to scattered homesteads in nearby areas. The rural homesteads in mountainous areas will first gather in a belt or cluster in the area with a sound road axis network and then form several small clusters on a large scale. With the continuous development and expansion of the agglomeration point, the road will guide the various elements and subjects to communicate and exchange along its directions and paths internally and spread the "potential energy flow" to the periphery to form new agglomeration potential zones externally. Finally, the microscopic shaping of the spatial distribution pattern of homesteads in mountainous areas and the macroscopic control of its spatial distribution pattern are realized. Thus, roads should generally be selected as the key axis of spatial reconstruction in mountain villages.

2.3.3. The Division of "Surface" of Reconstruction Unit and Its Dominant Function Measure

According to the principles of physics, all things in space have their potential energy and constantly transmit and diffuse this potential energy to the surrounding environment, which in turn affects each other [41]. Similarly, the spatial distribution pattern of homesteads is the result of the mutual game of the spatial potential energy of each rural residential land. The homesteads with high spatial potential energy and good conditions (the growth poles) have more advantages in the game, which can often attract homesteads with low spatial potential energy and poor conditions to move closer to them and form new agglomeration points. Therefore, the accurate identification of growth poles and their spatial influence range are crucial to the spatial reconstruction of farmers' homesteads. The weighted Voronoi diagram has obvious advantages in identifying and analyzing the influence and radiation range of homesteads [51,52]. Based on the measurement of farmers' homestead development capacity, this paper selected the farmers' homestead plots with high-level ability as the growth poles according to the principle of "taking the large" and used the weighted Voronoi diagram to divide the actual influence range of each growth pole on the spatial layout of the homestead as its spatial reconstruction unit.

According to the land use classification in the Technical Guidelines for the Preparation of Land Use Planning in Villages, and considering the actual land use situation, five main types of land use are classified in mountain areas: agricultural land, rual construction land, land for transportation and water conservancy facilities, tourism land, and ecological land. Among them, agricultural land mainly included arable land, garden land, and other agricultural lands; rural construction land included residential land, public service, and infrastructure land, and operating construction land; ecological land included ecological forests, waters, and natural reserves. Based on the relevant research results [53–56], the dominant function classification system of land use in mountain villages was established (Table 3), and the information entropy of each land use function is calculated to determine the dominant function of each reconstruction unit [57–59].

Table 3. Dominant function classification system of land utilization with "Production-Living-Ecology" in mountain village.

Function Form	Function Type	Land Use Type
Producing function	Traditional agricultural production function	Cultivated land
	Production function of ecological agriculture	Garden land
	Operational production function	Operating construction land, tourism land
Living function	Life function of habitability	Rural residential land
	Life service supporting function	Public services and infrastructure land, land for transportation and water conservancy facilities
Ecological function	Ecological conservation function	Ecological forest, other agricultural land, water areas, natural reserved area

3. Case Study

3.1. Overview of the Study Area and Data Sources

3.1.1. Study Area

Longfeng Village is in Xinglong Town, southeast of Meitan County, Guizhou Province, 12 km from Meitan County (Figure 2). The village has a good climate and ecological environment with rain and heat in the same season, an average annual temperature of 15.2 °C, an average annual precipitation of 1115.6 mm, and average annual sunshine hours of 1033.9 h. The land area of the whole village is 951.42 hm^2, with four villager groups under the jurisdiction of the Baodongba group, Fenghuang group, Pingshang group, and Egongba group. In the whole village, the arable land area is 257.43 hm^2, accounting for 27.06% of the total land area; the tea garden area is 174.03 hm^2, accounting for 18.29%; the forest land area is 422.27 hm^2, accounting for 44.38%; and the construction land area of the village is 46.32 hm^2, accounting for 4.87%. Longfeng Village is one of the demonstration sites of socialist new rural construction in Meitan County, with the tea industry as the leading industry and rural tourism as the supplement, focusing on the development of ecological tourism and leisure industry. Longfeng Village has been successively awarded the titles of "National Agricultural Tourism Demonstration Site", "National Demonstration Village of Democracy and Rule of Law" and "National Rural Tourism Key Village". In 2020, the village had a total of 3011 people, with a total annual per capita income of RMB 20,800 and an average household ownership rate of 91% for family cars. Farmers' household income is mainly derived from self-employment, labor income, farming, and so on. Due to the good location conditions and the basis of agricultural industry, Longfeng Village was positioned as a village of agglomeration and upgrading class in the rural revitalization strategy of Meitan County, which is also widely representative. From a comprehensive point of view, Longfeng Village has a high altitude (796–1084 m), complex and changeable terrain, and its natural endowment is basically same as that of most mountain villages. Meanwhile, the village also possesses unique cultural genes such as lantern drama and revolutionary culture and integrates traditional agriculture and modern tourism in its industrial structure. It can be seen that Longfeng Village not only has the common characteristics of general mountain villages in terms of natural conditions, industrial development, and social culture but also has its own unique differences. In addition, in recent years, under the background of industrial structure adjustment, rapid tourism development, and external policy support in this village, the changes in the scale, function, and layout of rural residential land have been very active, which is typical and of great practical significance as a study area, and it is expected to provide a strong reference for the spatial reconstruction of mountainous villages.

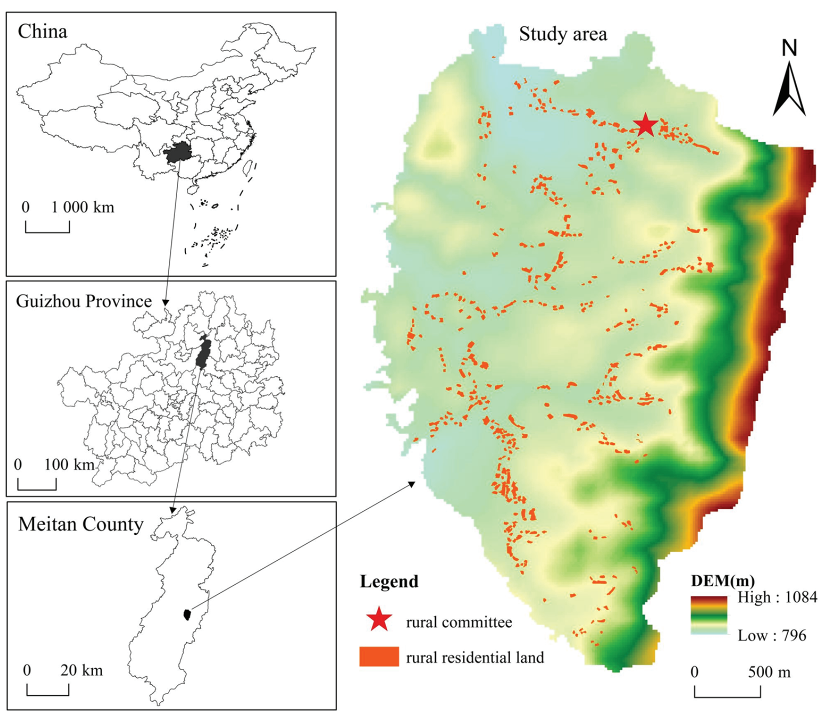

Figure 2. Location, elevation, and homestead distribution of the case village.

3.1.2. Data Source

The land use change data and remote sensing image map of Longfeng Village in 2020 were provided by Meitan County Natural Resources and Planning Bureau, and the farmers' data were obtained from the authors' field survey in June 2020. First, the farmer's questionnaire was prepared. The questionnaire includes 7 major items, including the farmers' basic situation, the utilization of homesteads, the situation of contracted land, farmers' industrial development, policy awareness and response, village planning awareness and other conditions, and 117 minor items such as farmers' income, housing endowment, and infrastructure status. Then, we took the form of field visits and communicated with farmers face-to-face. Considering the differences in educational level of farmers, take the path of "farmers respond, investigators record". Finally, in the ArcGIS10.2 software platform, we superimposed and registered the range of farmers' homestead plots with remote sensing image maps, and cut out farmers' homestead plots with the unit of farmers, and then fused the farmers' data and spatial attribute data obtained from the survey into a plot-scale homestead attribute database with farmers as the basic unit through data links and other tools.

3.2. Analysis of "Point-Line-Surface" Features of Spatial Reconstruction of Farmers' Homesteads in Longfeng Village

3.2.1. Analysis of the Characteristics of Farmers' Homestead Development Ability

According to the model constructed in this paper to measure the development ability value of farmers' homesteads in village domain, the development ability value of 667 farmers' homesteads is calculated between 0.2784 to 0.8439 in Longfeng Village, and the average value is 0.5160. Among them, 302 plots are greater than the average, accounting for 45.28% of the total number of homesteads, indicating that the overall level of farmers' homestead development ability in Longfeng Village needs to be further improved. The Natural Breaks method was used to classify the development ability value of whole farmers' homesteads into three grades in the present study: high (greater than or equal to 0.5898), medium (0.4571~0.5898), and low (less than 0.4571). Specifically, there are 185 homesteads with high ability value, accounting for 27.74%, and their area is 8.8132 hm^2, accounting for 29.19% of the total homestead area. There are 245 homesteads with medium ability, accounting for 36.73%, and their area is 10.9381 hm^2, accounting for 36.23%. The number of homesteads with low ability value is 237, accounting for 35.53%, and their area is 10.4385 hm^2, accounting for 34.58%. The homesteads with different ability values in Longfeng Village show significant spatial heterogeneity, and the overall value decreases from the northern and southern parts of the village to the interior. The homesteads with high-level ability values are clustered in a "T" shape in the Northern Baodongba group and show a long-strip agglomeration distribution in the Southern Egongba group. The homesteads with medium-level ability values are mostly distributed in the central region of the village and around the development axis. The homesteads with low-level ability values are mostly distributed along Fenghuang Mountain, and the rest are scattered throughout the village (Figure 3).

3.2.2. Analysis of the "Line" Characteristics of the Spatial Reconfiguration Axis of Farmers' Homesteads

The Eguan highway, which runs through the north and south of the village, is taken as the central development axis of the spatial reconstruction of the homesteads, while the other general roads in the village are taken as secondary or tertiary development axes, which together constitute the spatial development axes network of the homesteads in Longfeng Village. Based on the main development axis of the whole village, the buffer analysis was carried out according to the linear distances of 100 m, 300 m, 600 m, 900 m, and 1200 m (Figure 3), and the spatial distribution characteristics of the distance of homesteads in Longfeng Village from the Eguan Highway are obtained. In general, there are 593 homesteads within 900 m of the Eguan Highway, with an area of 27.0693 hm^2, and the proportion of both the number and area of homesteads reach about 90%. Among them, there are 152 homesteads within 100 m from the main development axis, accounting for 22.79% of the total, and the area of homesteads is 7.7798 hm^2, accounting for 25.77% of the total area. The number of homesteads located from 100 to 300 m away from the main development axis is 158, accounting for 23.69%; the area is 7.1612 hm^2, accounting for 23.72%. The number of homesteads located from 300 to 600 m away from the main development axis is 181, accounting for 27.14%; the area is 7.5515 hm^2, accounting for 25.01%. The number of homesteads from 600 to 900 m from the main development axis is 102, accounting for 15.29%; the area is 4.5767 hm^2, accounting for 15.16%. From the distribution characteristics of homesteads with different grade capability values along the main development axis (Table 4), within 600 m of the main development axis, the number and area of homesteads with high-level ability reach about 94%, indicating that homesteads with high-level ability are concentrated within 600 m of the main development axis. In the same distance (600 m) range, the proportion of the number and area of medium and low-capacity homesteads only reach about 74% and 58%. Under the condition of the same number and area ratio of homesteads (about 94%), the homesteads with medium and low-capacity values are 900 m and 1200 m away from the main development axis, respectively, which further illustrates that the number and area of homesteads with different grade ability values in Longfeng Village have significant gradient differentiation along the main development axis.

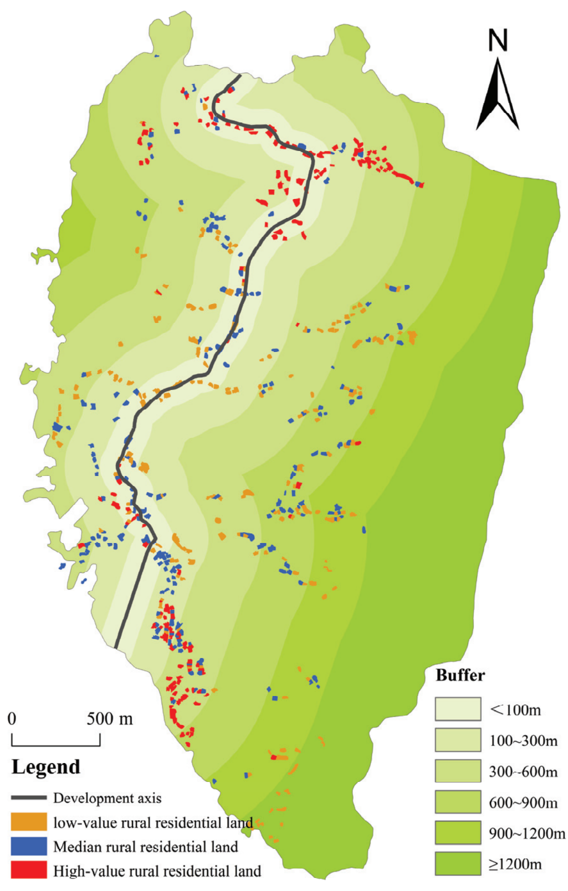

Figure 3. Distribution of homesteads with different capacity values along the main development axis in Longfeng Village.

Table 4. Distribution table of distance from homesteads to main development axis of different grade capacity values in Longfeng Village.

Index	Homestead with High-Level Ability				Homestead with Medium-Level Ability				Homestead with Low-Level Ability			
	Amount	Ratio (%)	Area (hm^2)	Ratio (%)	Amount	Ratio (%)	Area (hm^2)	Ratio (%)	Amount	Ratio (%)	Area (hm^2)	Ratio (%)
Distance < 100 m	58	31.35	3.0727	34.92	54	22.13	2.7752	25.34	40	16.81	1.9319	18.51
100~300 m	39	21.08	1.8423	20.94	73	29.92	3.1592	28.85	46	19.33	2.1596	20.69
300~600 m	77	41.63	3.3477	38.05	53	21.72	2.1422	19.56	51	21.43	2.0616	19.75
600~900 m	9	4.86	0.4155	4.72	47	19.26	2.1302	19.45	46	19.32	2.0309	19.46
900~1200 m	2	1.08	0.1208	1.37	15	6.15	0.6612	6.04	36	15.13	1.5797	15.13
Distance ≥ 1200 m	0	0.00	0.0000	0.00	2	0.82	0.0841	0.76	19	7.98	0.6747	6.46

3.2.3. Analysis on "Surface" Characteristics of Spatial Reconstruction Unit of Farmers' Homestead

This research selected the homestead plots with the high score as the growth poles from the settlements of Longfeng Village, took the growth poles as quality hearts and the development ability values of farmers' homesteads as the weight, then generated the weighted Voronoi diagram and divided out the spatial reconstruction units of farmers' homesteads through ArcGIS10.2, and the spatial reconstruction units were named according to the local small place names. Since the Fenghuang Mountain area in the eastern part of Longfeng Village is all ecological forest land, which has little influence on the spatial reconstruction of farmers' homesteads, this ecological forest land has been distinguished according to the boundary of the patches when dividing the reconstruction units (Figure 4).

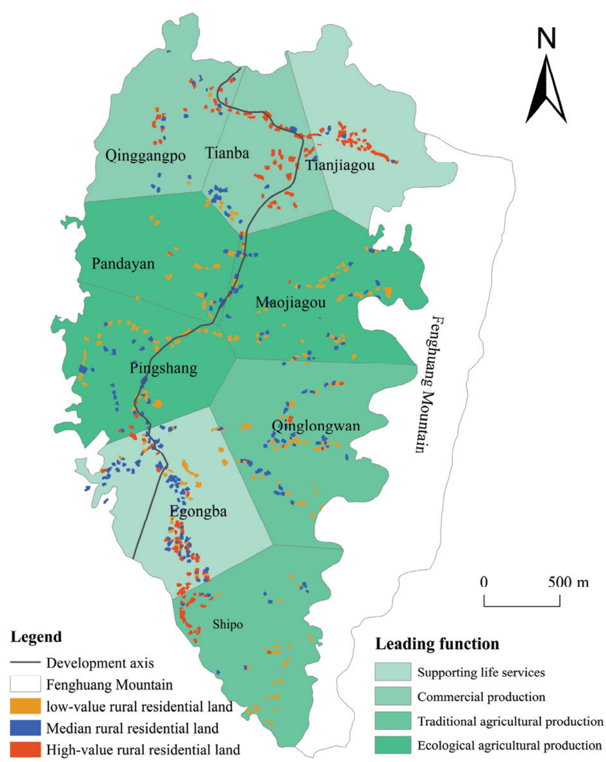

Figure 4. Leading functions of different reconstruction units and homestead distribution in Longfeng Village.

This paper divides Longfeng Village into nine spatial reconstruction units of farmers' homesteads. From the distribution of farmers' homesteads in each reconstruction unit, there are 41 households in Tianjiagou, accounting for 6.15% of the total number of households in the village; its homesteads have an area of 1.9388 hm^2, accounting for 6.42%. Tianba has 65 households, accounting for 9.75%; its household area is 3.7373 hm^2, accounting for 12.38%. Qinggangpo has 43 households, accounting for 6.45%; its household area is 1.7648 hm^2, accounting for 5.85%. Pandayan has 25 households, accounting for 3.75%; its homestead area is 1.2675 hm^2, accounting for 4.20%. Pingshang has 71 households, accounting for 10.64%; its homestead area is 3.5972 hm^2, accounting for 11.92%. Maojiagou has 98 households, accounting for 14.69%; its homestead area is 4.5254 hm^2, accounting for 14.99%. Qinglongwan has 92 households, accounting for 13.79%; its household area is 3.9001 hm^2, accounting for 12.92%. Egongba has 165 households, accounting for 24.74%; the household area is 6.7887 hm^2, accounting for 22.49%. Shipo has 67 households, accounting for 10.04%, and the area of homesteads is 2.6699 hm^2, accounting for 8.84%. From the perspective of the proportion of the number and area of farmers' homesteads in each reconstruction unit, the average household area of homesteads in Tianjiagou, Pandayan, and Maojiagou were basically equivalent to that of the whole village, and the average household area of homesteads in Tianba and Pingshang was larger than that of the whole village, while the average household area of homesteads in Qinggangpo, Qinglongwan, Egongba, and Shipo was smaller than that of the whole village. Judging from the classification of farmers' homesteads development capacity in each reconstruction unit (Table 5), the proportion of homestead area with high-level ability in Tianjiagou was 100%, the proportion of homestead area with high-level ability in Tianba and Qinggangpo was about 90%, and the proportion of homestead area with high-level ability in Egongba was 80.16%. The development capacity value of farmers' homesteads in the above four reconstruction units was high. The proportion of the medium and high-level capacity values of farmers' homesteads in the two reconstruction units of Qinglongwan and Shipo, which are located in the southern area of Longfeng Village, was between 50% and 60%, with general development capacity. And the development capacity value of farmer's homesteads in the three reconstruction units of Pandayan, Pingshang, and Maojiagou, which are located in the central area of Longfeng Village, was low. Overall, the development capacity value of the farmer's homestead of each reconstruction unit in Longfeng Village has the spatial differential features of "high in the northern region, low in the central region, and general in the southern region".

Table 5. Grading summary of development capacity of farmers' homestead in each reconstruction unit of Longfeng Village.

Reconstruction Units	Homestead with High-Level Ability		Homestead with Medium-Level Ability		Homestead with Low-Level Ability	
	Area (hm^2)	Ratio (%)	Area (hm^2)	Ratio (%)	Area (hm^2)	Ratio (%)
Tianjiagou	1.6217	83.64	0.3172	16.36	0.0000	0.00
Tianba	2.4142	64.60	0.9211	24.65	0.4020	10.76
Qinggangpo	0.9510	53.89	0.6834	38.73	0.1304	7.39
Pandayan	0.0472	3.73	0.2732	21.55	0.9470	74.72
Pingshang	0.2027	5.64	1.4368	39.94	1.9577	54.42
Maojiagou	0.1229	2.71	1.7634	38.97	2.6391	58.32
Qinglongwan	0.1841	4.72	1.8458	47.33	1.8703	47.95
Egongba	2.1685	31.94	3.2734	48.22	1.3468	19.84
Shipo	1.0868	40.71	0.4380	16.40	1.1451	42.89

According to calculating the location entropy of the dominant function of each reconstruction unit (Table 6), the dominant land use function of the reconstruction unit was determined in line with the principle of maximum value. The dominant functions of Tianjiagou and Egongba are life services, and the proportion of this functional area is 22.00%.

The dominant functions of Tianba and Qinggangba are operational production, accounting for 18.61%. The dominant functions of Pandayan, Pingshang, and Maojiagou are ecological agriculture production, accounting for 33.90%. The dominant functions of Qinglongwan and Shipo are traditional agricultural production, accounting for 25.49%. In the regional space, Longfeng Village has initially formed a multi-functional coexistence pattern. Tianjiagou and Egongba, at both ends of the north and south, are the supporting polar nucleus for village living services. Tianba and Qinggangba in the north are the operational production areas characterized by rural tourism, agri-business, and tea production, processing, and sales. Pandayan, Pingshang, and Maojiagou in the middle are the ecological agricultural production areas with the main features of tea planting. Qinglongwan and Shipo in the south are the traditional agricultural production functional areas characterized by rice, rape, and maize planting.

Table 6. Information entropy of dominant function of each reconstruction unit in Longfeng Village.

Reconstruction Units	Traditional Agricultural Production Function	Production Function of Ecological Agriculture	Operational Production Function	Life Function of Habitability	Life Service Supporting Function	Ecological Conservation Function
Tianjiagou	1.05	1.12	0.46	0.66	1.48	0.98
Tianba	0.62	0.77	3.98	1.47	1.25	0.93
Qinggangpo	0.86	0.77	2.16	0.57	0.58	1.17
Pandayan	0.43	1.66	0.76	0.45	0.61	1.27
Pingshang	0.75	1.50	0.66	1.08	0.97	0.96
Maojiagou	1.04	1.29	0.31	1.11	0.93	0.86
Qinglongwan	1.20	0.69	0.51	0.93	0.54	1.15
Egongba	1.37	0.53	0.69	1.83	2.32	0.83
Shipo	1.37	0.80	0.50	0.77	0.34	0.90

3.3. The Leading Modes and Strategies for the Spatial Reconstruction of Farmer's Homestead in Longfeng Village

3.3.1. Spatial Reconstruction Modes of Homestead in Different Reconstruction Units

Based on the spatial distribution features of the "point-line-surface" of farmers' homesteads in Longfeng Village, this article combined the conditions of farmers' needs, regional functions, and village resource endowments, then constructed four spatial reconstruction models of homesteads for different reconstruction units (Figure 5), to provide decision support for improving human settlement quality and creating beautiful and livable villages at the village level.

(1) Modern community type refers to the rural spatial development model with concentrated and orderly housing, a better public service system, a more sound infrastructure network, and co-governance by multiple social subjects, which has the remarkable features of infrastructure urbanization, community-based life service, and lifestyle citizenization. The centralized agglomeration area formed by this model has a spillover effect and domino effect on the surrounding areas [60]. It has a driving effect on the development of the surrounding areas, which has been widely popular in Europe and the United States, and other developed countries. The two units of Egongba and Tianjiagou in the north and south of the village domain have relatively flat terrain and good external traffic conditions, and the public service facilities such as the village committee, nursing home, and cultural center are concentrated in distribution. The areas of high-level and medium-level capacity homesteads also account for more than 80% of the total, which has the basic conditions for transformation into the modern rural community. Based on the spatial reconstruction of homesteads, it is necessary to standardize the site selection and housing construction style of farmers' homesteads, unify and improve the modern living conditions such as internal roads, greening, sanitation facilities, hydropower, and gas networks (tap water, electricity,

natural gas, broadband networks) of the supporting communities, and build it into a model of the rural inhabitable environment in the new era.

(2) Field and garden integration type refers to the construction of a comprehensive gathering platform based on the original rural residential area, led by the elements of industry, ecology, leisure, and tourism, focusing on the living life of multiple types of subjects (local villagers, industrial workers, foreign tourists), based on ecologically sustainable agriculture and supported by rural landscape leisure. This model embodies the integration of various resource elements, agricultural production, living, cultural landscape, leisure agglomeration, and comprehensive service are its main functions. Recently, the world has formed the development models of the advantageous and characteristic agricultural industry, cultural creativity driving the integration of three industries, urban and suburban modern agricultural sightseeing garden, agricultural creativity, and agricultural experience. The two units of Tianba and Qinggangpo in the northern part of the village are rich in resources and diverse in functions, and there are many modern rural agricultural tourism industry statuses such as Wanhuayuan scenic spots (including modern agricultural demonstration areas, flower and seedling display areas, leisure and health hot spring resorts, water parks, and other functional areas), homestay inn, agritainment, and tea production and processing bases, etc. And the employment channels of farmers mainly focus on rural tourism, tea production, and sales services, while the spatial utilization of homesteads in the domain has the composite features of residential and production services. Based on the background of developing rural tourism in Longfeng Village, relying on the beautiful pastoral scenery and good productive and living service supporting facilities in the domain, it is necessary to emphasize the harmonious coexistence of farmers' homesteads and pastoral (tea garden) landscape and create the homestead aggregation area of the field and garden integration type with both residential suitability and business service.

(3) Road-pointing type: unlike the natural elements, the influence between improving road traffic conditions and the spatial distribution of rural settlements is interactive. The rural settlement distribution remains unchanged while the road conditions are improved, and the road conditions remain unchanged and rural settlements are arranged towards the road, both can make the distribution of settlements tend to "road-pointing". This housing type often relies on the advantages of road traffic to achieve development, and its utilization activities and functions are mostly closely related to the "road economy". For example, the closer a rural residential area is to a road, the more road service-oriented places such as kiosks, water filling stations, automobile repair stores, and hotels are found significantly. The road is the axis connecting the homesteads, and the characteristics of rural homesteads distributed along the road axis in mountainous areas are significant. The number and area of homesteads within 100 m of the main development axis (Eguan Highway) in Pandayan, Pingshang, and Maojiagou units in the middle of Longfeng Village are about 65%, and the proportion of homesteads within 300 m reaches more than 95%. And the homesteads in the reconstruction unit of Maojiagou are mainly distributed along the roads of through-group roads. Therefore, the optimization of the spatial layout of homesteads in the above three units is mainly carried out along the main development axis of the Eguan Highway and the through-group roads. Among them, the terrain of Pandayan and Pingshang is gentle, and the main development axis of the Eguan Highway can be established as the middle line, which is symmetrically arranged along both sides of the road, while the main reconstruction measures of the Maojiagou unit are scattered layout along the through-group roads.

(4) Traditional residence type mainly refers to the architectural history of long-term, rich cultural genes, and unique architectural style with the characteristics of the traditional residential. Such buildings have significant national and local colors and also have important historical and cultural values. This type of residence is suitable for protection as a historical building, and it is particularly necessary to pay attention to the inheritance and renewal of key elements such as its cultural connotation, historical context, and architectural style. In the two units of Qinglongwan and Shipo in the southeast of the village, the area of

low-level capacity homesteads accounts for about 45%. The farmers are mainly engaged in cultivating traditional crops such as rice, rape, and corn, and their homesteads carry out the functions of living and agricultural production. Villagers' houses are represented by elements like small green tiles and sloping roofs, which are the traditional residential building forms in Northern Guizhou. It is a relatively complete area of traditional farming production and housing construction form in Longfeng Village. Therefore, based on giving full play to their living and production functions, the reconstruction directions of homesteads in the above two units are mainly to pay attention to the maintenance of the house facades and improve its external facilities (roads to homes, tap water, electricity, broadband networks, etc.).

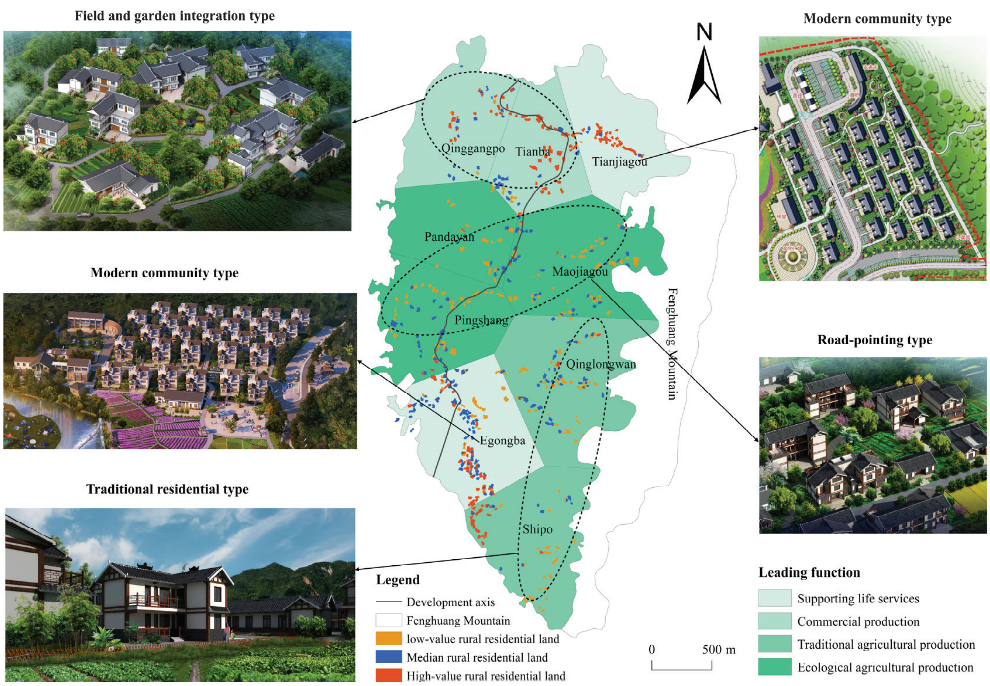

Figure 5. Distribution of spatial reconstruction patterns of farmers' homestead in Longfeng Village.

3.3.2. Analysis of Spatial Reconstruction Strategies of Homestead in Different Reconstruction Units

Considering the differences in resources and functions of different reconstruction units in the village domain, as well as the potential and positioning of the internal homesteads, the spatial reconstruction strategies of homesteads in different reconstruction units were formulated separately (Table 7).

Table 7. Spatial reconstruction strategies of different reconstruction units in Longfeng Village.

Reconstruction Units	Dominant Functions	Reconstruction Modes	Reconstruction Strategies
Tianjiagou, Egongba	Life service supporting	Modern community type	Improve the construction of modern community life supporting facilities, create a "dual-core" center in the north and south of Longfeng Village, and improve the degree of homesteads agglomeration. Gradually transform the existing houses according to unified standards, and guide residents to change to modern rural community life.

Table 7. *Cont.*

Reconstruction Units	Dominant Functions	Reconstruction Modes	Reconstruction Strategies
Tianba, Qinggangpo	Operational production	Field and garden integration type	Multi-channel financing to create a modern rural demonstration site with multi-functional integration of "residence + business + agricultural tourism + red culture". Encourage the circulation of vacant homesteads and realize the matching development of infrastructure construction and rural tourism.
Pandayan, Pingshang, Maojiagou	Ecological agriculture production	Road-pointing type	Integrating various preferential agricultural policies, deeply integrating the tea characteristic industry and traditional farming culture, to create ecological houses with tourism and sightseeing. Dividing the red line of the spatial layout of homesteads, strictly limiting the disorderly expansion of homesteads around the road axis, focusing on infrastructure construction, and continuously improving the production and living conditions.
Qinglongwan, Shipo	Traditional agricultural production	Traditional residential type	Carry out homestead consolidation and optimize the structure of rural homestead land. Encourage farmers to voluntarily withdraw from the homesteads for compensation, pay attention to the renovation of housing facades, build the regional houses of Northern Guizhou with cultural genes characteristics, and appropriately increase the basic supporting facilities such as domestic waste and sewage treatment.

4. Discussions

United Nations "Agenda 21" points out that many mountain areas around the world are facing environmental degradation, and, the sustainable development of mountainous areas is more important and urgent than ever [61]. Homestead, as the core component of the rural regional system in mountainous areas, has a good spatial development trend that can open the "meridian blockage" of the rural regional system and promote the "blood circulation" between the various elements in the system, which is an important path to solve the practical problems of empty waste, disorderly expansion, excessive area, and scattered layout of rural settlements in mountainous areas. Under this condition, the "point-line-surface" framework constructed in this study essentially reveals the common linear characteristics of the spatial evolution and layout of urban and rural settlements, which conforms to the general law of the development of urban and rural settlements in the global mountainous areas. To a certain extent, it breaks through the shackles of administrative boundaries, provides a new perspective for the optimization of international urban and rural settlements, and is of great significance for enriching the theoretical system of international rural spatial governance. In addition, although the study area focuses on a specific Chinese village, the typical representativeness of this case village in terms of natural conditions, industrial structure, and living space makes it expected to bring useful reference value to the spatial reconstruction of the same type of villages in other countries around the world (especially mountainous villages). However, this study still has the following limitations to be broken through. Firstly, the conceptual connotation and model framework of "point-line-surface" still need to be further deepened. This paper focuses more on case description and analysis, failing to deeply analyze the connotation and extension, morphological function, driving factors, and operational logic of "point", "line" and '"surface" at different scales. Therefore, how to continuously improve the "point-line-surface" model on this basis will become the focus of subsequent research work. Secondly, this study only uses the survey data of a single year to analyze the "point-line-surface" characteristics of rural housing in the case village and lacks long-term longitudinal analysis, which makes it difficult to grasp the long-term change characteristics of the rural homesteads at the micro level, especially how the internal structure and function of the rural homesteads change with the social and economic development.

With the strengthening of the interaction between urban and rural elements in the new era and the continuous drastic changes in the rural territorial system, the spatial optimization of rural settlements in mountainous regions not only undertakes a variety of policy management objectives from top to bottom but also appeals to multiple utilization demands from bottom to top. So, how to build a sustainable spatial equilibrium pattern of settlements under the influence of complex variables has become the key to revitalizing the world's countryside. Facing this complex background of global change, future research should focus on the following aspects. (1) Integration of multidisciplinary theories to continually enrich the theory of "point-line-surface" and provide new perspectives for the spatial planning and utilization of regional settlements. "Point-line-surface" is a theoretical framework characterized by openness, dynamism, and inclusiveness, which should not remain unchanged, but continuously update and improve the theoretical framework system through the continuous incorporation and integration of other proven effective theories and strategies, in order to satisfy the theoretical innovation needs raised by socio-economic changes. For example, the significant role of the "SWOT" framework for regional spatial planning has been widely confirmed [62–64]. Therefore, it seems to be a feasible and innovative program to enrich the evaluation index system, development status, and obstacle factors from four aspects of strengths, weaknesses, opportunities, and threats. Similarly, concepts and theories such as resilience [65], rurality [66], and center-periphery [67] should also be considered and integrated into the "point-line-surface" framework, so as to better provide theoretical support for evaluating and formulating regional spatial planning strategies. (2) Explore and expand the application scope and scenarios of the "point-line-surface" framework and evaluate its environmental and economic effects and social response behavior. The theoretical framework of "point-line-surface" should start from serving practice, and its scope of application should be extended from the spatial layout of urban and rural settlements to the fields of regional industrial layout, infrastructure construction, territorial spatial planning, etc. However, the application issues of "point-line-surface" in different fields such as obstacles, scenario simulation, and public response need to be studied in depth.

5. Conclusions

5.1. Main Conclusions

(1) In terms of the "point" characteristics of the homesteads, the article selected 20 indicators to build a model for measuring the development ability of the homesteads in the village and calculated that the development ability value of farmers' homesteads ranged from 0.2784 to 0.8439, and the overall level of development ability was not high. Among them, the number of high-value homestead plots accounted for 27.74%, with a "T" shape and long strip agglomeration distribution in the north and south of the village, respectively. The number of medium-value homestead plots accounted for 36.73%, which were mostly distributed in the middle village domain and around the development axis. And the number of low-value homestead plots accounted for 35.53%, which were mostly distributed along the Fenghuang Mountain, and the rest are scattered throughout the whole village.

(2) In terms of the "line" characteristics of the homesteads, within the 900 m buffer zone from the main development axis of Eguan Highway, the number and area of homesteads reach about 90%, and the spatial distribution of homesteads is characterized by axial development. In addition, there is a gradient decreasing law between the number and area of the homesteads with different capacity values and the distance from the main development axis in Longfeng Village, and within 600 m of the main development axis, the number and area of homesteads with high-level ability reach about 94%.

(3) In terms of the "surface" characteristics of the homesteads, nine spatial reconstruction units are divided by using the centroid of high-value homesteads as the weighted Voronoi diagram, and there are obvious differences among homesteads in each unit, among which the largest number and area of homesteads is in Egongba and the smallest is in Pandayan. Overall, the development capacity value of homesteads in each reconstruction unit has the spatial characteristics of "high in the northern region, low in the central region, and general in the southern region".

(4) According to the spatial characteristics of the "point-line-surface" of homesteads, this paper proposed four spatial reconstruction modes of homesteads for different reconstruction units in Longfeng Village, including modern community type, field and garden integration type, road-pointing type, and traditional residential type.

5.2. Implementing Suggestion

Among them: (1) The modern community type should improve the construction of modern community life-supporting facilities and guide residents to gradually adapt to modern rural community life. Focusing on the various elements of the whole life of the community, effectively integrating various resources, leading the participation of multiple social subjects, integrating various functions, and building a new type of intelligent service community for sustainable development. (2) The field and garden integration type should focus on building a multi-functional integration of modern rural residential demonstration sites and realizing the matching development of infrastructure construction and rural tourism. Based on ecologically sustainable agriculture, vertical integration will be realized by extending the industrial chain and developing the integration of planting (raising), processing, and marketing. And horizontal integration will be realized by expanding the diversified value and developing a variety of business modes of agriculture, culture, and tourism. (3) The road-pointing type should focus on controlling the demolition and construction of homesteads around the road axis and delimiting the boundary line of the spatial layout of homesteads. Give full play to the advantages of road transportation, improve the rural logistics network, open up the e-commerce into the village, the express into the home of the "last kilometer", and drive industrial products to the countryside and agricultural products into the city. (4) The traditional residential type can be created for regional houses in Northern Guizhou with the characteristics of cultural genes by carrying out rural homestead consolidation and other measures and adding basic supporting facilities. Meanwhile, we should fully understand the local and national culture in traditional architecture and realize the continuation and inheritance of characteristic architecture through innovative design and Internet platforms, online+ offline, architecture+ Internet+ culture, and other modes.

Author Contributions: Conceptualization, D.F. and Y.F.; methodology, J.L.; software, J.L.; validation, D.F., Y.F. and J.L.; formal analysis, Y.F.; investigation, D.F.; resources, Y.F.; data curation, D.F.; writing—original draft preparation, D.F.; writing—review and editing, Y.F.; visualization, J.L.; supervision, D.F.; project administration, Y.F.; funding acquisition, Y.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant no. 42261044.

Data Availability Statement: Not applicable.

Acknowledgments: The authors extend great gratitude to the anonymous reviewers and editors for their helpful reviews and critical comments.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Simultaneous Decisions to Undertake Off-Farm Work and Straw Return: The Role of Cognitive Ability

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Abstract: Using a sample of 1166 maize-planting farmers from Liaoning province in China, in this paper, we provide a new explanation for the slow-proliferation situation of straw return. Both our theoretical and empirical results indicate that the low rate of adoption of straw return can be partly attributed to the farmers' choice to undertake off-farm work. Probit, PSM, IV-probit, and bivariate probit models are utilized to estimate the interdependent nature of these two simultaneous decisions, with an identified causal effect ranging from −0.115 to −0.287. Instead of the "income-increasing effect", our research supports the dominant existence of the "lost-labor effect". Furthermore, intelligent and risk-tolerant farmers undertaking off-farm work are found to have additional negative impacts on the likelihood of straw return adoption. With regard to the mediating mechanisms, we find that the choice of off-farm work may decrease the probability of raising cattle and also downscale arable land, thereby reducing the likelihood of straw return adoption. In line with our proposed model, fluid cognitive ability contributes to the farmers' adoption of straw return by increasing their learning and updating efficiency. In contrast, crystal cognitive ability deters the undertaking of nonfarm work by establishing a comparative advantage in agricultural production, thus indirectly promoting the proliferation of straw incorporation. According to our theoretical and empirical findings, the proper policy interventions proposed mainly include three points. First, governments should endeavor to increase agricultural specialization by further promoting arable land transfer and human capital accumulation in farming. Second, it is beneficial to facilitate the process of learning by doing and social learning by enhancing the human capital levels of farmers. Last, it is necessary to cultivate farmers' inclination towards long-term investment by explaining the concrete benefits of straw return to farmers on a timely basis.

Keywords: off-farm work; straw return; PSM; IV-probit model; bivariate probit model

Citation: Zeng, J.; Lyu, J. Simultaneous Decisions to Undertake Off-Farm Work and Straw Return: The Role of Cognitive Ability. *Land* **2023**, *12*, 1599. https://doi.org/10.3390/land12081599

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 11 July 2023
Revised: 9 August 2023
Accepted: 9 August 2023
Published: 14 August 2023

1. Introduction

China has witnessed a fast and steady increase in agricultural production during recent decades. Accompanied by the growth in crop yield, straw resources annually produced by China have exceeded 700 million tons since 2014 [1]. Meanwhile, with the improving living standards of farmers, direct demand for straw for cooking and feeding livestock has reduced dramatically [2]. To enhance the demand for crop residuals, using straw as a base material along with biofuel and industry raw materials has been proposed by specialists. However, due to the high costs associated with stalk collection, transportation, and industrial treatment, open burning of straw is still common in some rural areas in China [3], causing significant damage to arable land, including soil erosion [4], soil infertility [5], and a decrease in farmland biodiversity [6]. Bearing this in mind, the 14th Five-Year Plan for Circular Economy Development issued by the State Council of China proposed that the overall utilization rate of crop straw should reach 86% by the year 2025 [7]. Among the five common treatment approaches for utilizing stalks, incorporating mechanically minced straw pieces into the field as manure is considered the most beneficial way of increasing crop yields and promoting arable land protection [8]. Therefore, an increase in the straw return rate has always been the target of relevant policies in recent years, and the recommendations of these policies range from the provision of direct subsidies for adopters of straw return to strict punishment for burning straw in open fields [9].

Compared with the quick diffusion in most developed countries such as the United States of America, Canada, and Japan, where about 70% of crop straw is directly returned to the soil [10], less than 50% of farming land in China adopted straw return in 2019 [11]. Furthermore, there are still great regional variations across China, where the straw return rate of the northeast region is relatively low due to huge straw resources and climate conditions [12]. In contrast to other regions that practice the wheat–maize double cropping system, the majority of farmers in the northeast region prefer to adopt maize mono-cropping due to lower temperature conditions. Our survey conducted in Liaoning province, which is situated in the northeast region, revealed that only 26.2% of the maize straw produced was utilized in the fields, indicating a suboptimal level of incorporation. As relevant research indicates, at least 70.4% of maize straw should be returned to the field to counterbalance the carbon produced in maize cultivation and to achieve the goals of soil protection and crop yield enhancement [13]. The subsidy for farm land with straw coverage of more than 60% was raised to CNY 90 per mu in 2023 by the Liaoning provincial government [14]. Surprisingly, the rising degree of policy stimulus and the lagging dissemination of straw return in Liaoning province have attracted little attention from researchers.

As a method for protective tillage or green agriculture production, straw incorporation benefits farmers in the long term. Furthermore, it is commonly believed that straw return can benefit arable land in several ways, such as by restoring land activity, reducing soil erosion, enhancing soil fertility, and enhancing field ecosystems. Nonetheless, due to combined factors such as the increased uncertainty regarding crop yield and externalities concerning the public environment, the adoption of straw return by farmers is a relatively long process in developing countries such as China. Thus, it is a clear aim for Chinese researchers to identify critical impeding factors to smoothen the transformation process. Based on new-classical economics, early research focused on the analytical framework of profit maximization, aiming to discern the effect of the scale of arable land, individual- and household-level factors, and relevant policies on the probability of straw return adoption [15,16]. The latest exploration has shifted to institutional and behavioral economics; hence, new human capital and bounded rational theory are utilized to explain farmers' conduct with respect to technology adoption [17]. The empirical results of frontier research reveal that the ability to obtain and process information [18], risk and time preference [19], and formal and informal institutional arrangements [20] are factors that have pronounced effects on the decision of a farmer to adopt straw incorporation.

While existing research has yielded fruitful results, there are still two aspects that require further exploration. The first aspect is that incomes from both farm and nonfarm activities determine the wellbeing of rural households [21]. This means that the adoption of new agricultural technologies may be closely related to the decision to undertake nonfarm employment. On the one hand, increased income can speed up the process of adopting modern technology by alleviating the financial constraints of rural households [22]. On the other hand, if time must be allocated between agricultural and non-agricultural activities, the process of adopting innovative technology may be prolonged [23]. The second aspect lies in the lack of exploration of the process of obtaining, updating, and analyzing relevant information about new agricultural technologies. To be specific, we should learn more about the interactive role of off-farm work and cognitive ability in deciding the maximization of total profits from farm production and employment. Theoretically speaking, cognitive ability not only has the power to explain the adoption of straw return to the field but is also an important factor in determining the income from nonfarm activities.

Based on the current state of straw return in China and the existing body of research, we investigated the joint decision between off-farm work and straw return among 1166 maize-planting farmers in Liaoning province. Additionally, we examined the specific influence of cognitive ability on these joint decisions. Our paper contributes to the existing literature in the following three aspects: first, in contrast to previous research neglecting the nature of joint decisions concerning straw return, we provide a convincing theory and empirical evidence that the choice of nonfarm employment significantly decreases the probability of adopting this technology. Second, we comprehensively examine the underlying influences of off-farm work on straw return by proposing the "lost labor effect" and "income-increasing effect". Our analysis of the mediating effect contributes to identifying the channels of off-farm work in respect of the straw-to-field process. Lastly, in addition to the choice of straw return, the determination of undertaking off-farm activities is explored. Concrete roles of human capital, such as cognitive ability and education, are examined to better understand the relationship between off-farm work and straw return. To our knowledge, this study is the first to measure fluid and crystal cognitive ability in the related research field of straw return.

The remaining content is organized as follows: the next section introduces relevant literature concerning straw return and off-farm work. In Section 3, we probe into the theoretical background and propose a hypothesis. Section 4 includes a description of the data and summary statistics. An empirical analysis is conducted in Section 5. We discuss our new findings, research limitations, and policy implications in Section 6. Finally, we present our conclusions in Section 7.

2. Literature Review

2.1. Straw Return Decision

From the angle of disciplines, most of the research on straw-returning determination is presented from the perspective of psychological and management studies. These studies use models such as the theory of planned behavior (TPB) [24], protection motivation theory (PMT) [25], and the unified theory of acceptance and use of technology (UTAUT) [26] to explore the willingness to adopt straw returning. Psychological and social variables such as perceived usefulness, perceived ease, perception of risks, subjective norms, and social trust are considered core determinants of the intention of farmers to utilize straw incorporation [27]. By revealing the psychological process of accepting an innovative technology, this approach has both merits and demerits. The core strength of this approach is the high explaining power of intention to adopt new technology by providing a systematic framework between the psychological constructs [28]. However, one of the drawbacks lies in the possibility that intention may not lead to action under certain circumstances. For example, some studies contend that there are huge discrepancies between willingness and behavior to adopt modern technology [29]. Another shortcoming is that rather than predetermined variables, psychological constructs such as the perceived usefulness of technology are in essence dependent variables, since it is more valuable to focus on how farmers formulate their perception of the usefulness of a new technology.

Instead of focusing on intention or willingness, economists pay more attention to farmers' behavior when adopting a new agricultural technology. In general, farmers are assumed to pursue maximization of profit or wellbeing, although the latest studies have begun to introduce frontier achievements in behavioral economics and new human capital theory. Furthermore, to explain the delayed dissemination of the modern approach to agricultural production, advancements in psychology such as the measurement of time and risk preference are also utilized. There are two major breakthroughs in the latest literature in economics.

The first breakthrough is to consider technology adoption as a dynamic and complex learning process, thus emphasizing the capacity of farmers in information acquisition and processing [30]. From this perspective, one central element entering the decision-making process is that farmers have bounded rationality, so "irrational" conduct such as postponing the adoption of a seemingly beneficial technology is in essence reasonable. During the learning process, farmers are literally Bayesian learners, continuously updating the information about the uncertainty of utilizing new technology [31]. Among the information-gathering channels, "learning by doing" and social learning are equally important in disseminating technology knowledge [32]. The differences between these two channels are that the efficiency of "learning by doing" is positively related to cognitive abilities, while farmers with low levels of cognitive ability are more likely to rely on social learning [33]. Empirical evidence indicates that if the adoption of technology is in combination with other factors such as different tillage, fertilization, and irrigation practices, the resulting uncertainty and complexity will entail a more influential role for cognitive ability [34]. The complexity of technology also highlights the salience of social learning, which not only means learning from others but also signifies learning together with others [35]. In addition to the evidence that the cumulative experiences of all the farmers in a village can positively lead to the diffusion of a technology [36], both the "threshold model" and network theory are proposed to signify the importance of tight social relationships in alleviating the constraints of information friction [37].

The second major breakthrough involves recognizing personal characteristics such as risk and time preference as factors that influence the spread of technology in underdeveloped countries. Recent research suggests that when adopting a new technology introduces uncertainty, the process of adoption may be delayed because farmers are more likely to avoid ambiguity [38]. This means that without proper intervention, the delayed diffusion process of technology adoption can be long-lasting [39]. Another interesting finding is that farmers do not simply conform to mean-variance analysis but pay more attention to the lower tail of the payoff distribution [40]. Concluding from the downside risk-averse feature of developing counties, the low adoption rate of straw return can be partly explained since, if it is not properly handled, straw return may lead to the downside risk of decreased crop yields caused by pests and disease. In addition to risk preference, time preference plays a significant role in explaining procrastination in relation to new technology in poor regions [41]. One viewpoint is that future-biased farmers may save up and thus be more likely to migrate to cities, with present-biased farmers remaining in rural regions [42]. Therefore, the problem lies in the fact that even if farmers make clear the payoff distribution of introducing a new technology, high subjective discounting rates can decrease the present value of a future investment [43]. In a survey of rural regions in Uganda, Bauer and Chytilová attributed the present-oriented feature of farmers to low education levels [44]. The negative impact of time preference on the straw return behavior of Chinese farmers was also identified by Mao et al., further demonstrating the importance of enough patience in evaluating the tradeoffs between intertemporal choices [45].

2.2. *Off-Farm Work and Agricultural Investment*

As China's economy is in transition, it has been relaxing its household registration system during the past forty years, generating a large number of rural migrant workers previously restricted to the countryside. According to official statistics, there will be about 285 million rural migrant workers in 2020 [46]. However, most of them were confined to nonstandard employment, pursuing contingent, precarious, and flexible jobs with few social security benefits [47]. Therefore, for most rural migrant workers, their household members still undertake farming production to maximize the total earnings of the family. Off-farm work provides important sources of monetary compensation in all developing countries where income from farming is more limited [48]. From the perspective of agricultural development, economists have conducted intensive research concerning the effect of off-farm activities on the proliferation of agricultural technology [49]. The conclusions diverge into two contradictory strands.

The first viewpoint is that off-farm work is complementary to the modernization of agriculture. This strand of literature contends that participation in nonfarm activities can alleviate poverty, thus contributing to relaxing the financial constraints hindering the adoption of new technology [50]. This viewpoint is consistent with the prediction that farmers, compared with urban inhabitants, are more susceptible to credit constraints because insurance and credit markets in rural regions are not well developed, especially in developing countries [51]. Separately setting income from off-farm work and expenditure on farming as the independent and dependent variables, the elasticity estimated by Kilic et al. is larger than 0.1, which means that more than 10 percent of nonfarm income is spent on agricultural production [52]. Another channel proposed by Oseni and Winters is the risk diversification mechanism in respect of maintaining a steady income stream, for profits gained from farming are vulnerable to natural disasters [53]. Khanal and Mishra confirmed that the income smoothing function for off-farm work can reduce the variability of yearly payoffs, which is also beneficial for long-term agricultural investment [54].

The second viewpoint is that off-farm work can substitute for the activities carried out in farming, consequently stifling the innovation of agricultural production. Although some studies admit that off-farm income-generating activities improve the overall wellbeing of rural households, some studies have revealed a negative effect on farm investment in technology [55]. This channel is called the lost labor effect, which stresses that if a member of a household is engaging in non-agricultural activities, time or other resources must be sacrificed [56]. Based on a sample from Jiangxi province in China, Feng et al. confirmed the lost labor effect by finding that soil-improving investments such as the use of green manure are significantly reduced by the decision to undertake nonfarm work [57]. Another study on rural regions in China also identified the pronounced negative effect of nonfarm work on the use of fertilizer and manure [58].

3. Theoretical Analysis

The choice of a straw-returning process can be split into two stages. In the first stage, farmers with bounded rationality will consider time allocations between nonfarm and farming activities based on their human capital levels. If higher levels of education and cognitive ability lead to a higher probability of nonfarm participation, then time spent on farming will diminish but labor earnings will rise, which can alleviate the financial constraints impeding the adoption of new agricultural technologies. In the second stage, based on the given time resources allocated to farming and the income level obtained from off-farm jobs, cognitive abilities determine efficiency through processing and updating the gathered information about the new technology. The other dimension of cognitive ability is the accumulated knowledge about maize planting, which contributes to a better understanding of the payoffs resulting from straw returning.

Relying on the above analysis, we developed a joint determination model of nonfarm employment and straw return based on the farm household model first proposed by Huffman and then revised by Goodwin B K and Mishra [59,60].

First, suppose a rural family consists of a household head and their spouse; the utility level U is determined by leisure L_l, and the consumption of goods and services is C.

The utility of the family can be modeled as follows:

$$U = U(L_l,\ C) \tag{1}$$

The maximization of utility is subject to the following three constraints. Then, income constraints are set as follows:

$$P_g G + W_f X_f = P_q Q + W_m L_m + A \tag{2}$$

where P_g and G stand for the price and amount of goods obtained in the market, respectively. X_f and W_f are the inputs of the farm and the price of adopting straw return from the market. $P_q Q$ denotes the income from farming, while $W_m L_m$ and A represent income from the labor market and assets initially possessed, respectively.

Time constraints are set as follows:

$$T = F(\Gamma) + L_m + L_l \tag{3}$$

Equation (3) signifies that the total time resources of this representative family are allocated among farming $F(\Gamma)$, off-farm work L_m, and leisure L_l.

The production function of farming can be set as follows:

$$Q = Q\Big[X_f(\Gamma), F(\Gamma), H, \Gamma, \mathrm{R}\Big] \tag{4}$$

Equation (4) supposes that the farming output depends on the input purchased from the market X_f, the total labor of husband and wife $F(\Gamma)$, the human capital level of household H, and the adoption intensity of technology Γ. In addition, suppose that there are two levels of Γ, i.e., Γ_0 and Γ_1, representing the adoption of straw returning or not, respectively. Let both the inputs of the farm and the time allocation depend on the adoption of straw return. Further, human capital H includes cognitive ability, education, and health.

For the above four equations, we further assume that the prices of input factors, commodities, and the wage rate of nonfarm work are all exogenously determined. Under this assumption, the first-order condition can be found using the Lagrange expression:

$$L = U(L_l,\ C) + \lambda\ \Big\{P_q\ Q\Big[X_f(\Gamma), F(\Gamma), H, \Gamma, \mathrm{R}\Big] - W_f X_f(\Gamma) + W_m L_m + A\Big\} + \mu(T - F(\Gamma) + L_m + L_l) \tag{5}$$

Then, the off-farm participation can be found from the following three equations conforming to the Kuhn–Tucker conditions:

$$\partial L/\partial \mathrm{F} = \lambda P_q\ (\partial Q/\partial \mathrm{F}) - \mu \tag{6}$$

$$\partial L/\partial \mathrm{L}_m = \lambda W - \mu \le 0 \tag{7}$$

$$\partial L/\partial \mathrm{L}_l = U_{L_m} - \mu = 0 \tag{8}$$

Under the corner solution specified by the following equation, this representative family chooses to participate in off-farm work.

$$W > \mu/\lambda = P_q\ (\partial Q/\partial \mathrm{F}) \tag{9}$$

To be specific, Equation (9) means that participation in off-farm work depends on whether the marginal benefits of market employment (wage rate from employment) are larger than the marginal benefits from agricultural production. Of the human capital variables, education plays a vital role in signaling productivity, therefore contributing to the likelihood of choosing off-farm work.

The total derivative of $\mathrm{dq}/\mathrm{d}\Gamma$ can be expressed as follows:

$$\frac{\partial L}{\partial \Gamma} = \lambda\Big\{P_q\ \Big[\Big(\frac{\partial Q}{\partial \mathrm{X}}\Big)\Big(\frac{\mathrm{dX}}{\mathrm{d}\Gamma}\Big) + \Big(\frac{\partial Q}{\partial \mathrm{X}}\Big)\Big(\frac{\mathrm{dX}}{\mathrm{d}\Gamma}\Big) + \frac{\partial Q}{\mathrm{d}\Gamma}\Big] - W\frac{\mathrm{dX}}{\mathrm{d}\Gamma}\Big\} - \mu\frac{\mathrm{dF}}{\mathrm{d}\Gamma} \le 0 \tag{10}$$

From Equations (9) and (10), we can obtain the following:

$$P_q\frac{\partial Q}{\mathrm{d}\Gamma} - W\frac{\mathrm{dX}}{\mathrm{d}\Gamma} - P_g\big(U_L/U_g\big)\ \frac{\mathrm{dF}}{\mathrm{d}\Gamma} \le 0 \tag{11}$$

The indication of Equation (11) is that if the marginal benefit of adopting straw returning is larger than the sum of the monetary marginal cost of farming inputs and the time marginal cost of the farming work, then adoption of this new production method is more profitable. Otherwise, farmers will not adopt straw returns. Based on the previous literature, fluid and crystal cognitive abilities both increase the marginal benefits of adopting straw return.

The above equations signify that the choice to undertake off-farm work may impact the adoption of straw return in two channels. The first channel is that off-farm work may increase the likelihood of straw return by raising the income level, which reduces the marginal cost of farming inputs. The second channel is via the "lost labor effect", which reduces the probability of adopting straw return, since off-farm work can crowd out the time needed to adopt straw return. Therefore, it is necessary to empirically test which of the channels dominates.

4. Methodology and Data

4.1. Methodology

4.1.1. Propensity Score Matching (PSM)

This method is used to estimate the treatment effect of undertaking nonfarm work on the probability of adopting straw incorporation. The notion of the propensity score was first proposed by Rosenbaum and Rubin [61] to denote the probability of an individual being treated given his observed covariates:

$$P = (D = 1 \mid X) = P(X) \tag{12}$$

Under the assumptions of unconfoundedness, the probability of being treated is totally determined by covariates but not by unobservable confounding factors. Moreover, if there is a large enough overlap region of common support, we can obtain a sample to derive the mean gap of two balanced groups with similar propensity scores. After reducing the estimation bias caused by unbalanced covariates [62], the average treated effect for the treated group (ATT) of undertaking nonfarm work on the probability of adopting straw incorporation can be expressed as follows:

$$\tau_{ATT}^{PSM} = E_{P(X)|D=1}\{E[Y(1)|\ D = 1, P(X)] - E[Y(0)|D = 0, P(X)]\} \tag{13}$$

4.1.2. Instrumental Variable Probit Regression (IV-Probit)

The endogeneity of undertaking nonfarm work on the adoption of straw return is generated by the feature of these two simultaneous joint decisions. Therefore, if the probit model is used, a biased coefficient will be obtained. In addition to the PSM method, another method by which to identify the causal effect of an endogenous variable on the binary dependent variable is to select a valid instrument satisfying the exclusion rule [63]. To be specific, the instrument variable does not impact the probability of adopting straw return but works through the channel of influencing the choice of nonfarm work.

The IV-probit model includes two regressed equations [64]. Firstly, the choice of choosing nonfarm work is regressed on the instrumental variable and the other independent variables.

$$P(O_i = 1) = \alpha X_i + \gamma Z + \rho_i \tag{14}$$

Secondly, the probability of adopting straw return is regressed on the predicted value of $P(O_i = 1)$ using a probit model.

$$P(R_i = 1) = \beta X_i + \delta \hat{O} + \sigma_i \tag{15}$$

Due to the exogenous nature of $\hat{O}$, the unbiased coefficient δ of $\hat{O}$ on $P(R_i = 1)$ can be estimated.

4.1.3. Bivariate Probit Model

This method can be used to explore the joint decision between off-farm work and straw returning. If they are negatively related, the negative effect of off-farm work on straw return can also be identified. These two decisions can be specified by Equations (9) and (11), respectively; we can therefore obtain the specific equations of joint decisions.

First, let O_i^* be a latent variable denoting the gap between the wage rate for off farm work and the marginal substitution rate between leisure and consumption. Although O_i^* is subjective and thus unobserved, we can observe the choice to undertake off-farm work O_i. The relation between O_i^* and O_i can be expressed by the following equation:

$$O_i^* = \alpha X_i + \varepsilon_i, \text{ where } O_i = \begin{cases} 1 & if\ O_i^* > 0 \\ 0 & otherwize \end{cases} \tag{16}$$

Second, let R_i^* be a latent variable representing the difference between the marginal benefit of adopting straw return and its marginal cost. R_i^* is also unobservable. Nonetheless, we can observe the actual choice of rural households in adopting this technology R_i. Their relationship can also be modeled as follows:

$$R_i^* = \beta X_i + \sigma_i, \text{ where } R_i = \begin{cases} 1 & if\ R_i^* > 0 \\ 0 & otherwize \end{cases} \tag{17}$$

The error term of Equations (16) and (17) can be denoted as follows:

$$\begin{pmatrix} \varepsilon_i \\ \sigma_i \end{pmatrix} \sim N\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{bmatrix} 1 & \rho_{\sigma\varepsilon} \\ \rho_{\varepsilon\sigma} & 1 \end{bmatrix} \right) \tag{18}$$

where $\rho_{\sigma\varepsilon}$ signifies the correlation coefficient between the error terms of Equations (16) and (17). If the value of $\rho_{\sigma\varepsilon}$ estimated using the bivariate probit method is significant, then we can conclude that these two decisions are related or interdependent.

4.2. Data and Variables

Among the three provinces situated in the northeastern region of China, Liaoning province boasts the largest population, with approximately 42 million individuals, of whom around 27% reside in rural areas. The data we gathered was derived from a cross-sectional household survey conducted between June and August of 2022, specifically targeting rural households engaged in maize cultivation in Liaoning province. To guarantee the random sampling rule, we first selected 11 regions of the 14 prefecture cities of this province according to the regional distribution of population, arable land per capita, and economic development level. The selected regions were Shenyang, Dalian, Fushun, Liaoyang, Benxi, Fuxin, Anshan, Huludao, Chaoyang, Jinzhou, and Tieling. We then used the approach of stratified sampling by randomly choosing one county for every region, four villages for every county, and 25–32 rural households for every village. We hired 35 investigators and trained them for a week in May. Then, for the following three months, 1333 household heads were interviewed face-to-face to record their answers to various questions at the individual, family, and village levels. After checking the validity, we finally obtained 1166 viable questionnaires.

Our dependent variable and core independent variable were both dichotomous, standing for the binary choices of straw return adoption and off-farm work, respectively. We first controlled the cognitive abilities of the household head, which were split into fluid and crystal cognitive abilities. Referring to the questionnaire of Frederick, fluid cognitive ability was evaluated using six questions on the abilities of reading, information acquisition, reasoning, and numerical analysis [65]. Seven questions concerning knowledge in respect of maize planting were designed to assess the crystal's cognitive ability regarding maize planting. For the thirteen questions, there was only one correct answer for the respondents to choose. Therefore, higher scores meant higher levels of ability. Time preference was measured using a subjective discounting rate by eliciting the equal value of CNY 100 in the next year [66]. We asked the subjects to respond to four binary choices, each with an increasing average maize yield but higher fluctuations, to evaluate their risk preference [67]. In addition to cognitive ability, human capital variables included years of formal education and the self-reported health conditions of the household head. Rather than measuring geographic distance, we used the social capital level as the efficiency of social learning to signify the complex contagion effect on the diffusion of straw return. To be specific, the family head's social capital levels were measured in four dimensions: social network, social trust, social reputation, and social participation [68]. In addition, variables at individual and family levels, such as age, gender, number of family members, family income, raising cattle or not, and arable land per capita, were all surveyed. Finally, the impact of the government, such as through propagation and punishment concerning straw return and burning, was also included.

Detailed descriptions of the variables are reported in Table 1.

Table 1. Descriptions of variables.

Variable Name	Variable Description
Straw return	1 stands for adopting straw return, 0 otherwise
Nonfarm work	1 stands for undertaking off-farm work, 0 otherwise
Fluid ability	Tested scores of fluid cognitive ability (Standardized)
Crystal ability	Tested scores of crystal cognitive ability (Standardized)
Time preference	Subjective discounted rate (%)
Risk preference	Risk aversion of the family head (standardized)
Age	Age of the household
Gender	1 stands for female, 0 for male
Education	Formal education years of the household head
Health	Self-reported health (five grades)
Family income	Total family income in 2021 (in thousand yuan)
Family number	Number of family members
Land per capita	Arable land per capita (mu)
Raising cattle	1 stands for raising cattle, 0 indicated no raising cattle
Social network	Social network of the family head (five grades)
Social trust	Social trust of the family head (five grades)
Social reputation	Social reputation of the family head (five grades)
Social participation	Social participation of the family head (five grades)
Propagation	Propagation of the government on straw return (five grades)
Punishment	Punishment of the government on straw burning (five grades)
Work * fluid	Nonfarm work * fluid cognitive ability
Work * risk	Nonfarm work * risk preference

5. Empirical Analysis

5.1. Summary Statistics

In order to facilitate a more comprehensive empirical analysis, Table 2 provides a systematic description of the variations in variable distribution between two distinct groups (adopters and non-adopters of straw return), as well as farmers engaged in nonfarm work versus those without such an occupation.

Table 2 indicates that only 54.1 percent of the maize farmers have adopted straw return in Liaoning province, and systematic discrepancies exist between nonadopters and adopters of straw return. To be specific, compared with nonadopters, a lower percentage of adopters undertake nonfarm work. Moreover, adopters apparently have higher levels of human capital and social capital, which can manifest as better fluid and crystal cognition, better education, and owning more social resources or recognition. Concerning personal preference, straw return adopters seem to be more future-biased but display little edge in risk tolerance. The statistical figures also show that straw return adopters are on average younger and healthier and possess larger amounts of arable land. Moreover, more than half of the straw return adopters raise cattle, which is much higher than that of nonadopters. Finally, it seems that the degree of propagation on straw return by the government is obviously higher for the adopters.

About 15% of farmers choose to pursue off-farm work, while the other 85% choose to undertake farming full-time. Striking differences can also be found between farmers engaged in nonfarm work and those who are not. One apparent difference is that it seems to be more likely for farmers without nonfarm work to adopt straw return. Nonetheless, the correlation between human capital and undertaking nonfarm work bifurcates. Specifically, although farmers engaged in nonfarm work are on average more intelligent and better educated, they obviously accumulate less knowledge about maize planting. Compared with full-time farmers, farmers undertaking nonfarm work are also younger, healthier, and wealthier, although they possess less arable land. In addition, there are small gaps in personal preference and the levels of social capital between them.

Table 2. Summary statistics.

Variable	Adopting Straw Return or Not		With or without a Nonfarm Job	
	Nonadopters	Adopters	Without an Off-Farm Job	With an Off-Farm Job
	Mean	Mean	Mean	Mean
Nonfarm work	0.19	0.11	0	1
Straw return	0	1	0.56	0.42
Fluid cognitive ability	−0.13	0.11	−0.04	0.21
Crystal cognitive ability	−0.07	0.06	0.04	−0.24
Time preference	9.34	8.90	9.12	9.01
Risk preference	0.77	0.79	0.78	0.78
Age	59.3	55.36	58.17	51.38
Gender	0.45	0.41	0.44	0.36
Education	7.33	7.71	7.37	8.49
Health	4.06	4.41	4.21	4.51
Family income	40.77	58.45	48.74	59.49
Family number	3.6	4	3.75	4.2
Land per capita	6.58	10.73	9.21	6.61
Raising cattle	0.037	0.55	0.33	0.25
Social network	3.36	3.49	3.42	3.45
Social trust	3.78	3.91	3.85	3.88
Social reputation	2.89	3.08	2.98	3.05
Social participation	3.45	3.69	3.6	3.48
Propagation	3.15	3.50	3.30	3.62
Punishment	4.26	4.19	4.21	4.27
Observations	535	631	993	173

In summary, our survey findings indicate that the straw return rate for maize in Liaoning province is lower compared to other regions in China. Additionally, there appears to be a negative correlation between the decision to engage in off-farm work and the adoption of straw return, as farmers involved in nonfarm activities are less inclined to incorporate straw. However, it should be acknowledged that further empirical analysis is necessary to test the causal relationship.

5.2. Empirical Analysis

5.2.1. Stepwise Regression Method

To disclose the effect of undertaking off-farm work on the probability of adopting straw return, we used the stepwise regression method by adding controlled and interaction variables stepwise. In Table 3, we present six probit regressions to show changes in the marginal effects of off-farm work and other controlled variables on the dependent variable.

According to Table 3, it is more likely for farmers with higher intelligence and more planting knowledge to adopt straw return. Nonetheless, inclusion of the "raising cattle or not" variable makes the direct effect of fluid cognitive ability insignificant, which means that more intelligent farmers have a higher probability of raising cattle. Despite the insignificant effect of risk preference, its interaction with a choice of off-farm work can exert pronounced impacts. In addition, it is more likely for healthier household heads, larger families, families with higher incomes, and families with more arable land to adopt a straw return. Concerning the social learning effect, both higher levels of social trust and participation facilitate the adoption of straw returns. In contrast to the significant effect of government propagation, punishment for straw burning in open fields seems to have an insignificant effect on straw return.

Table 3. Empirical results of stepwise regression of the probit model.

	(1)	(2)	(3)	(4)	(5)	(6)
Off-farm work	−0.170 ***	−0.231 ***	−0.223 ***	−0.235 ***	−0.115 ***	0.031
	(−4.23)	(−5.97)	(−5.77)	(−6.13)	(−3.51)	(0.41)
Fluid cognitive ability	0.058 ***	0.035 **	0.030 **	0.028 *	0.014	0.025 *
	(4.00)	(2.44)	(2.09)	(1.94)	(1.20)	(1.94)
Crystal cognitive ability	0.030 **	0.034 **	0.031 **	0.026 *	0.031 ***	0.031 ***
	(2.06)	(2.47)	(2.21)	(1.84)	(2.67)	(2.64)
Time preference	−0.016 *	−0.011	−0.013	−0.011	−0.007	−0.007
	(−1.91)	(−1.43)	(−1.63)	(−1.46)	(−1.07)	(−1.14)
Risk preference	0.022	−0.007	−0.033	−0.034	−0.027	−0.000
	(0.57)	(−0.19)	(−0.88)	(−0.89)	(−0.88)	(−0.01)
Education	0.014 **	−0.002	−0.004	−0.005	−0.001	−0.001
	(2.32)	(−0.28)	(−0.70)	(−0.79)	(−0.20)	(−0.16)
Age		−0.005 ***	−0.005 ***	−0.005 ***	−0.000	−0.000
		(−3.69)	(−3.81)	(−3.91)	(−0.03)	(−0.05)
Gender		−0.057 **	−0.054 *	−0.054 *	−0.019	−0.020
		(−2.02)	(−1.90)	(−1.92)	(−0.83)	(−0.87)
Health		0.079 ***	0.070 ***	0.071 ***	0.051 ***	0.050 ***
		(4.65)	(4.10)	(4.19)	(3.66)	(3.61)
Family income		0.001 ***	0.001 ***	0.001 ***	0.000	0.000
		(2.73)	(2.58)	(2.80)	(0.96)	(0.95)
Family number		0.034 ***	0.033 ***	0.032 ***	0.021 ***	0.021 ***
		(3.68)	(3.59)	(3.46)	(2.72)	(2.70)
Land per capita		0.003 **	0.003 **	0.002 *	0.003 ***	0.003 ***
		(2.10)	(2.05)	(1.69)	(2.79)	(2.80)
Social network			−0.014	−0.007	−0.032	−0.032
			(−0.42)	(−0.21)	(−1.21)	(−1.23)
Social trust			0.037	0.026	0.047	0.052*
			(1.07)	(0.76)	(1.64)	(1.82)
Social reputation			0.018	0.007	0.013	0.009
			(0.82)	(0.31)	(0.77)	(0.50)
Social participation			0.039 **	0.039 **	0.063 ***	0.063 ***
			(2.04)	(2.06)	(3.98)	(4.03)
Propagation				0.045 ***	0.050 ***	0.050 ***
				(4.39)	(5.75)	(5.78)
Punishment				−0.024	−0.026**	−0.026 **
				(−1.57)	(−2.00)	(−1.99)
Raising cattle					0.541***	0.540 ***
					(25.47)	(25.58)
Work * Fluid						−0.062 *
						(−1.94)
Work * Risk						−0.177 **
						(−2.02)
Pseudo R^2	0.0303	0.0944	0.1019	0.1144	0.357	0.3624
Observations	1017	1017	1017	1017	1017	1017

Note: ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively. Marginal effects rather than coefficients are reported.

For the effect of nonfarm activities, undertaking off-farm work significantly decreases the probability of straw return by more than 0.23. However, when the dummy variable "raising cattle or not" is controlled, this effect drops dramatically to 11.5%. More importantly, the interaction term between off-farm work and fluid cognitive ability is pronounced. This indicates that, for farmers with higher levels of fluid cognitive ability, undertaking off-farm work means a lower probability of adopting straw return. Similarly, risk-tolerant farmers have higher tendencies not to adopt straw return if they choose off-farm work. In summary, the empirical results of the stepwise regression support both the direct and interaction effects of off-farm work on the dependent variable. Of the variables, raising cattle or not seems to have a large effect on the pseudo R^2 value and the coefficient of off-farm work.

To further probe into the influencing channel of off-farm work on the dependent variable, the direct and indirect effects of this channel were empirically tested. We sequentially explored the mediating roles of raising cattle, arable land per capita, and health, as Table 4 reports. Of the mediators, raising cattle and land per capita were categorized into the lost labor channel, since undertaking off-farm work will decrease the probability of raising cattle and the scale of arable land due to the limitedness of time. Health acts as a mediator aroused by the income-increasing channel because off-farm work increases the family income and then positively impacts the health condition of farmers.

Table 4. Empirical test of mediating effects.

Channels	Mediator	Effects	Coefficient	Z	*p* > Z
Lost labor channel	Raising cattle	Indirect effect	−0.104 ***	−4.94	0.000
		Direct effect	−0.137 ***	−4.18	0.000
		Total effects	−0.241 ***	−6.01	0.000
	Land per capita	Indirect effect	−0.010 **	−2.12	0.034
		Direct effect	−0.137 ***	−4.01	0.000
		Total effects	−0.147 ***	−4.34	0.000
Income-increasing channel	Health	Indirect effect	0.009 **	2.09	0.036
		Direct effect	−0.137 ***	−4.14	0.000
		Total effects	−0.128 ***	−3.89	0.000

Note: *** and ** denote significance at 1% and 5% levels, respectively.

According to Table 4, the direct effect of undertaking off-farm work on the probability of adopting straw return is −0.137. The indirect effects of off-farm work on straw return via raising cattle and land per capita are, respectively, −0.104 and −0.01, which reveals that the lost labor channel is the main mechanism. To be specific, once employed, farmers have less energy to raise livestock or expand their farming scale. Raising cattle facilitates the adoption of straw return because digested crop straw will be returned to the field as manure. In addition, a larger scale of arable land can contribute to straw return due to the scale economy effect. For the income-increasing channel, rising income facilitates the improvement of health, which is beneficial to the adoption of straw returns. In summary, two channels and three mediators were identified, and the lost labor channel was more salient.

However, systematic discrepancies may exist between farmers undertaking nonfarm work and full-time farmers, as indicated by the results of the summary statistics. We therefore used the PSM and IV-probit methods separately to make these two groups more comparable by controlling or alleviating the self-selection bias.

5.2.2. PSM Method

Cross-sectional data analysis is prone to endogeneity, so we first utilized the PSM method to alleviate this problem. The core idea of the PSM method is to pair the treatment group and the control group together with similar propensity scores if random assignments are not available [69]. First, the logit model was used to calculate the probability of undertaking off-farm work, and the controlled variables included all the determinates in Table 3. Then, we utilized the three most commonly used PSM methods (radius matching, kernel matching, and the stratification method) to reduce the selection bias [70]. As recommended by Becker and Caliendo [71], we set the caliper of the radius match to 0.01. After excluding the unmatched units outside the common support region, most of the samples were kept.

Furthermore, as the table below indicates, bias between the treatment and comparison groups was reduced substantially after the implementation of matching. Especially for the radius- and kernel-matching methods, mean biases decreased to 3% and 2%, respectively. The four matching methods are hence effective in balancing the distribution of the covariates, since the initial mean bias is as high as 20.1%. After pairing the treated and untreated groups, we obtained a counterfactual effect of pursuing off-farm work on the probability of adopting straw return. The treatment effects for the treated group are reported in Table 5.

Table 5. Empirical results of PSM.

Matching Methods	Mean Bias	Treated	Controls	Difference (ATT)	T (Z) Value
Unmatched	20.1	0.416	0.563	−0.147 ***	−3.59
Radius	3.6	0.413	0.528	−0.114 **	−2.42
Kernel	2.5	0.413	0.546	−0.133 **	−2.86
Stratification	3.3	0.413	0.556	−0.144 ***	−3.62

Note: *** and ** denote significance at 1% and 5% levels, respectively.

Table 5 reveals that after controlling for the selection bias, the difference between treatment and comparison groups decreased slightly from −0.147 to more than −0.11. This means that the systematic discrepancies between these two groups cause a downward bias if not well controlled. In other words, PSM methods also indicate that the choice of off-farm work will significantly decrease the likelihood of straw return. In summary, the results of PSM are all greater than −0.100, a little larger than those of stepwise regression, which are about 0.115.

5.2.3. IV-Probit Model

One criticism of PSM is that if the effects of the unobservable variable on the propensity scores cannot be ignored, then the seemingly balanced matching method cannot efficiently decrease the selection bias. Against this background, an instrumental variable probit regression model was also used to control the bias. We argue that party membership in the CPC, road conditions, and the natural disasters of the past five years in this village are all valid instrumental variables [72]. This is because party membership and better road conditions mean more opportunities for off-farm work, but these two variables may not impact the choice of straw return directly. Furthermore, more severe natural disasters will negatively impact the income from farming, thus influencing the choice of off-farm work. As described in Section 4.2, the specification of the IV-probit model is similar to two-stage least-squares regression. The first-stage regression can obtain the predicted value of the treatment variable by regressing the instrumental variable and the other independent variables. Then, an unbiased estimation of the treatment effect can be achieved for the second regressed equation. Compared with PSM, IV-probit does not rely on the assumption of ignorability; thus, the results may be more robust. Table 6 reports the results of both the probit and IV-probit models.

The table above shows that after controlling the predicted value of the probability of undertaking nonfarm work, the t values of some independent variables dropped pronouncedly, although their coefficients remained almost the same. Specifically, the t values of nonfarm work, time preference, income of family, and social participation decreased significantly, partly because the predicted value already contained some of their information. Despite the decreasing significance, the results of the IV-probit model indicate that the marginal effect of nonfarm work on the probability of adopting straw return rises dramatically. Therefore, similar to the results of the PSM method, omitting the endogeneity problem causes a downward bias. In summary, in addition to PSM, the IV-probit model identifies a significant negative effect of nonfarm work on the adoption of straw return, and the estimated coefficient is larger compared with those of the probit and PSM models. Our results indicate that if self-selection bias is better controlled, the marginal effect increases from −0.115 to −0.287.

Table 6. Marginal effects of IV-probit models.

Variable	(1)	(2)	(3)
	Probit	**IV-Probit**	
		First Stage	**Second Stage**
Nonfarm work	−0.115 ***		−0.287 *
	(−3.51)		(−1.74)
Fluid cognitive ability	0.014	0.009	0.016
	(1.20)	(0.90)	(1.35)
Crystal cognitive ability	0.031 ***	−0.022 **	0.026 **
	(2.67)	(−2.21)	(2.00)
Time preference	−0.007	0.001	−0.007
	(−1.07)	(0.23)	(−1.00)
Risk preference	−0.027	−0.007	−0.028
	(−0.88)	(−0.26)	(−0.90)
Age	−0.001	0.008 *	0.001
	(−0.20)	(1.80)	(0.16)
Gender	−0.000	−0.006 ***	−0.001
	(−0.03)	(−5.77)	(−0.76)
Education	−0.019	−0.047 **	−0.030
	(−0.83)	(−2.36)	(−1.19)
Health	0.051 ***	0.037 ***	0.056 ***
	(3.66)	(2.68)	(3.79)
Family income	0.000	0.000	0.000
	(0.96)	(1.31)	(1.04)
Family number	0.021 ***	0.010	0.024 ***
	(2.72)	(1.56)	(2.98)
Land per capita	0.003 ***	−0.003 ***	0.002 **
	(2.79)	(−2.69)	(2.11)
Social network	−0.032	0.002	−0.031
	(−1.21)	(0.08)	(−1.16)
Social trust	0.047	−0.011	0.048*
	(1.64)	(−0.44)	(1.67)
Social reputation	0.013	0.004	0.013
	(0.77)	(0.28)	(0.77)
Social participation	0.063 ***	−0.043 ***	0.056 ***
	(3.98)	(−3.19)	(3.25)
Propagation	0.050 ***	0.023 ***	0.056 ***
	(5.75)	(3.00)	(5.74)
Punishment	−0.026 **	0.014	−0.026 **
	(−2.00)	(1.29)	(−2.01)
Raising cattle	0.541 ***	−0.084 ***	0.526 ***
	(25.47)	(−3.71)	(18.85)
CPC membership		−0.046*	
		(−1.92)	
Road condition		0.052 ***	
		(3.46)	
Natural disaster		−0.022 *	
		(−1.82)	
Pseudo R^2	0.357	0.1636	0.3513
Observations	1166		1166

Note: ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively. Marginal effects rather than coefficients are reported. The validity of the instrumental variable was checked, including weak IV and overidentification tests.

5.2.4. Bivariate Probit Model

We utilized the bivariate probit model to explore the interdependence of the two dependent variables and to estimate whether $\rho_{\sigma\varepsilon}$ was significantly different from zero. The logic is that the correlation coefficient between two variables is equal to the sum of the causal and reverse-causal effects between these two decisions. If their interdependent relationship does exist, then we can further ascertain the causal effect of nonfarm work on the probability of straw incorporation adoption.

Concerning the determination of independent variables, we assumed that the two decisions are both influenced by cognitive ability, time and risk preferences, and variables at individual and family levels. However, the straw return decision will additionally be impacted by variables at the government policy level, such as propagation and punishment.

To test the significance of $\rho_{\sigma\varepsilon}$, we first report the results of the first-stage regression in Table 7. It is noteworthy that cross-sectional data can provide the relatedness of the regressor and regressed, which is the sum of the causal and reverse-causal effects between them. Under the guidance of our theoretical analysis, we interpreted the meaning of the coefficients.

Table 7. Empirical results of bivariate probit.

Variable	(1) Off-Farm Work	(2) Straw Return
Fluid cognitive ability	0.0290	0.0532
	(0.59)	(1.14)
Crystal cognitive ability	−0.106 **	0.136 **
	(−2.16)	(2.82)
Time preference	0.00517	−0.0277
	(0.50)	(−1.27)
Risk preference	−0.0323	−0.107
	(−0.24)	(−0.87)
Education	0.0557 **	−0.00907
	(2.59)	(−0.47)
Age	−0.0261 ***	0.00272
	(−5.43)	(0.58)
Gender	−0.238 **	−0.0513
	(−2.32)	(−0.56)
Health	0.197 **	0.187 **
	(2.88)	(3.16)
Family income	0.00150	0.00101
	(1.58)	(0.88)
Family number	0.0567	0.0791 **
	(1.63)	(2.56)
Land per capita	−0.0155 **	0.0127 **
	(−2.13)	(2.65)
Social network	0.0132	−0.130
	(0.12)	(−1.28)
Social trust	0.0118	0.180
	(0.10)	(1.53)
Social reputation	0.0377	0.0501
	(0.48)	(0.69)
Social participation	−0.178 **	0.265 ***
	(−2.53)	(3.71)
Propagation		0.197 ***
		(5.48)
Punishment		−0.102 **
		(−2.09)
Cattle	−0.516 ***	2.183 ***
	(−4.67)	(16.00)
Constant	−0.433	−2.972 ***
	(−0.70)	(−4.87)
Rho21	−0.252 ***	
	(−3.40)	
N	1166	1166

Note: *** and ** denote significance at 1% and 5% levels, respectively.

As reported in Table 7, education contributes to the choice to undertake off-farm work yet exerts no significant effect on increasing the straw return rate of farmers. It is more likely for a healthier and younger rural household to simultaneously choose nonfarm work and straw return. As a long-term investment, the adoption of straw returns is stifled by higher subjective discounted rates. A larger scale of arable land can deter farmers' from choosing to undertake off-farm work and facilitate the proliferation of straw returning through the scale economy channel in agricultural production. Additionally, the effects of crystal cognitive ability and social participation on straw incorporation are significantly positive, while they are both significantly negatively related to the choice to undertake nonfarm work.

The empirical findings demonstrate that different human capital factors have unique impacts on the decision to engage in nonfarm work or agricultural production. While education primarily has a positive influence on off-farm work, fluid cognitive ability is more important in agricultural production. Interestingly, there has been ongoing debate regarding why education has limited explanatory power in predicting farming productivity. This is because education is significant in respect of signaling abilities in the labor market, whereas small-scale farmers do not need to signal their productivity to themselves as they are self-employed.

In summary, Rho21 is significantly less than zero, which indicates that the decisions to undertake nonfarm work and adopt straw return are negatively related. Even if the two decisions are made jointly, we can still interpret the choice to undertake off-farm work as having a pronounced negative effect on the decision to engage in straw returning.

5.3. Robustness Check

To check the robustness of the previous conclusions, we deleted samples that reported that they adopted straw returns only because the local government required them to do so. If their choice to undertake straw return was compulsory, then undertaking both off-farm work and cognitive abilities do not have explaining power. After removing 149 subsamples, our sample was reduced to 1017. Using the new sample, we ran the stepwise regression, as shown in Table 8.

Table 8. Empirical results of stepwise regression of the probit model (new sample).

	(1)	(2)	(3)	(4)	(5)	(6)
Off-farm work	−0.136 ***	−0.208 ***	−0.204 ***	−0.212 ***	−0.086 ***	0.038
	(−3.19)	(−5.06)	(−4.97)	(−5.14)	(−2.58)	(0.51)
Fluid cognitive ability	0.037 **	0.014	0.014	0.013	0.001	0.011
	(2.33)	(0.90)	(0.92)	(0.85)	(0.04)	(0.81)
Crystal cognitive ability	0.018	0.024	0.023	0.021	0.027 **	0.027 **
	(1.14)	(1.63)	(1.56)	(1.41)	(2.27)	(2.25)
Time preference	−0.021 **	−0.013	−0.015 *	−0.014 *	−0.009	−0.009
	(−2.37)	(−1.64)	(−1.81)	(−1.69)	(−1.38)	(−1.45)
Risk preference	0.013	−0.016	−0.032	−0.031	−0.031	−0.005
	(0.30)	(−0.40)	(−0.78)	(−0.75)	(−0.95)	(−0.15)
Education	0.016 **	−0.003	−0.004	−0.004	0.002	0.002
	(2.48)	(−0.47)	(−0.62)	(−0.67)	(0.34)	(0.36)
Age		−0.007 ***	−0.007 ***	−0.007 ***	−0.001	−0.001
		(−4.97)	(−4.95)	(−4.97)	(−0.96)	(−1.00)
Gender		−0.067 **	−0.062 **	−0.062 **	−0.014	−0.015
		(−2.22)	(−2.04)	(−2.05)	(−0.57)	(−0.62)
Health		0.041 **	0.035 *	0.037 **	0.022	0.022
		(2.22)	(1.85)	(1.99)	(1.55)	(1.53)
Family income		0.002 ***	0.002 ***	0.002 ***	0.001 **	0.001 **
		(4.49)	(4.27)	(4.34)	(2.14)	(2.12)
Family number		0.025 **	0.025 **	0.024 **	0.011	0.010
		(2.47)	(2.46)	(2.39)	(1.30)	(1.27)
Land per capita		0.002	0.002	0.001	0.002 **	0.002 **
		(1.35)	(1.17)	(0.99)	(2.36)	(2.39)
Social network			−0.020	−0.015	−0.040	−0.041
			(−0.58)	(−0.45)	(−1.52)	(−1.57)
Social trust			0.079 **	0.073 **	0.086 ***	0.091 ***
			(2.15)	(1.97)	(2.96)	(3.14)
Social reputation			0.002	−0.004	0.006	0.003
			(0.09)	(−0.18)	(0.35)	(0.15)
Social participation			0.012	0.013	0.046 ***	0.046 ***
			(0.55)	(0.65)	(2.83)	(2.86)
Propagation				0.025 **	0.030 ***	0.030 ***
				(2.25)	(3.35)	(3.39)
Punishment				−0.020	−0.020	−0.021
				(−1.22)	(−1.58)	(−1.63)
Raising cattle					0.535 ***	0.534 ***
					(30.74)	(30.88)
Work * Fluid						−0.056 *
						(−1.71)
Work * Risk						−0.152 *
						(−1.73)
Pseudo R^2	0.0213	0.0942	0.0994	0.1038	0.3983	0.4031
Observations	1017	1017	1017	1017	1017	1017

Note: ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively. Marginal effects rather than coefficients are reported.

Compared with the results of Table 3, Table 8 reports identical outcomes. However, two noticeable differences can still be found. The first difference is that the coefficient of off-farm work on straw return is a little smaller in Table 8, because the deleted subsample comprised only straw-return adopters. For the same reason, the coefficients of the two interaction terms also decreased slightly. The second difference is displayed in the change in Pseudo R^2. Taking regression (6) as an example, Table 8 seems to have a higher Pseudo R^2 value than Table 4. We therefore conclude that the deletion of compulsory adopters in fact increases the explaining power of the probit model. In summary, Table 8 indicates that most of the farmers in Liaoning province can freely choose whether to adopt straw return or not, and off-farm work does have a significant hindering effect on the proliferation of straw return.

6. Discussion

6.1. New Findings Compared to Previous Studies

Unlike previous studies, we have presented new findings in the three following aspects.

First, unlike most of the research that neglects the joint nature between the choice to undertake off-farm work and the adoption of straw return, we demonstrated that the two decisions are negatively related. This finding means that when making choices, farmers in fact jointly evaluate the benefits of farm and off-farm activities. Nonetheless, in most developing countries, undertaking off-farm activities is common, which can significantly impact the process of technology proliferation.

Second, we have contributed to the development of human capital theory by finding that human capital variables such as fluid cognitive ability, crystal cognitive ability, education, and health play different roles in the joint decisions to undertake off-farm and farm activities. Compared with other dimensions of human capital, education levels endow farmers with comparative advantages in terms of off-farm work by providing a screening tool. In contrast, cognitive abilities, especially fluid cognitive ability, matter more in the dynamic changes of agricultural production.

Thirdly, our findings support the fact that not all agricultural technology adoption is sensitive to income or financial constraints. On the contrary, the proliferation of certain technologies, such as straw return, is more susceptible to time allocation constraints. Hence, we believe that our empirical findings can be generalized to most developing countries where the adoption of straw return is mostly time-consuming; hence, the “lost labor effect” will dominate over the “income-increasing effect”.

6.2. Research Deficiencies and Prospects

Although this study offers a new perspective by utilizing a simultaneous decision approach, two shortcomings can still be identified.

First, we developed a theoretical framework to measure risk and time preferences by asking respondents to choose from the items listed instead of using experimental methods. Some researchers argue that risk and time preferences should be tested in the same questionnaire with real money incentives; otherwise, the results obtained from the tests will be biased [41]. Since we conducted more than 1100 interviews, the total cost of using the money incentive method would be more than CNY 100,000. For this reason, we gave up the experimental method and accepted the probably biased measured variables.

Second, both simultaneous and self-selection bias can cause endogeneity, which calls for panel data to properly solve this problem. However, it is difficult to survey highly mobile farmers at different times who intend to migrate. In this environment, cross-sectional data require more complicated empirical methods, and for this reason, we utilized different models to reach a relatively robust conclusion.

Based on the research deficiency analysis, future research should endeavor to ensure that the measurement of relevant variables is more accurate and create longitudinal data for more strict empirical analysis.

6.3. Policy Implications

Based on our empirical findings, four recommendations can be proposed.

The first valuable policy implication of effectively intervening in the proliferation of agricultural technologies is to increase agricultural specialization. Concrete policies include the promotion of transferring arable lands among farmers and increasing the efficiency of human capital accumulation. Since farmers' decisions are made in the context of allocations between nonfarm and farming activities rather than farm operations alone, edges in farming may be generated through the mechanisms of economies of scale and accumulated knowledge in planting. Scale economies in agricultural production and livestock breeding will cultivate more professional farmers who put little energy into nonfarm activities.

Secondly, the modernization of agricultural production entails the enhancement of human capital levels; thus, it is necessary to adopt aggressive training programs to smooth the channels of learning by doing. In a changing economic environment, farmers must continually make allocative decisions, thus strengthening the role of cognition in obtaining, processing, and updating relevant information concerning the adoption of new technologies. Compared with fluid cognitive ability, crystal cognitive ability is easier to cultivate. In addition, forming more cohesive social relations among farmers can compensate for the dysfunction of formal institutions by reducing the cost of information gathering through mutual and social learning.

Thirdly, we propose that in addition to providing subsidies to encourage farmers to adopt straw-returning practices, targeted strategies should prioritize cultivating farmers' inclination towards long-term investment. Specifically, these strategies should encompass comprehensive training programs for smallholder farmers, enabling them to fully comprehend the long-term benefits and develop patience in resisting the allure of immediate consumption. It is worth noting that low-income households tend to exhibit risk aversion and present bias, which often leads to underinvestment in profitable long-term projects. Therefore, alongside offering loans and subsidies, it is crucial to effectively communicate the tangible advantages of straw returning, such as increased crop yields and reduced agricultural production risks, to farmers in a timely manner.

Lastly, considering the low levels of cognitive abilities for most of the farmers, a portfolio of incentive policies and instructions should be adopted to realize the effect of straw return on the protection of arable land. When several new production methods are combined, it is more difficult for farmers to find the best practices. Taking the proliferation of the no-tillage farming method as an example, the government should not only propagate the concrete method of straw return but also instruct farmers to alternate fertilization and irrigation practices to achieve the best effects in arable land protection.

7. Conclusions

Based on a sample of 1166 maize-planting farmers, we estimated the causal effect of off-farm work on the adoption of straw return. Our conclusions mainly include three points:

First, through different empirical methods, our research robustly demonstrates that undertaking nonfarm work has a significant negative effect on the decision to adopt straw returning. Instead of supporting the income-increasing effect, our research identified a strong effect of the lost-labor hypothesis. Due to limited time resources, nonfarm employment substitutes for the adoption of straw incorporation by reducing the time allocated to agricultural production. Our conclusion suggests that although nonfarm employment provides an important source of financial compensation for farmers, the lost-labor effect reduces the diffusion of time-consuming agricultural practices.

Second, cognitive abilities matter in the joint decision to undertake off-farm work and straw returning, with fluid and crystal cognition playing different roles. Specifically, the fluid cognitive ability of a rural household significantly contributes to the proliferation of straw returning, while crystal cognitive ability significantly deters the decision to undertake nonfarm work by providing a comparative advantage in agricultural production. This conclusion confirms the theory that fluid cognitive ability can speed up the process of adopting new production practices by increasing learning and updating efficiency, whereas crystal cognitive ability can increase agricultural specialization by creating a competitive edge in farming.

Third, mechanism analysis shows that off-farm work not only interacts with fluid cognitive ability and risk preference but also exerts indirect effects through mediators such as raising cattle, the scale of arable land, and health. For the interaction effect, we found that more intelligent and risk-tolerant farmers undertaking off-farm work will have additional negative impacts on the likelihood of adopting straw return. Furthermore, the choice to undertake off-farm work will decrease the probability of raising cattle, downscale arable land, and reduce the likelihood of adopting straw return further.

Author Contributions: Conceptualization, J.Z. and J.L.; methodology, J.Z.; software, J.Z.; validation, J.Z.; formal analysis, J.Z.; investigation, J.Z.; resources, J.Z.; data curation, J.Z.; writing—original draft preparation, J.Z.; writing—review and editing, J.Z. and J.L.; visualization, J.Z.; supervision, J.Z.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Major Program of the National Social Science Fund of China (22&ZD083-4).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding author with the permission of the interviewees.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

The Impact of Rural Location on Farmers' Livelihood in the Loess Plateau: Local, Urban–Rural, and Interconnected Multi-Spatial Perspective Research

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Abstract: With the strengthening of regional and urban–rural interactions, farmers' livelihood activities are becoming increasingly complex, and environmental factors that influence farmers' livelihoods have multi-spatial effects. Consequently, comprehending farmers' livelihoods from a multi-spatial perspective is imperative. Based on surveys conducted in 65 villages and 451 households in Jia County on the Loess Plateau, China, rural locations were deconstructed into natural, traffic, and positional advantages to explore the relationships and mechanisms between the rural environment and farmers' livelihood stability from local, urban–rural, and interconnected multi-spatial perspectives. We found that 77% of the villages achieved a moderate or high Rural Location Advantage Index (RLAI) rating; 45% still lack natural advantages and are mainly located in hilly and sandy areas because of the fragile ecological environment of the Loess Plateau. Additionally, the Livelihood Stability Index (LSI) was moderate overall, but with significant spatial heterogeneity, and 72% of farmers possess strong transition capacity and have shifted away from relying on monoculture as their primary livelihood strategy. While a certain coupling correspondence exists between the LSI and RLAI, the interaction is intricate rather than a simple linear agglomeration process. The spatial variation in the LSI results from the superposition or interaction of multi-spatial location factors. The rural–urban spatial location factors are the key control element of the LSI and the interaction between rural–urban and local spatial location factors has the greatest influence on the LSI. It is simple for interconnected spatial location factors to produce a scale correlation effect, and have non-negligible effects on farmers' livelihoods when they interact with other spatial location factors. Understanding the impact of rural location on farmers' livelihood from a multi-spatial perspective is of great practical significance for identifying the causes of spatial heterogeneity in livelihoods and enhancing multi-level policy coordination on rural revitalization and livelihood security.

Keywords: livelihood stability; location advantage; geographic detector model; muti-spatial perspective; the Loess Plateau

Citation: Wang, Y.; Min, D.; Ye, W.; Wu, K.; Yang, X. The Impact of Rural Location on Farmers' Livelihood in the Loess Plateau: Local, Urban–Rural, and Interconnected Multi-Spatial Perspective Research. *Land* **2023**, *12*, 1624. https://doi.org/10.3390/land12081624

Academic Editors: Dingde Xu, Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 14 June 2023
Revised: 31 July 2023
Accepted: 16 August 2023
Published: 18 August 2023

1. Introduction

Rural poverty has emerged as a worldwide issue for regional sustainable development [1]. Spatial variation in farmers' livelihoods exists at scales as small as counties and villages and as large as nations and regions. Farmers engage in agriculture-based livelihood activities without a stable income and are more vulnerable to the external environment, frequently leading to crises in their means of subsistence [2]. In addition to individual differences of farmers, the external environment plays an important role in the process of farmers' livelihood activities [3]. It is generally accepted that the better the external environment, the more stable farmers' livelihoods are. However, factors like capital, resources and labor force have intensified interaction and accelerated flow at multiple spatial scales with urbanization, resulting in an increase in the multilocal and complex factors of rural livelihoods [4,5]. According to alternative development theory, farmers are more likely to turn to non-agricultural activities for stable livelihoods under a chaotic external environment (conflict, natural disasters, backward development, etc.) [6]. It can be seen that there is no longer a completely positive correlation between farmers' livelihoods and their external environment. The factors affecting livelihood stability are no longer limited to the rural local space, but exhibit multi-spatial correlations throughout the human–land system [7]. Given the increasing regional and urban–rural interaction, it is imperative to adopt a muti-spatial perspective to understand farmers' livelihoods, to shed light on the complex and dynamic rural issues faced by developing nations [8].

Since the introduction of its Targeted Poverty Alleviation strategy (TPA) in 2013, China has lifted nearly 100 million rural residents out of poverty. Owing to China's vast territory and diverse geographical regions, it is inevitable that resources will exhibit heterogeneous characteristics. Farmers' livelihoods frequently exhibit the phenomenon of overcoming poverty and living with poverty concurrently within a certain range [9]. Then, is the spatial difference of regional resources consistent with the spatial difference of the level of farmers' livelihoods? Do farmers with better external conditions have more stable livelihoods? How do rural location conditions affect the livelihood of rural households? Which factors are most important to the farmers' livelihood stability from the multi-spatial perspective? A scientific response to these questions will make differences and inequalities in specific locations transparent and plain, as well as facilitating the implementation of measures for village revitalization and livelihood protection. Farmers' livelihoods have been widely considered by various disciplines. Scholars have extensively discussed the impact of the external environment on farmers' livelihoods in various regions, and found that geographical location, terrain conditions, resource endowment, ecological environment, infrastructure level, and institutions are significant driving factors of farmers' livelihoods [10–14]. Nonetheless, there are the following restrictions: (1) Changes in the external environment are generally regarded as abnormal factors, and the impact of sudden perturbations of certain factors (natural disasters, virus spread, dam construction) on farmers' livelihoods is usually felt [15,16]. The long-term and continuous influence of the normal factors such as geographical location, as well as the correlation and coupling between factors and farmers' livelihoods, are ignored. (2) Farmers' livelihood activities are spatial-scale dependent [17]. Existing studies generally focus on the impact of changes in local conditions on farmers' livelihoods, and rarely discuss the specific ways and degrees of impact from the perspective of multi-spatial interaction [18]. (3) In terms of research scope, macro, medium and micro regional scales are all involved. The county scale has received more attention because of its relatively independent and complete political, economic and social functions [19,20]. However, the specific experience and quantitative research are uncommon on typical poverty-stricken regions with gully, sandstorm and mountainous morphologic areas in the county.

In view of the intricacy and multi-spatial trend of the external environment's impact on farmers' livelihoods, this study aims to enhance the multi-spatial comprehension of rural livelihoods by introducing two concepts: (1) Stability. The concept of stability, originally derived from ecology, pertains to the capacity of an ecosystem or biome to persist despite external disturbances or changes in internal parameters [21]. Although concepts such as resilience and adaptability have been widely applied by scholars in livelihood research, stability is an overarching concept and can be fully or partially described by the six properties of constancy, resilience, persistence, resistance, elasticity, and the domain of attraction [22]. To measure the state of farmers' livelihood by stability itself contains recovery and adaptation thinking. When applied to research on livelihoods, it emphasizes the dynamic ability of farmers' livelihood systems to remain impervious to risks and maintain stability. Compared with the concepts of adaptability and resilience, livelihood stability is more comprehensive and inclusive. It places greater emphasis on the fact that farmers are not easily destroyed and will not alter in response to various disturbance factors in different locations [23]. Consequently, the concept of stability is more appropriate for livelihood studies from multi-spatial and cross-scale perspectives. (2) Location advantage. It is an important economic concept which reflects the current state and potential for comprehensive regional development. Location advantage refers to the objective existence of favorable environmental factors in a region. Unilateral advantage is often difficult to convert to a regional advantage, so it encompasses a region's natural environment, transportation infrastructure, urban radiation, policy opportunities, and many other aspects [24]. The concept of location advantage has been applied to residential areas, tourist attractions, enterprise site selection, local roads, and urban development [25–28]. In the research into rural residential resettlement arrangements, locational advantage also demonstrates originality [29]. We apply this concept to multi-spatial livelihood studies in order to precisely quantify rural location conditions in various topographic areas. Due to its abundant geographical spatial connotations, the concept of location advantage can help to identify multiple influencing factors of farmers' livelihoods from a multi-spatial perspective.

We are particularly concerned with the livelihoods of rural people living in poverty in the Loess Plateau. Since the national rural revitalization strategy (RVS) was proposed in 2017, efforts have been made to enhance rural environmental conditions, agricultural productivity, and public service, which has systematically altered rural administration [30,31]. However, issues of soil erosion, ecological degradation, and farmer poverty resulting from the combination of an inherently fragile natural environment and long-term, extensive human utilization have garnered significant attention from government agencies and academic institutions [32–34]. Furthermore, the Loess Plateau contains a variety of distinct terrains, including terraces, beams, and hills. Given its multiple yet fragile environmental background, the Loess Plateau presents a good case study for the impact exploration of the external environment on rural livelihoods from a multi-spatial perspective, based on surveys conducted in 65 villages and 451 households located in Jia County, a county with three distinct topographic regions on the Loess Plateau. By building a bridge between rural location conditions (community level) and farmers' livelihood stability (household level), and utilizing a geographic detector model, we quantitatively analyzed the effects of rural environment on farmers' livelihoods from three spatial perspectives: (1) local perspective, (2) urban–rural perspective, and (3) interconnection perspective. This study contributes to: (1) a focus on long-term and continuous external environment of farmers' livelihoods and the correlation and coupling between rural location factors and farmers' livelihoods, that is beneficial to propose persistent countermeasures for rural man–land relationships, (2) the development and integration of a multi-spatial perspective into livelihood studies, providing a more nuanced understanding of the complex and dynamic issues of rural livelihoods, and (3) demonstrating empirical insights in a typical county with complex topography that can serve as a reference for addressing similar rural livelihood challenges in other regions with similar geographical characteristics worldwide [35,36].

2. Conceptual Considerations and Analysis Framework

Based on the theory of "man-land relationship regional system", a multi-spatial research framework on the impact of rural location on farmers' livelihood systems was constructed (Figure 1). The administrative division system in China has obvious hierarchical characteristics, and the province, city, county, township, and administrative village are five interacting organizational levels from high to low. The county urban–rural system consists mainly of one county capital, several townships, and multiple rural communities. Capital, resources, and labor forces flow between these administrations of different sizes and levels. As an important part of urban–rural regional systems, the rural community is the most basic spatial entity carrying out rural economic activities. There are natural links between rural communities and farmers' livelihoods in geographical space, resource space and economic space [35]. Various geographical locations mean that rural communities have different characteristics like resource endowment, functional positioning, and interaction frequency [37]. These differentiation characteristics can be regarded as spatial factors of different scales, and their impact on farmers' livelihoods has cross-scale effects, resulting in spatial heterogeneity of rural livelihood assets, livelihood strategies and livelihood outcomes [38]. According to the three-tier organizational structure of the county urban–rural regional system, the impact of rural location on farmers' livelihoods can be developed from local, urban–rural and interconnection perspectives [18]. Firstly, local conditions are mainly based on natural conditions (e.g., land, water source), which influence the quantity and quality of farmers' natural capital and the convenience of irrigation, thereby affecting their livelihood levels. The more favorable the natural conditions, the simpler it is for farmers to obtain a higher agricultural input–output ratio and a stable livelihood [39]. However, farmers in the Loess Plateau face severe challenges because they are highly dependent on agricultural revenue and natural resources, making them more vulnerable to disruptions caused by droughts, floods, and other natural disasters. Farmers with inadequate natural conditions will reduce the scale of planting and investment and turn to non-agricultural livelihoods because of inadequate economic returns. Natural location conditions have an effect on farmers' livelihoods at a local scale. Secondly, urban–rural conditions are mainly related to the position of rural communities in the urban–rural regional system. The spatial spillover effect of urban infrastructure, technological progress and economic development generally declines with distance [40], and different positions determine the extent to which it is driven by urban radiation. For farmers with superior positional conditions, such as suburban households, the excess household labor is easier to absorb, with more nonagricultural employment opportunities and more stable sources of income, and nonagricultural transformation is simpler to achieve. Positional location conditions have an effect on farmers' livelihood at an urban–rural scale. Thirdly, interconnection conditions are mainly related to traffic conditions. As a link between rural and urban areas, transportation has a cross-scale interconnection effect on farmers' livelihoods by affecting the efficiency of the introduction of production factors (e.g., technology, capital, and information). Moreover, traffic conditions have an effect on farmers' livelihood modes and choices by influencing the sales scope of agricultural products. In short, location conditions are closely connected with the entire livelihood system through local impacts, urban–rural impacts and interconnected impacts, by influencing the structure and accumulation of farmers' livelihood capital, selection of livelihood modes, and output of livelihoods.

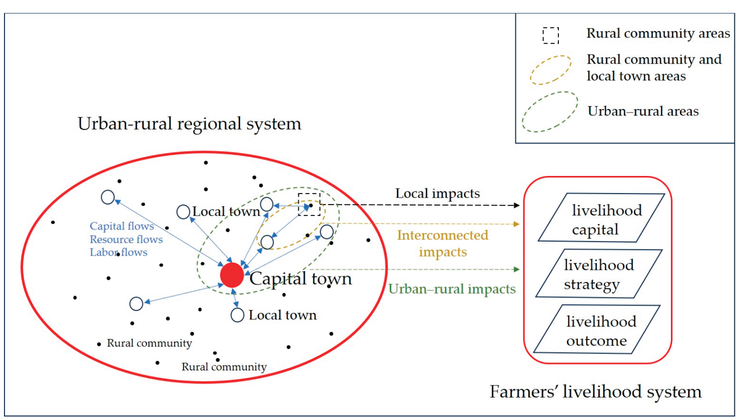

Figure 1. Framework of the influence of rural location on household livelihood systems.

3. Materials and Methods

3.1. Study Area and Data Collection

This study was conducted in Jia County, east of the Loess Plateau (Figure 2). This area experiences a semi-arid continental monsoon climate with 403.8 mm annual precipitation distributed unevenly throughout the year. This location exemplifies the traditional agricultural practices of China. The county has a total area of 2029.82 km^2, of which 86.7% is covered with loess. The terrain is elevated in the northwest, while it is flat in the southeast. Due to soil erosion, three distinct geomorphic regions were formed: a hilly and sandy region in the north, a hilly and gully region in the southwest, and a hilly and stony region along the southeastern Yellow River. The Mu Us Desert is connected to hilly and sandy regions and accounts for 30.4% of the total area. The soil is of low quality and has weak water- and fertilizer-retention capacities. Agricultural production is primarily based on the rotation of cereals and grass. The southwest hilly and gully region, which covers 52.2% of the county area, is dotted with ravines and suffers severe soil and water loss. Most agricultural production consists of oil and cash crops. The southeastern bank of the Yellow River comprises 17.4% of the county's undulating rock area, where stone gullies are deep, soil erosion is severe, and agricultural production is intercropped with valley jujubes. Affected by natural disasters, such as landslides, droughts, and summer rainstorms, agricultural production and farmers' livelihoods face significant challenges. In addition, the topography of the study area is extremely diverse, as are the livelihood outputs and strategies of producers in each region.

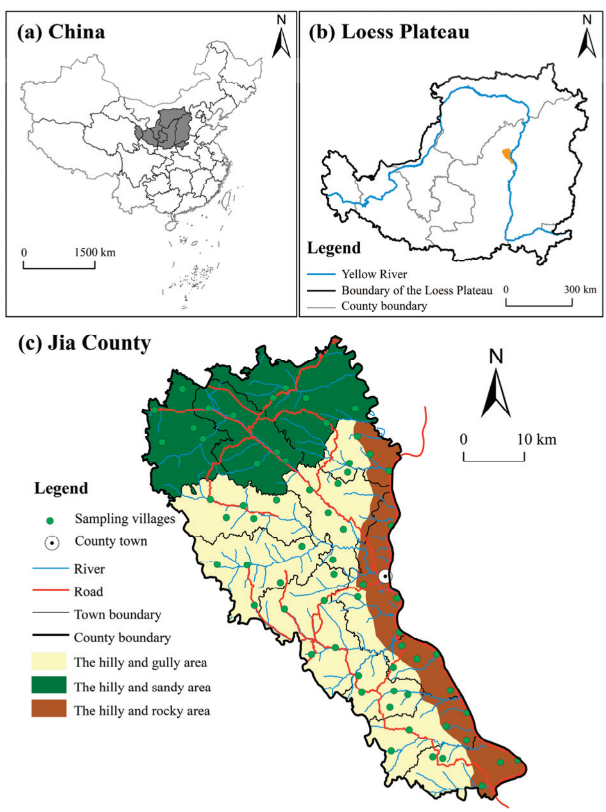

Figure 2. Location of the sample county and villages.

The research data comprise: (1) Geospatial DEM data with 30 m resolution obtained from the geospatial data cloud (http://www.gscloud.cn) accessed on 15 June 2021; (2) Space vector data from the Bureau of Statistics, Bureau of Natural Resources, meteorological department, and other government agencies for road, water system, administrative boundary, and village patch information; and (3) data from a questionnaire survey. Microlevel survey data were collected from rural households in Jia County from 2017 to 2021. We chose five villages from each town using the stratified convenience sampling approach for a total of 65 sample villages, and 52 interview materials and audio recordings were acquired by questioning key figures in each village (e.g., village cadres, leaders, and cooperative members). Then, 5–7 rural residents in each village were interviewed to learn about their basic family information, livelihood capital, livelihood strategy, and subjective perceptions. With an efficiency rate of 99.1%, 451 valid questionnaires were collected from the three topographic regions: 105 from the wind-sand area, 234 from the gully area, and 112 from the rocky area.

3.2. Approaches to Measuring Livelihood Stability

In essence, livelihood stability is characterized by actors' assets, abilities, and strategies for maintaining their livelihood standard in the face of external or internal pressures and is also a key component of farmers' sustainable livelihoods [41]. Existing livelihood stability measurement frameworks differ in terms of composition dimensions and content. At present, a more widely used evaluation method is the sustainable livelihood approach framework (SLA), which characterizes livelihood stability primarily by livelihood capital [42]. However, the framework focuses exclusively on the stock of livelihood capital, and to some extent ignores the adaptability of farmers themselves [43]. Many studies have also shown a positive correlation between total income and non-farm income share, and diverse livelihood systems are more stable than undiversified ones [44]. Therefore, on the basis of buffer capacity (livelihood capital), we added adaptive capacity and transition capacity to jointly measure the stability of farmers' livelihoods. Based on the preceding discussions and adjusted to the reality of the study area, we complemented the SLA framework with concepts of adaptation and livelihood diversity. The livelihood stability index (LSI) measurement framework was created using three essential dimensions: (1) buffer, (2) adaptive, and (3) transition capacities (Table 1). These three dimensions can be further deconstructed into 11 indicators based on the literature, expert consultations, and field experience. According to the SLA approach, buffer capacity is the ability of a livelihood system to withstand disturbances and maintain its original structure, function, and feedback, which can be represented by farmers' livelihood capitals. Adaptive capacity is defined as the ability to adapt to potential threats, capitalize on an advantageous opportunity, or cope with consequences, including the level of education, understanding of policies and farmers' skill levels. These are related to the ability of farmers themselves, and are essential for building livelihood stability for rural households [33]. Transition capacity emphasizes the ability to utilize recombining sources of experience and knowledge to realize livelihood transformation, that is, traversing thresholds into a new livelihood style by utilizing crises as opportunities for novelty and innovation [45]. We chose livelihood diversity and the income dependence indicator to present transition capacity. In addition, the majority of farmers in the studied area rely on traditional dry farming, which has long been constrained by drought and water scarcity. We therefore added the indicator of resource dependence.

Table 1. Assessment system for evaluating livelihood stability.

Dimension	Indicators	Description	Attribute	Weight *
Buffer capacity	Human capital	Ratio of labor to the total population in a household	+	0.09
	Financial capital	Ratio of annual household income to total population	+	0.08
	Social capital	Proportion of trustworthy neighbors (1: 0–20%; 2: 20–40%; 3: 40–60%; 4: 60–80%; 5: 80–100%)	+	0.06
	Material capital	Housing condition: (1: dilapidated; 2: earth kiln; 3: stone brick kiln; 4: stone brick kiln; 5: building)	+	0.07
	Natural capital	Household cultivated area per person	+	0.07
Adaptive capacity	Education years	The schooling years of household labor force	+	0.11
	Policy awareness	Policy concern degree, rated on a 5-point Likert scale	+	0.09
	Participation in skill training	Amount of participation in technical training	+	0.11
Transition capacity	Livelihood diversity	Number of sources of income	+	0.12
	Income dependence	The extent to which a household relies on a single source of income for survival $D_{inc} = -\sum_{n=1}^{S} \frac{X_n(X_n-1)}{X(X-1)}$ where x_n is the household net income under the n_{th} income source; x is the total household income	-	0.11
	Resource dependence	The proportion of irrigated land to cultivated land	-	0.09

* Weight is calculated with the entropy evaluation method.

The comprehensive index method was used to measure the LSI, which was calculated using Equation (1):

$$LSI = w_1 \times l_1 + w_2 \times l_2 + w_3 \times l_3 \tag{1}$$

where l_1 represents the buffer capacity dimension, l_2 represents the adaptive capacity dimension, and l_3 represents the transition capacities, respectively. w_1, w_2 and w_3 denote the weights of each dimension.

Data standardization was performed using the following equations:

$$x_i = \frac{x - x_{min}}{x_{max} - x_{min}} (x \text{ is a positive indicator}) \tag{2}$$

$$x_i = \frac{x_{max} - x}{x_{max} - x_{min}} (x \text{ is a negative indicator}) \tag{3}$$

where x is the observed value in an array of observed values for a given variable; x_{max} is the highest value in the same array; and x_{min} is the lowest value in that array.

3.3. Approaches to Measuring Rural Location Advantage

According to location advantage theory, location advantage refers to an objective existence that can be conducive to industrial development and layout of the regional favorable factors [46]. It refers to the relative difference, not the absolute difference. Therefore, we evaluated rural location advantage from local, urban–rural scales, and interconnection perspectives. Variables were selected from three dimensions—(1) natural advantage, (2) traffic advantage, and (3) positional advantage—by referencing relevant studies and integrating them with the actual circumstances of the study area (Table 2) [32]. As there are three geographical divisions with great differences in Jia County, topography has the most basic impact on farmers' livelihoods in the natural environment [47]. Based on the aforementioned factors, slope gradient and elevation were chosen to evaluate the rural location advantage at local spatial scale. In addition, farmers are highly dependent on rain-fed agriculture and sensitive to the disturbance of drought in the Loess Plateau. Water source is one of the important local affecting factors. The position of the rural community in the urban–rural system affects the livelihood strategies of farmers and their access to high-level services [48], and the proximity to cities affects the patterns of rural employment and livelihood patterns [49]. Bert Ingelaere et al. emphasized that secondary towns occupy an intermediate position between rural and urban areas that are familiar to residents, and generally become their first choice for off-farm employment opportunities and income diversification [50]. Therefore, economic, administrative, and market distances were chosen to represent the rural location advantage at the urban–rural scale. Rural–urban interactions play significant roles in shaping rural lives. Tristan Berchoux et al. found that proximity to main traffic roads increases the village's access to external communication [35]. It can be seen that traffic advantage has interconnected impacts on farmers' livelihood by affecting the flow efficiency of capital, resources and labor forces in different sites. Traffic convenience, traffic accessibility, and internal traffic conditions were selected as the evaluation criteria for the rural location advantage at the interconnection scale.

Table 2. Assessment framework for evaluating rural location advantage.

Dimension	Indicators	Description	Attribute	Weight *
Natural advantage	Slope gradient	Average slope gradient of the village	–	0.12
	Elevation	Average elevation of the village	–	0.11
	Water availability	Distance to the river	–	0.14
Positional advantage	Economic distance	Distance to the regional capital	–	0.10
	Administration distance	Distance to the local town	–	0.09
	Market distance	Distance to the market fair	–	0.08
Traffic advantage	Traffic convenience	Whether township roads pass through (yes: 1; no: 0)	+	0.12
	Traffic accessibility	Distance to roads above county level	–	0.13
	Internal traffic	Ratio of hardened road length to village area	+	0.11

* Weight is calculated with the entropy evaluation method.

The comprehensive index method is used to measure the Rural Location Advantage Index (RLAI), which is calculated using Equation (4):

$$RLAI = a_1 \times r_1 + a_2 \times r_2 + a_3 \times r_3 \tag{4}$$

where r_1 represents the natural advantage dimension, r_2 represents the traffic advantage dimension, and r_3 represents the positional advantage dimension. a_1, a_2 and a_3 denote the weights of each dimension, respectively. Additionally, before entering the equation, as previously indicated, the data must be prenormalized.

3.4. Geographical Detector Model

The geographical detector model is a spatial analysis method used to calculate the relationships between geographical phenomena and their influencing factors [30]. Spatial differentiation and factor detection modules were used to analyze the relationship between rural location advantage factors and livelihood stability. Specifically, it was calculated using Equation (5):

$$q = 1 - \frac{\sum_{h=1}^{p} N_h \sigma_h^2}{N\sigma^2} \tag{5}$$

where q is the degree to which the *RLAI* factors can account for the *LSI* spatial difference, and the value range is [0, 1]. The strength of this interpretation increases with the q value. The *RLAI* factor categorization is represented by p. Class h and the entire sample size are denoted as N_h and N, respectively. The square deviations of class h and the entire sample are denoted as σ_h^2 and σ^2.

4. Results

4.1. Livelihood Stability Index

The calculated results demonstrate that the average value of the LSI in Jia County was 0.485. Additionally, we divided the LSI results of the 451 sampled households and their dimensionality capacities into three groups using the natural breakpoint method: low, medium, and high. Table 3 shows the detailed distribution of households in the three categories. According to Table 3, the proportion of households with moderate livelihood stability was the highest, reaching 42%, whereas the proportions of households with high and low stability were equal (29%). This demonstrates that most households in Jia County have moderate livelihood stability. From each constitutive dimension of the LSI, the proportion of households in the moderate grade was also higher than that in the low and high grades. Particularly in the transition capacity dimension, the proportion of low-grade households was the lowest (28%). This indicates that most farmers in Jia County no longer rely on a single source of income and are capable of non-agricultural transformation and diversified methods of living.

Table 3. Percentage distribution of the LSI and each dimension index.

Categories	LSI	Buffer Capacity	Adaptive Capacity	Transition Capacity
L [1]	0.29 (133 [4])	0.34 (152)	0.32 (144)	0.28 (126)
M [2]	0.42 (189)	0.38 (173)	0.52 (235)	0.49 (221)
H [3]	0.29 (132)	0.28 (126)	0.16 (72)	0.23 (104)

[1] L—Low, [2] M—Moderate, [3] H—High, [4] Values in parenthesis indicate the number of households.

To investigate the spatial pattern distribution of livelihood stability in Jia County, we used sampled villages as units and visualized the mean value of the LSI and its fractal index using ArcGIS 10.3 software (Figure 3). The greater the value, the larger the circle is. Farmers with a high LSI were distributed throughout all geographical regions, especially in the east along the Yellow River around the capital of the county. Farmers with moderate and low livelihood stability were widely distributed in the northern hilly and sandy region and western hilly and gully regions. From the dimension of buffering capacity (Figure 3b), the buffering capacity of farmers in the western and eastern stony regions was generally better than that of farmers in the northern sandy region. The northern part of the county is located on the southern border of the Mu Us Desert, which is eroded by wind and sand, forming a large expanse of dry river platforms and moving sandy lands. Low soil fertility, wide planting, and low harvest rates are not conducive to farmers' livelihoods and capital accumulation. From the adaptive-capacity dimension (Figure 3c), farmers in the hilly and stony region were still more adaptable than those in other regions. To integrate educational resources, most rural institutions have merged into the capital of the county since 2002, and the education gap between rural and urban areas has begun to widen. The educational level, agricultural skills, and policy awareness of farmers in the hilly and stony region, where the capital is located, have significantly improved, which is the reason for their higher adaptive capacity. From the transition-capacity dimension (Figure 3d), farmers have a relatively robust transformation ability in all regions. Under the influence of urbanization and non-agriculture, farmers are no longer restricted to a single agricultural livelihood strategy and typically turn to a non-agricultural or diversified livelihood mode.

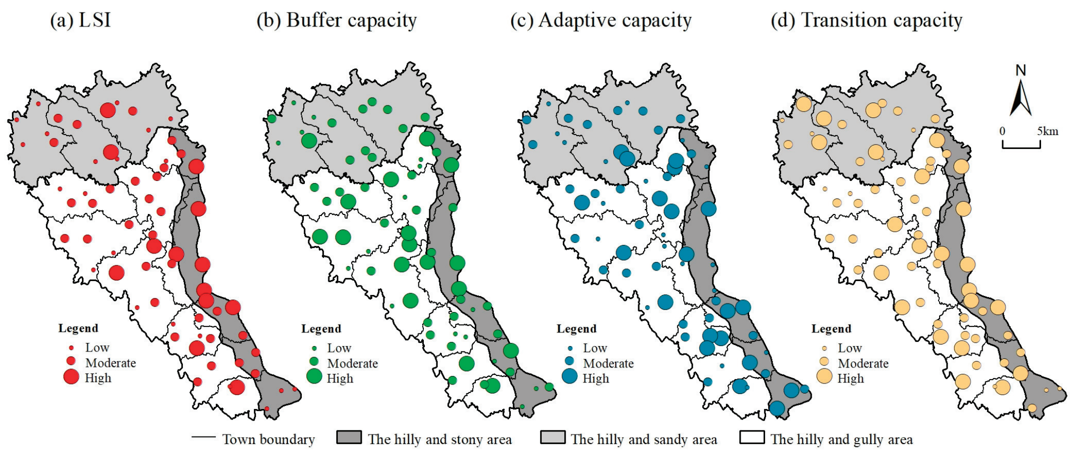

Figure 3. Spatial distribution of the Livelihood Stability Index and its dimensions.

4.2. Rural Location Advantage Index

The results demonstrate that the average RLAI value was 0.540. Using the natural breakpoint method, the RLAI and its dimension index results for the 65 sampled villages were classified as high, moderate, or low. This provided us with a grade for each village's RLAI and natural, traffic, and positional advantages, and 77% of the sampled villages achieved a moderate or high RLAI, as illustrated in Table 4. The percentage of villages with a high or moderate grade of traffic advantage was 78%. This demonstrates that through a series of authority control measures and policies, most villages in Jia County have relatively optimistic development conditions (natural environment, transportation conditions, and administrative level). Notably, the proportion of villages with low natural advantage was relatively high, reaching 45%. This is related to the delicate ecological environment of the Loess Plateau.

Table 4. Percentage distribution of the Rural Location Advantage Index and each dimension index.

Categories	RLAI	Natural Advantage	Positional Advantage	Traffic Advantage
L [1]	0.23 (15)	0.45 (29)	0.34 (22)	0.22 (14)
M [2]	0.51 (33)	0.41 (27)	0.40 (26)	0.69 (45)
H [3]	0.26 (17 [4])	0.14 (9)	0.26 (17)	0.09 (6)

[1] L—Low, [2] M—Moderate, [3] H—High, [4] Values in parenthesis indicate the number of households.

To further clarify the geographical spatial pattern of the RLAI and each dimensional advantage index of Jia County, the Kriging interpolation method was used to interpolate the entire county space with the data of 65 sample villages. The spatial distribution patterns of the RLAI and each dimensional advantage index were determined (Figure 4a). High RLAI areas were found in the county's central and eastern districts, primarily in hilly and stony regions. Low RLAI areas were prevalent in the county's northwest and northeast, mainly in the hilly and sandy and hilly and gully regions. Moderate RLAI areas were widespread and distributed, spanning all topographic regions. For the natural advantage from a local spatial perspective (Figure 4b), the eastern part of Jia County has a low elevation and relies on the Yellow River for water; therefore, this region has high natural advantages despite the county's overall complex terrain, broken surface, and lack of water resources. For the positional advantage from an urban–rural spatial perspective (Figure 4c), the areas with a high positional advantage were along the Yellow River in the eastern part of the county. Because the county government is positioned east of the county's geometric center, administrative radiation is weaker than that from the county seat, according to the principle of diminishing marginal benefits. The eastern part of the county is adjacent to the Yellow River. With the growth of the tourism industry along the Yellow River, the accelerated development of rural areas in this region has been driven by the expansion of tourism resources. For the traffic advantage from an interconnected spatial perspective (Figure 4d), the county's high-grade traffic arteries stretch from the eastern county seat to the eastern and western sides. Furthermore, the road network at the angle between the western and central and northeastern transportation corridors is sparse, resulting in a lack of traffic in this region. The spatial pattern of the RLAI was described as "decreasing gradually from the capital town to the north and south" due to the combined factors of local, urban–rural, and interconnected scales.

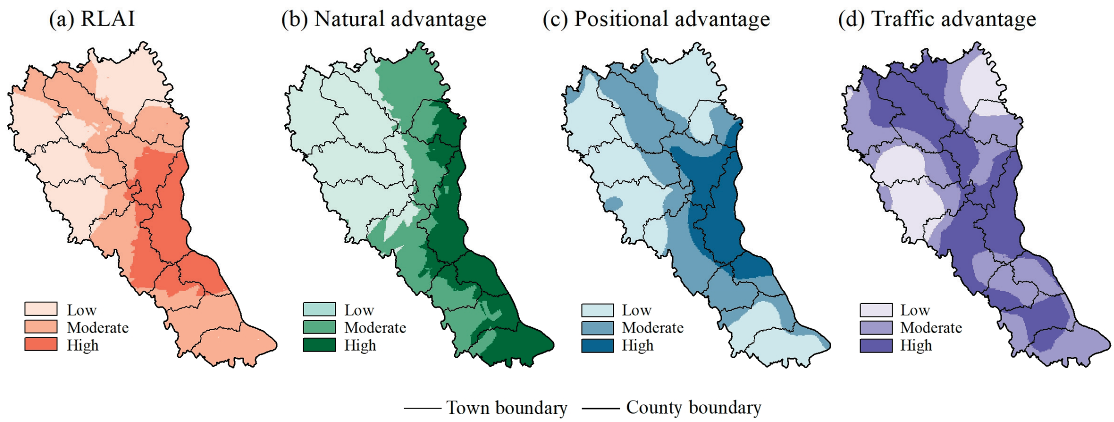

Figure 4. Spatial distribution of the Rural Location Advantage Index and its dimensions.

4.3. Relationship between the Rural Location Advantage Index and the Livelihood Stability Index

Through matching LSI and RLAI level statistics of all sample villages, it is possible to combine nine varieties of H-L, H-M, M-L, L-L, M-M, H-H, L-H, L-M, and M-H, as illustrated in Table 5. Villages with RSI levels equivalent to RLAI levels (L-L, M-M, and H-H) accounted for 56.92% of the total sample villages. The proportion of villages in the RAI superior group was slightly higher than that in the RSI superior group. There is a certain coupling correspondence between the LSI and RLAI, and the LSI has a certain lag relative to the RLAI.

Table 5. Statistics on the spatial coupling between the rural location advantage index and the livelihood stability index levels.

Spatial Coupling Categories	LSI Superior			Equivalent			RLAI Superior		
	H-L	H-M	M-L	L-L	M-M	H-H	L-H	L-M	M-H
Quantity	2	8	3	10	18	9	2	7	6
Percentage		20.00			56.92			23.08	

To explore the coupling correspondence between the LSI and RLAI more intuitively, the RLAI was taken as the horizontal coordinate and the LSI as the vertical coordinate to plot the situation of 65 sample villages into a scatter plot (Figure 5). As illustrated in Figure 5, most sample points are clustered around the "lower-left-upper right" trend line, indicating that there is a certain spatial correspondence between the LSI and RLAI, that is, there is a certain positive correlation between farmers' livelihood stability and their rural location conditions. Nonetheless, 43.08% of the sample villages were still discrete (i.e., the LSI and RLAI levels were distinct), indicating that the relationship between the two was complex and not entirely positive, necessitating additional analysis.

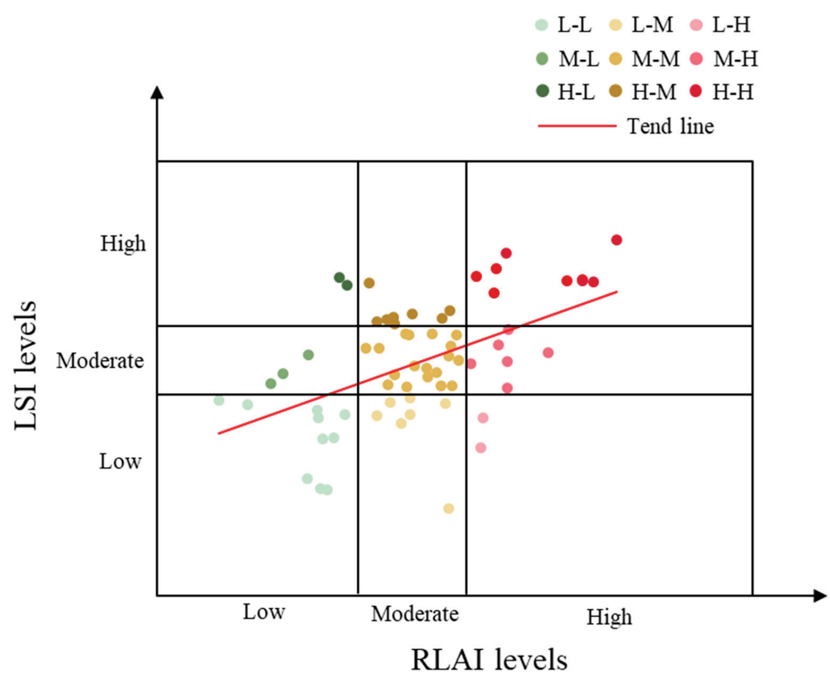

Figure 5. Spatial coupling between the rural location advantage index and the livelihood stability index.

Using a geographical detector model, we investigated the impact factors of the LSI to examine how rural location conditions influence farmers' livelihood stability from the muti-spatial perspective. First, the dimensions of each impact factor were reduced using a stepwise regression method, and indicators that were unsuitable for inclusion in the model were eliminated. The five location factors that passed the test were traffic accessibility, internal traffic, slope gradient, elevation, and economic distance. We then incorporated the LSI as the dependent variable and the five factors as independent variables into the geographical detector model to determine the explanatory power q value of each factor for farmers' livelihood stability (Table 6). The results demonstrated that the q values were in descending order: economic distance > elevation > slope gradient > traffic accessibility > internal traffic. The findings indicate that farmers' livelihoods are impacted by multi-spatial location factors.

Table 6. Explanatory power of each location factor for the livelihood stability index.

Location Factors	q	Sig.
Elevation (local scale)	0.196	0.01
Slope gradient (local scale)	0.173	0.01
Traffic accessibility (urban–rural scale)	0.162	0.01
Internal traffic (interconnected scale)	0.129	0.00
Economic distance (interconnected scale)	0.214	0.00

Based on the complex relationship between the LSI and RLAI, farmers' livelihood activities in villages are frequently subject to interaction by multi-spatial location factors, meaning that the combined effect of two or more spatial location factors is greater than that of a single spatial factor. To verify this hypothesis, we investigated the impact of multi-spatial factor interactions on farmers' livelihood stability using a geographical detector model. The results indicate (Table 7) that the explanatory power after the interaction of any two location factors is greater than the sum of it when the two factors operate alone; that is, it will have a "1 + 1 > 2" influence on livelihood stability. The explanatory power of the economic distance factor in the interaction was greater than that of other factors, indicating that the urban–rural scale factor is a significant control factor for livelihood stability, which is consistent with the single-factor detection results. The interactive explanatory power of economic distance and slope is the largest, which is 0.737, indicating that the interaction between urban–rural scale and local scale location factors has the greatest influence on livelihood. The interaction between slope gradient and elevation has an explanatory power of 0.640, indicating that the interaction of location factors within a local scale on livelihood stability cannot be overlooked. When traffic accessibility interacted with other factors, its explanatory power increased to more than 50%, showing that the interconnected scale factors easily form scale correlation effects on farmers' livelihoods when interacting with other scale factors. Therefore, the spatial variation in the RLAI is due to a combination of multi-spatial location factors.

Table 7. Effect of interaction between factors on the livelihood stability index.

	Elevation	Internal Traffic	Slope Gradient	Traffic Accessibility	Economic Distance
Elevation	-	-	-	-	-
Internal traffic	0.437	-	-	-	-
Slope gradient	0.640	0.398	-	-	-
Traffic accessibility	0.629	0.525	0.578	-	-
Economic distance	0.718	0.577	0.737	0.658	-

5. Discussion

5.1. Understanding Farmer's Livelihoods from a Multi-Spatial Standpoint

The distribution of rural poverty has obvious spatial heterogeneity [34,42], which is manifested in the inconsistent development level of rural communities and the income gap of rural households within the county. The spatial heterogeneity leads to the lack of precision and targeting of macro policy implementation. In order to fulfill the sustainable development aim of vigorous rural development and stable farmer livelihoods, China's rural revitalization policies frequently support development at the village level to eliminate poverty at the household level. The relationship between rural communities and peasant households is the most basic man–land relationship in urban–rural regional system. Having a solid understanding of the relationship is a forceful way to enhance actual effects of macro policies. The relationship between the rural community and farmers was investigated using the economic and ecological concepts of location advantage and stability to quantify the essential characteristics of village scale and household scale. With the advancement of urbanization, farmers' livelihood activities are no longer limited to the local space in rural areas, and the location conditions of villages should also be comprehensively considered based on different spatial scales of the urban–rural regional system. In view of this, we classified the evaluation indicators of rural location advantage into three categories: local, urban–rural, and interconnected, and identified the key factors affecting farmers' livelihood from a muti-spatial perspective. It is found that impacts of rural location conditions on farmers' livelihoods are complex, and livelihood stability is not a linear agglomeration process towards well-located villages. With increasing urban–rural interactions, non-agricultural livelihood plays a prominent role in the farmers' modern livelihood strategies. Even if local location conditions are insufficient, farmers can obtain stable livelihoods by going out for work or engaging in local non-agricultural livelihoods (such as sales, catering, etc.). An encouraging result for areas like the Loess Plateau, where natural conditions are essentially inadequate, is that the constraining effect of local location constraints on farmers' livelihoods is waning. Naturally, such a shift would require public investment in infrastructure like rural roads and electricity. Locational factors at local, rural–urban, and interconnected scales might not only affect rural livelihoods independently, but also produce cross-effects through mutual influence. Among them, the significant influence of rural–urban scale and interconnection scale location factors on the LSI further confirms that the increasing rural–urban interaction has a greater impact on farmers' livelihood activities. It reveals that it is fruitful to consider the intersection of multi-scale spatial factors and scale-dependence relationships in livelihood research.

5.2. Enhance Livelihood Stability Utilizing Rural Location Advantages

Farmers' livelihoods are a way for farmers to survive by utilizing internal and external resources, and it is helpful to understand how rural residents are connected with rural geographical environments. The geographical location of villages has a noticeable effect on rural economic activities and farmers' livelihoods, particularly in traditional agricultural planting areas. The limiting effects are more pronounced in regions with complex terrains and relatively low productivity, such as the Loess Plateau. Countermeasures and suggestions to improve farmers' livelihoods can be sought from a spatial perspective, which can be guided and managed from the following aspects. Combined with the resident population scale, industrial structure, and functional orientation of villages, appropriate policies should be adopted to gradually narrow the spatial imbalance in rural livelihoods. For villages in the northwest counties with poor natural conditions, fragmented land can be integrated through a land contractual-operation system. Agricultural intensification and industrialization can be accomplished through land leveling and terrace construction. Simultaneously, early warning and emergency mechanisms should be established to release meteorological disaster information in a timely manner to reduce damage to agricultural production caused by natural disasters. To address the scarcity of water supplies, water conservation projects such as reservoirs and irrigation canals should be developed. Sprinkler- and drip-irrigation techniques should be popularized. The construction of rural road networks should be encouraged to improve the travel environment for rural families in western, central, and northeastern villages with inadequate traffic conditions. To compensate for the weak links in agricultural development, rural infrastructure and public service supply should be enhanced; connectivity between urban and rural areas should be promoted. And more public services, such as education, healthcare, and social security should be provided to rural communities, especially in settlements at the edge of the county with poor position conditions, expanding income access for people experiencing poverty combined with agricultural subsidy policies [51]. Immigration policies should appropriately relocate the rural population to areas where farmers' livelihoods are unstable due to multiple location factors' superposition. Additionally, the labor force's educational background and agricultural expertise, non-agricultural transfers, and the supporting role of livelihood diversity in farmers' livelihood stability should be enhanced.

5.3. Study Limitations

Farming households are the most fundamental production and living units in rural areas, and their livelihoods are closely tied to the external environment. Most current re-search on the impact of external environment on farmers' livelihoods mainly focuses on the local scale, and the specific impact mode or impact degree are rarely discussed from the muti-spatial perspective [20,52]. Our research focused on county areas, investigating the human–land relationship in poor areas from the perspectives of local, urban–rural and interconnected scales. However, this research has some limitations, as follows: (1) Despite our efforts to incorporate relevant theories and existing research into the development of the index system and include key indicators to prevent any potential bias resulting from omitted components, data availability constraints limited our selection of indicators. Nevertheless, although we borrowed from pertinent theories and existing studies when building the assessment system and included key indicators to avoid the deviation of study results caused by the omission of components, the selection of indicators is constrained by data availability, which is not completely sufficient. Therefore, we ensured the accuracy of our findings by adjusting the index weights and verifying a series of models. Additionally, we integrated our intuitive field-research experience with previous research conclusions to compare and validate our results [48,49]. (2) We took the county area as the fundamental unit of analysis for the case study, and mainly considered the radiation driving effect of the capital and local towns on the rural area. Although it has stronger operability, the selection of scale has certain limitations. Future studies should incorporate the neighboring large cities into the interaction to explore the mechanism of rural spatial disparities while continuously enhancing the livelihood research methods. This will contribute to a more comprehensive multi-scale sustainable livelihood research experience. (3) Our research is mainly based on the current situation of a typical county. However, owing to the vast area and significant internal spatial heterogeneity within the Loess Plateau, there are variations in the livelihood strategies employed by farmers across different regions. In the future, longitudinal comparative analysis of time series should be strengthened to carry out dynamic tracking research on livelihood issues. Simultaneously, attention should be paid to horizontal comparative analyses among different counties to explore the common guidelines for multi-scale rural livelihood research [35].

6. Conclusions

Taking Jia County on the Loess Plateau as a case study, we integrated location theory with household livelihoods using survey and geospatial data and investigated the livelihood problems of farmers from a multi-spatial perspective. The three dimensions of buffer capacity, adaptive capacity, and transition capacity were used to construct a livelihood stability assessment framework, and the natural, traffic, and positional dimensions were used to deconstruct rural location advantage. The complex interaction between rural location advantage and livelihood stability was explored from local, urban–rural, and interconnected spatial perspectives. Our study provided new empirical evidence for multi-scale factors on the spatial differentiation of farmers' livelihoods. According to the results, 77% of the villages achieved moderate or high RLAI values. Owing to poor natural conditions, villages with a low RLAI are mainly distributed in hilly and sandy areas, which are related to the vulnerable ecological environment of the Loess Plateau. Overall, the LSI was moderate; however, spatial heterogeneity was evident. Most farmers possess strong transition capacity and no longer rely on monocultures for their livelihoods. There is a certain coupling correspondence between the LSI and the RLAI, but it is not a simple linear agglomeration process. The spatial variation in the LSI was due to the superposition or interaction of multi-spatial factors. The rural–urban spatial location factors are the key control element of LSI and the interaction between rural–urban and local spatial location factors has the greatest influence on LSI. It is simple for interconnected spatial location factors to produce a scale correlation effect, and have non-negligible effects on farmers' livelihoods when they interact with other spatial location factors.

According to our research, farmers' livelihoods are significantly affected by differences in geographical location within a county. These findings enhance our multi-spatial understanding of livelihoods and have implications for developing more effective policies to target rural revitalization and poverty reduction. Farmers' livelihoods are dynamic and significantly affected by geographical differences in the county area. They will take into account multiple factors (natural, human-made, and human–land interactions) and constantly modify their strategies with changes in their capital and the external environment. Farmers in different locations experience various external conditions and resources, resulting in different livelihoods. This is one of the reasons why livelihood issues are becoming increasingly complex. The spatial heterogeneity of farmers' livelihoods results from the superposition and interaction of multi-spatial location factors. We found that the combined effect of two spatial location factors was greater than the sum of their individual effects, resulting in a "1 + 1 > 2" impact on farmers' livelihood. Therefore, attention should be paid to the comprehensive effect of multi-spatial location factors in modern livelihood researches.

Author Contributions: Conceptualization, Y.W. and W.Y.; methodology, Y.W.; software, D.M.; validation, Y.W., D.M. and K.W.; investigation, X.Y.; writing—original draft preparation, Y.W. and D.M.; writing—review and editing, Y.W.; visualization, Y.W.; supervision, X.Y.; funding acquisition, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 41771574.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We would like to thank Dian Min, Wenli Ye, and Kongsen Wu for contributing to the household survey and data collection.

Conflicts of Interest: The authors declare no conflict of interest.

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How to Rebalance the Land-Use Structure after Large Infrastructure Construction? From the Perspective of Government Attention Evolution

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Abstract: Large infrastructure projects play a crucial role in regional development but can also negatively impact cultivated-land protection. This study focuses on the role of local governments in land-use conflicts and the rebalancing of land-use structures during large infrastructure construction. Using the construction of a reservoir in the Huaihe River as a case study, the research examines the evolution of government attention and the process of township local governments promoting land-use adjustment. The findings reveal that local governments go through a process of "Create–Reinforce–Adjust–Delivery" in their attention to reservoir construction to maximize their interests. Attention fluctuates in terms of reservoir construction, cultivated-land protection, and immigration-development assistance. Biased land-use decisions were made at different stages, leading to four stages of rebalancing efforts: "Generation–Challenge–Marked effect–Continuous negative impact". This process provides insights into land-use decision-making and the rebalancing of land-use structure. The study suggests that the superior government should guide local governments to enhance attention to cultivated-land protection through laws and policies, while local governments should focus on the quality protection of cultivated land and mitigate the negative impact of rebalancing efforts.

Keywords: government attention; large infrastructure; cultivated-land protection; reservoir area; China

Citation: Gao, J.; Zhang, X.; Yu, C.; Ma, Z.; Sun, J.; Guan, Y. How to Rebalance the Land-Use Structure after Large Infrastructure Construction? From the Perspective of Government Attention Evolution. *Land* **2023**, *12*, 1632. https://doi.org/10.3390/land12081632

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 1 August 2023
Revised: 15 August 2023
Accepted: 16 August 2023
Published: 20 August 2023

1. Introduction

Cultivated land and its agricultural production functions play a crucial role in ensuring food security and are essential for achieving the United Nations 2030 goal of "eradicating poverty and hunger" [1]. Currently, approximately 10% of the global population lives in extreme poverty, with around 820 million people suffering from hunger. It is, therefore, imperative to protect cultivated land, as it serves as a vital guarantee for addressing these challenges. Simultaneously, the "Global Infrastructure Outlook" report highlights a projected investment gap of USD 15 trillion in global infrastructure by 2040, particularly in developing countries [2]. The demand for infrastructure construction poses significant pressure and challenges for safeguarding cultivated land, particularly in developing nations. China, as the world's most populous developing country, has impressively achieved its goal of eliminating absolute poverty ten years ahead of schedule; nonetheless, the protection of cultivated land remains a strategic priority due to its large population of 1.4 billion [3]. Both cultivated-land conservation and large infrastructure construction are critical and pressing issues. However, the construction of large infrastructure inevitably results in the occupation of various types of land, particularly arable land. Failure to address the reduction and imbalance of cultivated land caused by large infrastructure projects could pose hidden risks to regional food production and overall food security.

With the rapid development of the global economy and society, the situation of large infrastructure occupying cultivated land is increasingly serious. Various types of large infrastructure construction, such as Roads [2], Airports [4], Water conservancy facilities [5], and Ports [6], directly occupy cultivated land, which not only changes the regional land-use pattern but also affects the regional landscape pattern [7]. The resulting increase in service demand has promoted the development of regional cities and towns, increased competition risks in land use [8], and even led to consequences such as the degradation of habitat quality [9], the reduction of ecosystem service value [10,11], and the forced transformation of local residents' livelihoods [12]. Therefore, many scholars try to find solutions by explaining the influencing factors and formation mechanism of land-use function conflict, quantity imbalance, and space occupation using stakeholder theory and game theory [13,14]. It is generally believed that the scarcity of land resources and the different demands of stakeholders are the underlying causes of many land-use problems [15,16]. These problems evolve in the mutual game of multiple subjects [17], with the interest subjects including land managers, land investors, and land users. Their game relations involve the game between the three parties and the internal game of land managers.

The main influence in rural areas, where the game among the three parties is usually represented by "local government–enterprises (developers)–farmers", is reflected in the improper operation of land acquisition, replacement, compensation, and other aspects [18,19]. This leads to government and people compensation disputes, which have a negative impact on the livelihood of local residents and the surrounding environment [20]. To effectively prevent conflicts and benefit rural communities and the surrounding environment [21], the government and enterprises should fully consider the demands of farmers and formulate transparent, open, and clear processes and policies according to the site selection, planning, construction, and management of large infrastructure.

The internal game of land managers is mainly the interaction between different levels of government. Having different dominant holders of land planning leads to different game processes. In countries or regions where land-use planning is dominated by the local government, land planning is primarily carried out at the county or city level or in urban areas [22]. Large infrastructure construction is entrusted by the federal government to the state government, and the degree of achieving the goals is assessed. The local government is then responsible for specific construction and maintenance with the support of the state government [23]. However, if the local government is unwilling to restrict the use of land or cultivated land for the construction of large infrastructure, their land-use decisions may damage the construction and operation of important national large infrastructure [24]. The study suggests that the federal government, state governments, and local governments must "share the challenges" and make responsible land-use decisions through cooperative efforts to protect cultivated land for global food security [25]. In countries or regions where the state dominates land planning, the land-use planning power of local governments comes from the authorization of the central government, which is a series of top-down and prospective planning systems [26]. This makes the construction and operation of key national infrastructure unaffected by local land-use decisions. However, this does not mean that local governments lack institutional space to exercise their power [27]. The central government often implements the requirements of land use and land protection from the perspective of national protection of public interests; Local governments pursue the property value of land and rely on land financing to promote regional development [28]. The central and local governments have different views on the value of large infrastructure construction and cultivated-land protection from different perspectives, which makes the local governments not only need to protect the public interests but also need to consider the financial benefits brought by the land, thus leading to the local governments to carry out the rebalancing efforts of land use. The research recommends that the central government should build a cultivated-land protection system with economic incentives as the core, introduce economic means into cultivated-land protection, and improve the management system of construction land indicators [29]. It is also noted that if the local government can implement effective cultivated-land protection decisions, the reduction of cultivated-land area will be curbed to a certain extent [30].

The existing research rarely treats large infrastructure construction and cultivated-land changes from the perspective of land-use decision-making of local governments and fails to clarify the rebalancing-efforts process carried out by local governments to consider large infrastructure construction and cultivated-land protection. However, in RLCCP, the role of local governments as actual executors, participants, and stakeholders is irreplaceable. Local governments cannot make the most perfect decision, but can only comprehensively evaluate and weigh multiple factors to make "relatively reasonable and relatively satisfactory" decisions, thus forming a shift in the focus of government attention [31,32]. As decision-makers, local governments have limited attention to a specific issue under the influence of multiple factors such as organizational systems, social factors, sudden public events, and personal cognition. Therefore, the process of decision-makers actively choosing the focus of attention will lead to a shift in the limited attention of the government, resulting in a shift in the direction of government decision-making [33]. However, scholars analyze government decision-making behavior from a completely objective and rational perspective or analyze government decision-making results from the perspective of fully considering farmers' interests and demands, it is an ideal situation, and the conclusions drawn may not be in line with reality. Local governments face multiple driving forces from different entities, such as farmers, enterprises, and governments at all levels, requiring continuous weighing of decision-making directions. Among them, farmers' interest demands for land resource utilization, personal economic development, and personal living conditions, etc., are only one aspect of government decision-making considerations. Therefore, the perspective of government attention can better explain the process of local governments making "relatively reasonable and relatively satisfactory" decisions based on limited attention driven by multiple factors.

This study focuses on RLCCP, which examines the land-use structure changes caused by the construction of large reservoirs. The main objective is to explore the government's attention from three perspectives. First, it examines the changes that have occurred in the land-use structure during large reservoir construction. Second, it analyzes the changes in local government's attention at different stages of the construction and the resulting adjustments in land use. Lastly, it identifies the driving factors that influence the local government's efforts in land use rebalancing based on the changing level of government attention. By addressing these questions, the study aims to provide theoretical support for promoting the coordinated development of large infrastructure construction and cultivated-land protection.

2. Materials and Methods

2.1. Overview of the Study Area

The Huaihe River basin, located in the transition climate from a subtropical to a warm temperate zone, is one of the seven major basins in China. It serves as a crucial grain production area, accounting for about 11.7% of the total cultivated area and approximately 17.4% of the total grain output of the country [34]. The study area, situated in a township in the upper reaches of the Huaihe River basin, consists mostly of agricultural land, with rice being the primary food crop. In light of the frequent drought and flood disasters in this region, the central government approved the construction of a large reservoir project in 2011. This significant project, which completed its acceptance process in 2021, is the only flood control system on the upper reaches of the Huaihe River trunk line. It holds great importance in the mitigation of flood-related issues and disaster reduction. The study area encompasses a total area of 13,944.37 hectares, with the submerged area of the large reservoir comprising 14.39% of the total area. Furthermore, it is worth noting that the registered resident population of the township was 55,892 as of 2019. Within the township, there are 75 industrial enterprises, one of which is classified as above designated size. The total output value of the township reaches 903 million yuan, and the per capita net income of farmers amounts to 17,807 yuan.

2.2. Research Method

2.2.1. Spatial Analysis

This study utilized the ArcGIS spatial analysis technology platform (Esri; Berkeley, CA, USA; Version 10.7) to examine the spatial distribution characteristics of land-use data. Spatial analysis methods, including kernel density analysis and buffer zone analysis, were employed for this purpose. Kernel density analysis was utilized to determine the density of point elements or line elements in the neighborhood. On the other hand, buffer analysis involves creating a polygon layer surrounding geographical elements to assess the relationship between them by overlaying with the target layer. In this study, nuclear density analysis was used to measure the degree of concentration of village construction land and road network density. Moreover, buffer zone analysis was applied to assess the relationship between village construction land and cultivated-land abandonment at various distances.

2.2.2. Natural Language Processing

This paper utilizes NVIVO 11 (QSR International; Burlington, MA, USA; Version 1.6.1) for natural language analysis (NLP). Natural language is classified and quantified through semantic coding. The semantic code of "Reservoir Construction" (RC) comprises the staged decision-making in the process of reservoir construction and resettlement. The semantic code of "Immigration-development Assistance" (IA) encompasses support measures such as community management, employment assistance, and fund distribution. Lastly, the semantic code of "Cultivated-land Protection" (CP) involves measures like cultivated-land protection publicity, food planting, pollution control, and supervision measures.

2.3. Data Source and Processing

2.3.1. Land-Use Data Sources and Processing

The land-use data in the study area is derived from the second and third national land survey databases. However, since there are differences in statistical caliber, principles, and methods between the two surveys, it is necessary to revise the land types and names based on the actual survey in the study area and the Second National Land Survey Technical Specification (TD/T 1014-2007). In this revision, agricultural land includes 11 land types, construction land includes 8 land types, and unused land includes 4 land types, resulting in a total of 23 land types (Table 1). Specifically, the cultivated land mentioned in this paper encompasses Paddy Field, Irrigated Land, and Dry Land. Additionally, the land for reservoir construction consists of Reservoir Surface and Hydraulic Construction Land.

Table 1. Classification of land-use status.

Land Category Name		Land Category Name	
Agricultural Land	Paddy Field	Construction Land	Mining Land
	Irrigated Land		Urban Residential Land
	Dry Land		Village Land
	Orchard		Special Land
	Tea Garden		Railway Land
	Other Gardens		Road Land
	Woodland		Reservoir Surface
	Other Woodland		Hydraulic Construction Land
	Pond Water Surface	Unused Land	Other Grassland
	Ditch		River Surface
	Facility Agricultural land		Inland Tidal Flat
			Bare Land

2.3.2. Natural Language Processing Data Source and Processing

The publication of government work reports is the right and obligation of governments at all levels under the Constitution of China. The government work report is more instructive and authoritative as compared to general administrative decision-making and is considered the highest decision-making document on an annual basis [35]. The data for natural language processing (NLP) in this study is from the 2011–2022 government work report of the study area. By searching keywords, this paper carries out semantic coding to reveal the law of local government's policy change among different issues through "local government's attention change". Additionally, a quantitative comparison is conducted by constructing an indicator of "local government attention intensity" which refers to the degree of local government's attention to an issue, expressed by the proportion of the text of the government work report.

The land-use situation before reservoir construction in the research area was represented by the Second National Land Survey data in 2009. Due to the start of reservoir construction in 2011, 2011 was chosen as the starting stage for local government attention changes. The data from The Third National Land Survey in 2019 represented the land-use situation after the reservoir storage, as the reservoir construction officially began to store water in 2019. To further explore the trend of land-use policy changes after the completion of reservoir construction, 2022 is chosen as the deadline for local government attention to change analysis (Figure 1).

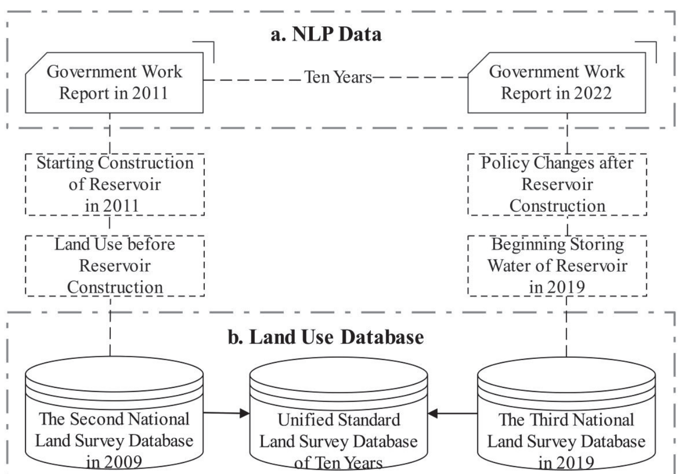
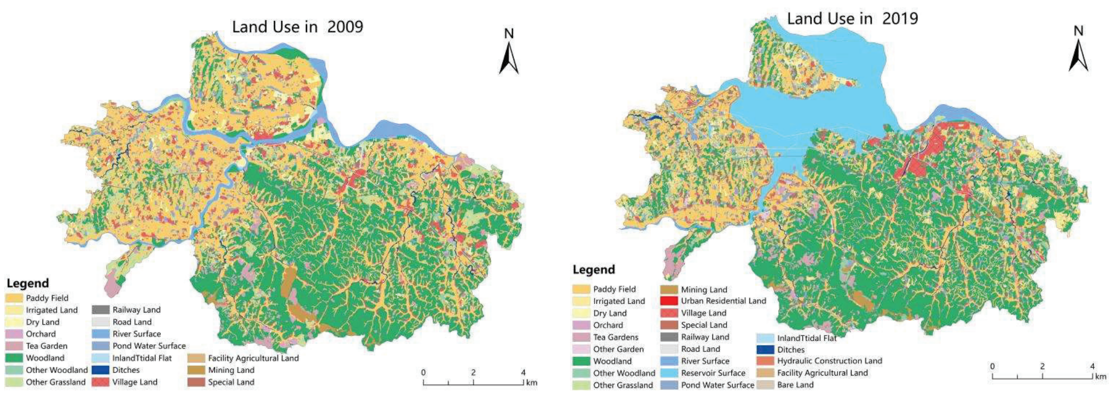


Figure 1. The relationship between land-use data and NLP data.

3. Results

3.1. Comparison of Land-Use Status from 2009 to 2019

From 2009 to 2019, the main trend of land-use change in the study area was a decrease in agricultural land and an increase in construction land, as well as the efficient utilization of previously unused land (Figure 2). The total area of agricultural land, which was the primary land-use type, decreased by 9.11% during this period, leading to a change in the dominant land-use type. In 2009, paddy fields accounted for 36.21% and forest land accounted for 32.27% of the land use. The remaining land-use types were all less than 10%. By 2019, forest land had become the predominant land-use type, accounting for 34.45%. The significant decrease in paddy field area was the main reason for the reduction in agricultural land and the change in the primary land-use type in the study area. Over the past ten years, the area of paddy fields decreased to 22.20%. As paddy fields were the primary cultivated land in the study area, the decrease in paddy field area directly led to a decrease in the overall cultivated land area. Compared to 2009, the scale of cultivated land decreased by 40.19% over the ten years. In 2019, the scale of construction land in the study area was 2.67 times larger than it was ten years ago, mainly due to changes in reservoirs, transportation infrastructure, and village construction land. The construction of reservoirs contributed the most to the growth of construction land, accounting for 98.17% of the increase. Additionally, the proportion of road network area increased by 59.89% compared to 2009, resulting in a significant improvement in traffic accessibility, reflected by the maximum linear density increasing from 0.74 to 1.91. The maximum nuclear density of village construction land also increased from 0.27 to 0.48, indicating a significant increase in concentration. Moreover, the rate of unused land decreased from 9.07% to 2.18% as previously unused land was developed and utilized. Among these changes, grassland and river water surfaces had the highest rates of reuse, accounting for 60.68% and 36.98% of the decrease in unused land, respectively.



(**a**) Land Use in 2009. (**b**) Land Use in 2019.

Figure 2. Land use in the study area from 2009 to 2019.

According to the comparative analysis of land-use change from 2009 to 2019, the primary type of cultivated-land use, paddy field, directly led to a sharp decline in the scale of cultivated land in the study area. Additionally, the construction land increased significantly due to the reservoir construction. The effective utilization of other grasslands and rivers was also observed. To determine the direct relationship between the change and result of this land-use adjustment and the land-use decision of the local government in the study area, it is necessary to combine the reservoir construction process, analyze the characteristics of land-use transfer in the study area, and further explain the process of regional land-use structure adjustment.

3.2. Results of Land-Use Adjustment from the Perspective of Government Attention

As a leader and stakeholder in reservoir construction and cultivated-land protection, the local government's attention distribution and transfer process (Figure 3) directly influences land-use decision-making and is manifested in the form of land-use adjustment (Figure 4). Land-use change, which serves as a reflection of the government's land-use decisions, reflects society [36].

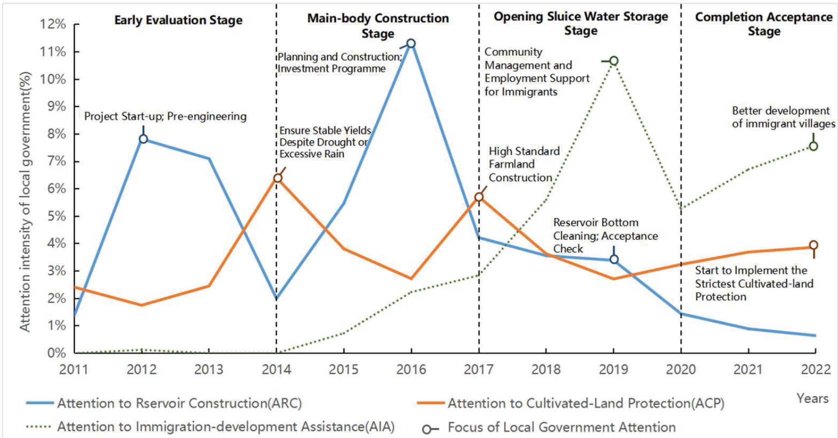


Figure 3. Changes in government attention intensity from 2011 to 2022.

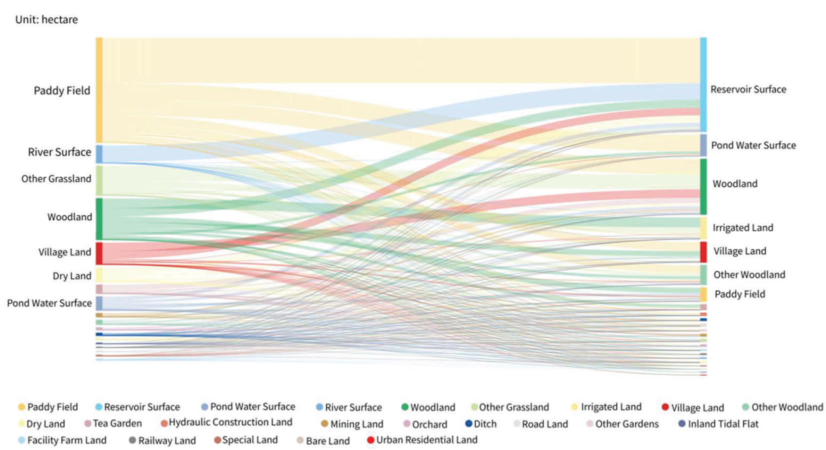


Figure 4. Land-use transfer in the study area from 2009 to 2019.

3.2.1. Create Attention: Reservoir Construction as the Center of Gravity

From 2011 to 2014, during the Early Evaluation Stage of large reservoir construction, the local government in the study area exhibited a shift in focus toward reservoir construction. Initially, while the central government decided to build the large reservoir, the local government still placed a higher emphasis on protecting cultivated land rather than reservoir construction. However, in 2012, the local government swiftly increased its attention towards reservoir construction by 7.82%, while simultaneously decreasing its focus on cultivated-land protection, as indicated by the "Attention to Cultivated-Land Protection" (ACP) metric. Although the ACP eventually rebounded, the average attention given by the local government towards reservoir construction remained 1.32% higher than that towards cultivated-land protection during this stage. This deliberate emphasis on reservoir construction suggests both the significance of the project and the local government's determination to improve its implementation. To demonstrate this, the local government created the "Attention to Reservoir Construction" (ARC) initiative, highlighting its importance in the area.

In the study area from 2009 to 2019, the local government implemented land-use adjustments in response to the construction of large reservoirs. These adjustments included increasing the scale of land designated for reservoir construction. Notably, the reservoir construction land experienced the largest increase in scale, accounting for 60.96% of the total area increase in the study area. Within this category, the scale of the reservoir inundation area saw the greatest increase, representing 59.24% of the total area increase. Consequently, the reservoir surface land in the flooded area became the third largest land-use type in the study area, covering 14.39% of the total region. Additionally, the local government adopted the "Reservoir Construction as the Center of Gravity" approach during land-use adjustment, prioritizing construction land planning. Thus, significant changes occurred in the area and distribution of construction land, particularly in villages, leading to a restructuring of land use in the study area and setting the stage for the beginning of RLCCP.

3.2.2. Reinforce Attention: Building Reservoirs at the Expense of Cultivated Land

The main-body construction stage for the construction of the large reservoir was from 2014 to 2017, during which the local government significantly prioritized its focus on the construction of the large reservoir. This focus has been further strengthened by the local government's continued efforts to enhance the ARC, which has direct implications for the ACP. Notably, there is a strong negative correlation coefficient (−0.93) between changes in ARC and changes in ACP during this period. This means that the higher the intensity of the local government's focus on ARC, the lower the ACP. In particular, in 2016 when the ARC peaked at 11.39%, the ACP accounted for only 2.72%. Consequently, the shifting attention of the local government towards prioritizing the construction of large reservoirs has directly influenced their decision-making process, leading them to prioritize completing the construction planning of these reservoirs at the cost of cultivated lands in their land-use adjustments.

According to the results of the land-use structure adjustment, the paddy fields transferred out are mainly used for water surface land of the reservoir, accounting for 43.31% of the paddy fields transferred out. The water surface of the reservoir mainly comes from paddy fields and rivers, accounting for 48.36% and 17.37% of the newly increased area of the reservoir. In addition, 92.67% of the reduced river water surface land is converted to the reservoir water surface. However, as the main grain production cultivated land in the study area, the quality of paddy fields distributed along the river is often better. Therefore, the local government chose to give priority to completing the construction planning of the large reservoir, sacrificed some high-quality cultivated land, and planned the reservoir inundation area along the river flow direction. This decision has brought challenges and crises for local governments to carry out RLCCP. The other types of transferred out-land do not exceed 20%.

3.2.3. Adjust Attention: Scale of Supplementary Cultivated Land

From 2017 to 2020, the local government has readjusted its focus. The emphasis has shifted to the construction of the large reservoir, specifically the Opening Sluice Water Storage Stage, with the Agricultural Cultivated-Land Protection (ACLP) gradually being de-emphasized. As a result of completing the main reservoir construction, the local government has reduced the ARC by 2.78% and shifted its attention primarily to cleaning the reservoir bottom. Interestingly, the local government has placed slightly more attention on cultivated-land protection compared to reservoir construction, by 0.91%. It is worth noting that since 2017, there has been a significant increase in the local government's attention to Immigration-development Assistance (AIA). In 2019, this peaked at 10.23%, focusing on fund allocation, community management, civilized guidance, and employment assistance for immigrants. This adjustment in attention, following the completion of the main reservoir works, has led the local government to decide to supplement the scale of cultivated land rather than significantly increase land for reservoir construction during the land-use adjustment process.

The increase in cultivated-land-use scale in the study area mainly comes from agricultural land (forest land) and unused land (other grasslands), accounting for 42.75% and 19.80% of the increase in cultivated land, respectively. Among them, the newly increased cultivated land is mainly irrigated land and paddy fields, accounting for 59.13% and 37.78% of the increased cultivated land. The increase of irrigated land has changed the structure of cultivated-land use in the study area, surpassing dry land as the second largest type of cultivated-land use. The proportion of paddy fields, dry land, and irrigated land has changed from 170:14:1 in 2009 to 20:1:3. Therefore, the increase in irrigated land has effectively alleviated the imbalance in the amount of cultivated land, contributing to the positive results achieved through readjusted attention by local governments in addressing the issue.

3.2.4. Divert Attention: Negative Impact of Newly Cultivated Land

During the Completion Acceptance Stage of the construction of the large reservoir from 2020 to 2022, the negative impacts on the newly cultivated land have not been completely resolved. One issue is the decline in the quality of cultivated land in the study area. The process of land-use adjustment from 2009 to 2019 revealed that local governments took over a significant amount of paddy fields to build reservoirs. Although a large amount of irrigated land was subsequently added, the overall quality of the cultivated land in the study area decreased. Additionally, a new problem of cultivated-land abandonment has emerged. Despite the land-use adjustment, more than half of the newly cultivated land remains uncultivated, with some types of land reaching abandonment rates exceeding 80% after the transition to irrigated land. This phenomenon is related to the agglomeration of village construction land following the relocation of reservoir area immigrants (Figure 5). Due to the abandonment of cultivated land by immigrants and their relocation to the resettlement areas built by local governments, only 13.48% of immigrants continue to engage in agricultural work after relocation. Consequently, the construction of the large reservoir not only increases the extent of agglomeration for village construction land but also reduces the proportion of reservoir immigrants involved in agricultural work. It has also been observed that the rate of newly cultivated-land abandonment, particularly for newly irrigated land, increases with distance from the village construction land. In the buffer zone located 50 m to 350 m away from the village construction land, the rate of newly irrigated land abandonment ranges from 34.65% to 65.85%.

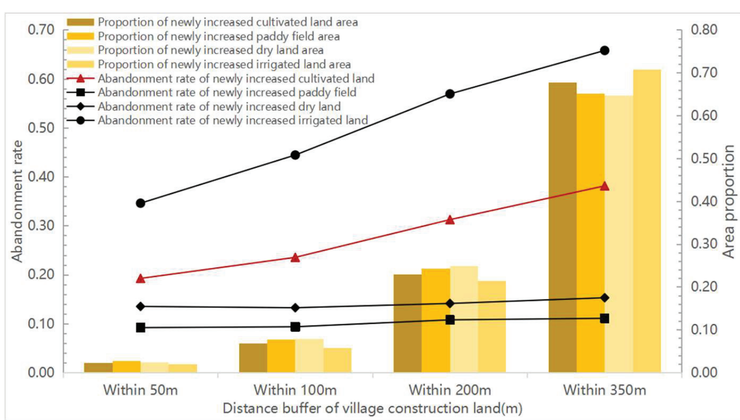


Figure 5. Abandonment degree of newly added cultivated land in the construction land buffer zone of different villages.

The average annual growth rate of AIA of local governments at this stage is 0.11% higher than that of ACP. This indicates that as the reservoir construction comes to an end, the local government is shifting its focus toward the management of immigrant communities, employment assistance, mental outlook, and other aspects of development assistance. Additionally, more attention is being given to solving the feedback problems related to cultivated-land protection from superior supervisors, investigating and handling cases of illegal occupation of cultivated land, and soil pollution control. However, there is no effective attention being given to RLCCP's "Continuous negative impact"—the decline in the quality of newly cultivated land and abandonment.

3.3. RLCCP Evolution Mechanism from the Perspective of Local Government

The development process of RLCCP during the construction of large reservoirs is influenced by the attention trend of local governments. The local government's attention to the "Create-Reinforce-Adjust-Divert" large reservoir construction leads to various rebalancing efforts aimed at mitigating the impact on cultivated land. These rebalancing efforts undertaken by local governments can be categorized into four stages: "Generation—Challenge—Marked effect—Continuous negative impact" (GCMC), resulting in different outcomes in land-use adjustment. To understand the evolution mechanism of RLCCP, it is necessary to analyze the driving factors and decision-making purposes of local governments in land-use decision-making at different stages of large reservoir construction (Figure 6).

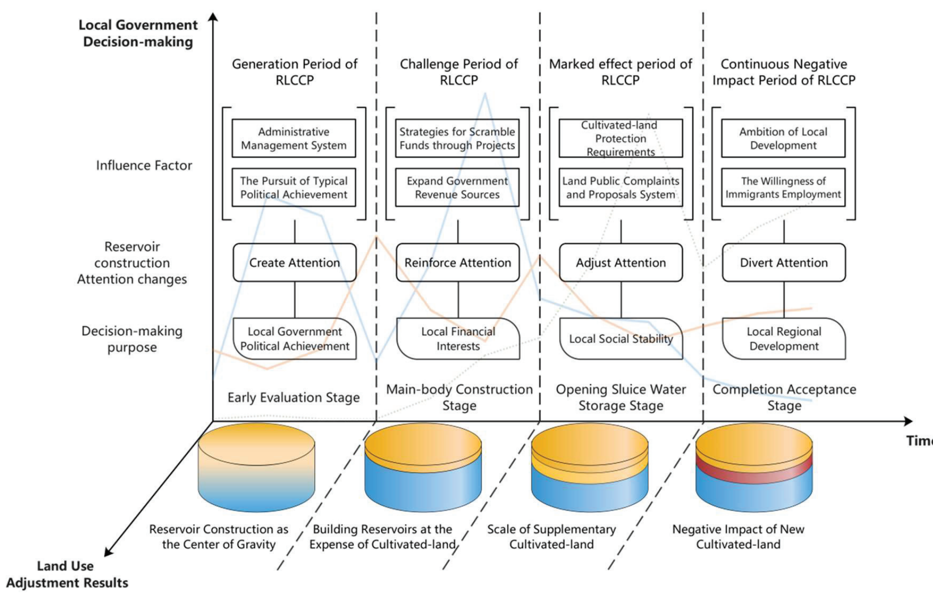


Figure 6. RLCCP evolution mechanism from the perspective of local government attention.

3.3.1. Create Attention: Generation Period of RLCCP

On the one hand, local governments, as administrative subordinate organs established by the central government, must obey and fulfill the goals and requirements of the central government. Thus, when the country faces the national demand for Huaihe River governance and water for people's livelihood, the central government assigns the task of "large reservoir construction" to the local governments. Consequently, the administrative management system and the land state-owned system require the local government to take immediate action upon accepting the task. This prompt response creates the "ARC" in the study area. Additionally, the requirement of cultivated-land protection is also a long-term top-down task. Therefore, the local government needs to continuously pay attention to cultivated-land protection during the reservoir construction period, resulting in a continuous ACP. Moreover, local governments must build large reservoirs.

The status of cultivated-land protection in the performance appraisal is more similar to the "thankless" work, thus leaving many hidden dangers for the work of cultivated-land protection. On the other hand, factors such as the implementation of the important tasks of the superior and the efficiency of completion are not only the standard of the daily performance appraisal of the government but also the typical political achievement of "breaking through the tight encirclement" in the performance appraisal of the local government. The typical practices of the local government in the study area during the planning and construction of large reservoir and resettlement areas have been visited, investigated, and studied by the superior government and other local governments in the reservoir area as excellent cases many times. The resettlement work has won the third-class collective credit three times, and won the title of "Top Ten Influential Water Conservancy Projects in China".

Therefore, based on the requirements of China's administrative management system and the land state-owned system, the local government maintains an "optimistic" attitude toward the future advantages brought by the construction of large-scale water conservancy infrastructure. This is primarily driven by the consideration of improving the local government's political achievements. To achieve this, the local government created the ARC program, which focuses on selecting large reservoir construction projects that can bring significant political achievements. However, it is also recognized by the local government that the construction of large-scale infrastructure can lead to various issues related to land utilization. Therefore, the local government has adopted a comprehensive approach that emphasizes the protection of cultivated land while addressing these issues and has implemented a series of rebalancing measures.

3.3.2. Reinforce Attention: Challenge Period of RLCCP

With the development of large reservoir construction, the local government's self-interest appeal is highlighted, which intensifies RLCCP in implementing the strategy of "Strategies for Scramble Funds through Projects" and expanding the source of tax revenue. Finance and taxation are the core elements for local governments to seek their interests. Local government decision-making is a rational choice between the explicit achievements of project construction and the implicit achievements of cultivated-land protection. However, local governments in villages and towns often find it difficult to achieve financial self-sufficiency. Driven by the project system governance in China, large reservoir construction projects, as state-level projects, have led the local government to focus more attention and energy on exploring derivative projects that can rely on large reservoir construction. To seek superior financial support, the local government further strengthened ARC. As a result, the resettlement area in the reservoir area has become a new "Cornucopia", which is used as a bargaining chip to compete with the superior government, compete with the same level government, and successfully obtain nearly 15 million special financial allocations from the superior government.

The local government in the study area has chosen to expand the area of construction land by occupying cultivated land to support large reservoir construction and resettlement projects. This decision was made to cultivate tax subjects and support backbone tax sources. On one hand, the government obtains land finance tax through land acquisition, land transfer, and land development. On the other hand, it attracts investment through the construction of large reservoirs and resettlement areas. As a result, the average annual tax revenue in the study area has increased from 5.3083 million yuan/year to 12.5133 million yuan/year since 2019, demonstrating the success of land management decision-making. However, this has also led to an increase in demand for Public Complaints and Proposals (PCP) from local residents and immigrants. During the Early Evaluation Stage, only 1.01% attention was given to PCP by the local government in the reservoir area for the construction of the large reservoir. However, as the main-body construction stage commenced, the local government started paying closer attention to PCP, raising the degree of attention to 3.41%. This mainly pertains to land disputes in resettlement, land acquisition, and production land adjustment.

The local government has focused on large reservoir construction projects as a means to achieve significant financial benefits, making it one of the interesting subjects of RLCCP. However, the implicit achievement of cultivated-land protection has contributed minimally to local financial growth. Consequently, the decision to occupy cultivated land for the construction of a large reservoir and resettlement area was made by the local government to meet its financial interests. As a result, the rebalancing efforts of the local government are facing challenges and crises.

3.3.3. Adjust Attention: Marked Effect Period of RLCCP

The local government of the study area has implemented a series of measures, such as "Supplementary cultivated land", "Land reception", and "Control of soil pollution", by the requirements of "Basic cultivated-land protection", "the red line for the protection of cultivated land", "cultivated-land balance", and "Increase and decrease connection of land". These measures were taken to fulfill the tasks and requirements stipulated by the central government through land management laws and policies, to protect the quantity of cultivated land. In addition, from 2017 to 2019, intensive efforts were made in the "Production land adjustment of immigrant" work, resulting in the resettlement of 12,978 people for production purposes and the transfer of 26.28 hectares of land. These actions have to some extent met the production land demand of some immigrants. The rigid constraints of the Cultivated-land Protection Requirements and the supervision constraints of the Land Public Complaints and Proposals System have prompted local governments to confront the crisis of cultivated-land loss.

Residents in the study area have repeatedly exercised the right to supervise the land acquisition process from the bottom up to the local government through PCP. At the stage of impoundment, the local government proposed to carry out the "PCP Responsibility Implementation Year" activity in depth, focusing on the PCP stabilization of reservoir demolition cases. Resolving problems related to reservoir construction accounted for 86% of the total PCP in the township. Furthermore, the local government mediated nearly a thousand conflicts and disputes caused by reservoir construction and successfully resolved nearly a hundred resettlement problems.

In the process of land-use adjustment, the top-down cultivated-land management policy rigidly restricts the behavior of local governments to occupy cultivated land based on their interests. This, in turn, affects the effectiveness of the bottom-up mass supervision mechanism, which also restricts local governments. To stabilize social governance, local governments have prioritized the protection of cultivated land and carried out supplementary works to alleviate challenges faced during previous rebalancing efforts. However, the local government's attention has mostly been focused on increasing the quantity of cultivated land rather than ensuring its quality, resulting in insufficient supervision. Consequently, the study area has experienced a decline in the quality of cultivated land as a result of the decrease in paddy fields and the increase in irrigated land.

3.3.4. Divert Attention: Continuous Negative Impact Period of RLCCP

The local government's commitment to the construction of large reservoir projects, such as the RLCCP, has helped maintain the regional land balance. However, this initiative has also resulted in detrimental consequences, primarily the decline in the quality of newly cultivated land and widespread abandonment. Currently at the Completion Acceptance Stage, the construction of large reservoirs has diverted the local government's attention away from safeguarding cultivated land due to its Ambition for Local Development and the Willingness of Immigrants for Employment.

With the construction of the large reservoir nearing completion, the local government has demonstrated its ambitions for local development in various sectors such as economy, tourism, and culture, with the large reservoir acting as the primary focal point. The aim is to utilize the resources surrounding the large reservoir, utilizing the immigrant village as the main spatial carrier, and leveraging regional advantages to establish a vibrant town that encompasses healthcare, vacationing, leisure, culture, and sports. The goal is to create an appealing and livable home suitable for residents, workers, and tourists alike. Simultaneously, the local government takes proactive measures to guide immigrants in finding employment and engaging in entrepreneurial activities in their respective hometowns. To transform the perception of migrant employment, it is crucial to develop a comprehensive migration education and training system, which emphasizes professional skill-building and quality education. Moreover, to expand employment opportunities for immigrants, the government has planned and constructed an immigrant entrepreneurship park, which has successfully attracted over ten enterprises. Additionally, the government encourages immigrants to actively participate in the development of the tourism industry by providing guidance and support in establishing services such as homestays and farmhouses, thus promoting the growth of tertiary industries.

The local government in the study area has aspirations for the future development of the region and the immigrants residing there. They aim to utilize the resources of the large reservoir, devise plans for tourism development, and stimulate the growth of catering, accommodation, and other service industries to enhance the income of immigrants. However, this ambitious outlook surpasses the realm of existing infrastructure construction and the prevailing business environment conditions in the region, resulting in a conflict between reality and the local government's aspirations. A survey conducted highlighted that in 2022, the primary employment intentions of migrants will still be in the realm of migrant work, with only 7.52% of migrants engaged in tourism-related activities. Although more than 60% of the migrants possess the necessary time, capital, and energy to participate in the tourism industry, a significant majority (74.61%) still perceive engagement in the tourism industry as difficult and risky. Moreover, the local government does not prioritize the cultivation of new farmland, the migrants residing after relocation are far removed from cultivated land, and the remaining households who did not relocate are relatively older (43.89% of farmers are over 50 years old). Consequently, after relocation, most migrants neither involve themselves in tourism work as desired by the local government nor return to large-scale farming on cultivated land, which further exacerbates the "Negative Impact of New Cultivated Land" that remains unresolved by RLCCP.

4. Discussion

Cross-disciplinary solutions have become the main trend of current research in addressing issues such as functional conflict, quantity imbalance, and space occupation in the adjustment of land-use structure [37]. The attention perspective, which focuses on government decision-making, holds theoretical significance in explaining the process and mechanism of land-use rebalancing. It also offers a new analytical perspective and interpretation method for research in this field. In the analysis, the question of whether "people and land" can develop harmoniously and uniformly involves various phenomena in land use such as function conflict, quantity imbalance, and space occupation [38]. Tracking the process and dynamic changes in land use is crucial in addition to focusing on the outcomes of land-use adjustment [39]. The decision-making of stakeholders is closely linked to the process and dynamic change of land use. Previous research on land-use structure adjustment primarily regarded the government or its policies as one of the influencing factors, considering local government decision-making as only a part of the outcomes of land-use adjustment [40,41]. Consequently, this study aims to address this gap by examining land use from the perspective of the local government as a stakeholder, providing a more comprehensive understanding of the influencing factors, decisions, and objectives of the local government in land-use structure adjustment. Furthermore, this study elucidates the strategies employed by the government to achieve land-use rebalancing, which serves to compensate for the limitations in the analysis of policy influencing factors resulting from restricted land spatial use data acquisition time and varying resolution quality. Moreover, this approach facilitates a deeper-level analysis of the thought process and actions of interest subjects in the "rebalancing" process. Government decision-making in the process of land-use adjustment involves decentralized information [42]. In the analysis process, the government's attention perspective, through text analysis, tends to focus on comprehensive texts and coherent timelines. This includes government official documents, government news, and meeting minutes. These texts not only summarize and analyze past work content and planning schemes [43,44], but also organize and plan future work. This perspective aids in understanding the process and future trends of land-use structure adjustment from a "planner" perspective.

The evolution of RLCCP is a land-use rebalancing scheme with Chinese characteristics. To understand and practice RLCCP, this article discusses its evolution mechanism from the perspective of local government. It combines specific construction cases with current research on land-use function conflict and spatial adjustment of "construction land and cultivated land". This helps to provide Chinese ideas and plans for local governments. First, the process of land-use change involves the increase in construction land and a reduction in cultivated land due to the construction of large infrastructure. Similar to construction land expansion, cultivated land is also sacrificed for expansion. In this article, the process of land-use structure change is consistent with the conclusions of the existing research on "construction land and cultivated-land change" [45,46]. Second, the underlying reason for local governments to rebalance land use is the conflict between stakeholders [19]. This study explains that the central government assigns large infrastructure tasks to local governments to fulfill national needs and public interests. Meanwhile, local governments take this opportunity to achieve their own performance and financial interests. In this process, local governments carry out rebalancing efforts. Lastly, the strategy for land-use rebalancing efforts is influenced by top-down rigid land constraints and bottom-up mass supervision constraints [39]. This study verifies the "resolution" stage of land-use conflict as the ultimate goal. As a type of construction land, large infrastructure land shares similarities with other construction land structure adjustments. However, large infrastructure construction led by local governments has characteristics such as wide area coverage, involvement of many people, and complex land types. These factors make government policy changes closely related to land-use evolution. The local government supplements the number of cultivated land and carries out "Production land adjustment of immigrant" work to mitigate the imbalance caused by construction land occupation. Based on previous studies, this study focuses on the construction stage of large infrastructure and explains the decision-making focus, reasons, and results of land-use changes caused by local governments at different stages. This forms a cultivated-land evolution model of "balance–imbalance–rebalance" under the influence of multiple factors.

After the local government has conducted land-use rebalancing efforts, there is still a certain "continuous negative impact"—the low quality of newly cultivated land and the abandonment problem. The low quality of supplementary cultivated land shows that the local government does not pay enough attention to the protection of cultivated land quality. This is due to China's cultivated-land protection system's focus on protecting the quantity of cultivated land rather than its quality. The lack of a complete and systematic set of laws and regulations on cultivated-land protection, as well as a lack of incentives and requirements for cultivated-land quality protection, contribute to this problem [47,48]. The local government's priority is on how to supplement the quantity of cultivated land, disregarding the quality of cultivated land after large-scale infrastructure construction. Consequently, this results in challenges to food security as it leads to the problems of "being unable to abide by" and "lax law enforcement" in the process of cultivated-land protection by the local government. The problem of newly cultivated-land abandonment is related to the inadequate consideration of the local government's newly cultivated-land and village location planning. Previously, Qiu et al. found that village location and accessibility significantly impact cultivated-land abandonment. In this study, it is further revealed that the local government's practice of combining resettlement construction with the planning of the new area has promoted urban-rural integration. However, the distance between the newly cultivated land and the village has not been fully considered in the planning process, resulting in the abandonment of most of the newly cultivated land [49]. To address these issues, improving the assessment mechanism of cultivated-land protection and strengthening the assessment of cultivated-land quality protection levels is crucial. Promulgating the Cultivated-Land Protection Law and implementing other measures would urge and encourage local governments to prioritize the protection of cultivated-land quality during the large-scale infrastructure construction process.

5. Conclusions

This study discusses a series of land-use rebalancing efforts made by the local government in the reservoir area under multiple driving factors and the resulting land-use adjustment results, based on the perspective of government attention. The main conclusions are as follows: First, the impact of large infrastructure construction on cultivated land objectively exists. In rural areas, the sharp decrease of cultivated land and the increase of large infrastructure land occur simultaneously during the process of land-use structure adjustment. In countries with public ownership of land, priority is given to large infrastructure construction projects that promote national development and social stability. Local governments tend to sacrifice cultivated land in favor of large infrastructure construction, with subsequent efforts made to establish new cultivated land. Second, local governments focus on the "Wind vane" of regional land-use structure adjustment. The issues that receive more attention from local governments during large infrastructure construction serve as a basis for government decision-making. This directly influences the planning ideas of local governments for regional land-use adjustment, resulting in a targeted land-use structure adjustment plan at different stages of large infrastructure construction. Finally, the land-use adjustment decision resulting from changes in the local government's attention represents a series of land-use rebalancing efforts with Chinese characteristics, as a subject of interest in land-use. Driven by goals such as Local Government Political Achievement, Local Financial Interests, Local Social Stability, and Local Regional Development, local governments make land-use adjustment decisions to intensify their interests and development. Through various means, these local governments supplement cultivated land and adjust productive land, attempting to achieve a balance between large-scale infrastructure construction and cultivated-land protection objectives through rebalancing efforts.

6. Prospect

From the perspective of government attention, this study has limitations on RLCCP research. On one hand, the NLP analysis reveals that local governments will continue to prioritize cultivated-land protection and food security from 2020 to 2022. However, the land survey data used in the analysis only covers 2009 and 2019, restricting the ability to examine the process of land-use structure adjustment. Thus, future research should monitor the adjustment and changes in land-use structure after 2020, and explore the impacts of improved ACP on land-use structure. On the other hand, existing research on government attention typically relies on semantic coding of government work reports, news, and other texts, quantifying the proportion of texts related to the research topic as an indicator of attention intensity changes. To provide a more comprehensive and objective representation of government decision-making attention trends, it is recommended that future studies explore alternative methods of quantifying government attention and consider diverse data acquisition channels.

Author Contributions: Conceptualization, J.G.; Investigation, Z.M., J.S. and Y.G.; Data curation, X.Z., C.Y., Z.M., J.S. and Y.G.; Writing—original draft, J.G. and X.Z.; Writing—review and editing, C.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (U1904125); Scientific and Technological Innovation Talents in Colleges and Universities of Henan Province in China (2021-CX-027); Soft Science Project of Science and Technology of Henan Province (222400410186); Nanhu Scholars Program of XYNU (2022).

Data Availability Statement: The rural land-use data in the study area is obtained from the second and third national land survey databases. At present, it is only used for research and is not fully disclosed. All government work reports can be retrieved on the official website and are fully disclosed.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

The Influence of Aging Population in Rural Families on Farmers' Willingness to Withdraw from Homesteads in Shenyang, Liaoning Province, China

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Abstract: Population aging presents a significant global challenge. In China, the aging of the rural population coincides with inefficient rural homestead utilization. While the Chinese government has enacted policies to address this, their impact remains limited. Utilizing survey data from 403 rural families in Shenyang, Liaoning Province, China, this study applies the binary Logit and mediating effect models to analyze the impact of rural family population aging on farmers' willingness to withdraw from homesteads with compensation and their compensation preference. Key findings include: (1) Family population aging intensifies farmers' willingness to withdraw from homesteads, with a stronger preference for non-monetary compensation as aging increases. (2) Regarding the willingness to withdraw with compensation, farmers' cognition of homestead security value masks the effect by 4.71%, while asset value cognition has no mediating effect. (3) With regard to promoting non-monetary compensation choices, farmers' homestead asset value cognition fully mediates at 16.01%, but security value cognition is without mediating effect. Based on these findings, it is recommended that the government crafts tailored homestead withdrawal policies considering farmers' family age structure. Further, efforts should aim at refining farmers' understanding of homestead values, promoting a blend of non-monetary and monetary compensations.

Keywords: rural family population aging; farmers' willingness to withdraw from homestead with compensation; homestead withdrawal compensation preference; cognition of homestead value; mediating effect

Citation: Gu, H.; He, Y.; Wang, B.; Qian, F.; Wu, Y. The Influence of Aging Population in Rural Families on Farmers' Willingness to Withdraw from Homesteads in Shenyang, Liaoning Province, China. *Land* **2023**, *12*, 1716. https://doi.org/10.3390/land12091716

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 5 August 2023
Revised: 31 August 2023
Accepted: 31 August 2023
Published: 2 September 2023

1. Introduction

As life expectancy increases and population fertility rates decline, populations are aging at an accelerating rate globally [1]. The aging of the population is the inevitable result of demographic transition and an important issue facing human society in the 21st century [2]. Aging can be defined as a dynamic process where the proportion of the elderly population increases within the total population due to a decrease in the number of young people and an increase in the number of elderly people. According to international consensus, when the elderly population over 60 years old accounts for 10% of the total population in a country or region, or the elderly population over 65 years old accounts for 7% of the total population, that country or region is considered an aging society. Referring to the World Population Prospects (2019 Revision) released by the United Nations, from 2000 to 2020, the proportion of the elderly population aged 60 and above increased from 9.9% to 13.5% [3]. Projections suggest that by 2035, the global aging process will continue to advance, and the proportion of people aged 60 and over in the total population will rise to 17.8%. By 2050, the world is predicted to enter a moderately aging society, with the proportion of elderly people aged 60 and overreaching 21.4%. The aging of the population has thus emerged as a major challenge for all countries worldwide. In this context, it is crucial to explore strategies for achieving sustainable economic development.

In parallel with these demographic shifts, the rapid advancement of urbanization has been driving a significant change in the population's place of residence, from rural to urban areas. This rural depopulation is a global phenomenon, observed in regions like Australia, Japan, Europe, and North America [4]. As per United Nations data, about 56% of the world's population resided in urban areas by 2021, a proportion projected to reach 61% by 2031. Moreover, the latest State of the World's Cities 2022 report by UN-HABITAT predicts that the global urban population will swell by 2.2 billion by 2050, raising its share to 68% [5]. This population migration primarily involves the young and middle-aged labor force moving to cities and towns, resulting in accelerated aging of the rural population. This shift has triggered a series of issues. The aging of the rural population directly impacts agricultural production, primarily through a sharp decline in the labor force. This reduction leads to the abandonment of arable land and the downsizing of agriculture. Moreover, this rural aging phenomenon also contributes to the gradual "hollowing out" of villages, reflected in the long-term idleness of numerous rural houses and significant land wastage. In light of today's food security concerns and rural revitalization efforts, realizing efficient utilization of land resources becomes paramount.

In China, we face the above problems as well. Like many other countries, China's reform and opening-up in the late 1970s sparked rapid urbanization and industrialization, resulting in a significant migration of rural populations to cities [6]. According to statistics, the rural population dwindled from 790 million to 560 million between 1978 and 2018 [7]. In stark contrast, the total area of homesteads ballooned by 14 million hectares from 1995 to 2014 [8]. As of 2018, China's idle rate for rural homesteads was at least 20% [9], while China is currently facing a contradiction between the red line of arable land and urban construction land expansion. According to the third national land survey, the total area of national construction land increased by 85,333.3 square kilometers compared to the second survey, marking a growth rate of 26.5%. Concurrently, the cultivated land area decreased by 75,333.3 square kilometers. China's existing cultivated land spans 1.278 million square kilometers. If the decline continues at this pace, it is projected that within 10 years the area may fall below the set red line of 1.2 million square kilometers, potentially jeopardizing the food security of 1.4 billion Chinese people. In response to this situation, the "Rural Revitalization Strategic Plan (2018–2022)" was formulated and implemented by the central government of China. Meanwhile, the plan has emphasized the need to guide rural collective economic organizations to unleash the potential of collective land and other resources and assets. Thus, the urgent need to revitalize rural idle homesteads and promote intensive and efficient use of rural land resources is evident.

Given this situation, strategies for revitalizing rural homestead resources and unveiling their asset value have become an important facet of China's rural land system reform. To tackle the above issues, the Chinese central government has rolled out a series of policies aimed at cautiously advancing the reform of the rural homestead system. In 2015, the central government approved 15 counties and cities as pilot sites for this reform, with a focus on exploring mechanisms for voluntary homestead withdrawal with compensation. By 2020, the number of pilot sites had been expanded to 104 counties and cities and three prefecture-level cities. The No. 1 document issued by the Central Government from 2017 to 2023 addresses rural homestead reform and encourages farmers to voluntarily withdraw from the homestead with compensation according to law. Nevertheless, farmers are often reluctant to leave their homesteads, mainly due to worries about the cost of living upon relocating to the city [10]. This reluctance is particularly pronounced in the context of increasing rural aging, as the burden of supporting the elderly has become a significant factor impeding farmers' withdrawal with compensation from their homesteads [11]. According to the seventh national census data, the proportion of elderly individuals aged 60 and over in rural areas is 23.81%, which is 7.99 percentage points higher than in cities and towns [12]. Compared to a 4.3 percentage point gap in 2015, this difference has grown significantly. As an important security asset of farmers' families, withdrawal with compensation from the homestead not only involves the property income of farmers, but also is closely related to the old-age security of farmers' families. The potential impact of rural aging on homestead withdrawal with compensation cannot be overlooked, but current compensation policies seem to pay scant attention to the old-age security of farmers [13]. Therefore, in the face of the practical problems of the increasing aging of the rural population, it is necessary to explore the relationship between the aging of the population and the willingness to withdraw from the homestead and their compensation preference.

Research on population aging originated from the United Kingdom, France, and other leading industrialized countries in Western Europe [14]. As the problem of global population aging becomes increasingly prominent, the related research on aging has been continuously expanded and deepened. Typically, the research mainly involves the impact of population aging on social and economic development [15–17], the impact of population aging on medicine [18–20], the impact of population aging on the construction of social security systems for the elderly [21–23], and research on the evolution trend of population aging [24–27]. In addition, some Chinese scholars have analyzed the impact of population aging on agricultural production [1,28,29].

The vast majority of foreign countries have adopted private ownership of land, thereby focusing foreign scholars' research on aspects such as farmland conversion and rural land transfer [30–33]. However, the concept of the rural homestead holds a unique place within the Chinese background. In China, a rural homestead refers to land that is owned by the rural collective, but where individual Chinese citizens hold the right to build houses, by law. The academic community has shown an increasing interest in the complex issue of rural homesteads in China recently. Currently, scholars have conducted extensive theoretical and empirical studies on the matter of homesteads. These studies span a wide range of methodologies and topics. For example, Lu Xiao et al. employed CiteSpace and VOSviewer to perform a visual analysis and mapping of articles in homestead-related fields [34], while Bao et al. utilized the case analysis method to delve into examples of local homestead reform [35]. Su et al. focused on the functional evolution and dynamic mechanism of homesteads, using the comprehensive index model evaluation method [36]. Furthermore, binary logistic models [37,38], structural equation models [39–41], and mediating effect models [42,43] are among the most common methodologies that scholars employ to explore farmers' willingness and behavior regarding withdrawing from rural homesteads from various angles. In terms of content, homestead withdrawal is a hot topic in current research. This topic encompasses several sub-areas, primarily including practical exploration [44], mechanism construction [45], and the behavioral intention associated with compensation for rural homestead withdrawals. Notably, among these, the research focusing on farmers' willingness to withdraw from their homesteads is the most extensive. Some scholars have identified the fact that farmers' personal characteristics or family characteristics significantly influence their willingness to withdraw from the homestead with compensation, through field research [46–48]. Some scholars also found that ownership consciousness [49] and risk expectation [50] also had an impact on their willingness to withdraw from the homestead with compensation. These explorations have underscored that a farmer's decision to withdraw from the homestead with compensation is not solely dictated by objective individual conditions, but also significantly influenced by subjective factors such as individual cognition.

Despite the fact that there are large extensive studies, a significant portion has overlooked the reality of the intensifying issue of rural population aging in China. Only Sun et al. investigated the effects of this demographic shift on the farmers' behavior regarding the withdrawal with compensation from homesteads [51]. Their findings suggested that the larger the proportion of family members over 60 years old, the stronger the inclination to retain homesteads. Indeed, the interplay between factors such as farmer differentiation [52], their property rights cognition [53], and their willingness to withdraw from the homestead with compensation comprises a complex mechanism. The farmers' value cognition of their homestead and local attachment serve as intermediary factors, while intergenerational differences play a regulatory role [54,55]. Previous studies have established that age differentiation can result in variations in individual behavior and cognition and that the farmers' value cognition of the homestead significantly impacts their willingness to withdraw with compensation [54]. Despite these findings, no research has yet explored the relationship between these three factors. Researchers such as Wang et al., Chen Ming, and Gong et al. have systematically studied how farmers' heterogeneity impacts their preferences for homestead withdrawal compensation [56–58]. Their findings indicate that the heterogeneous characteristics of farmers' family income differentiation, regional living differences, and urban housing ownership can influence these preferences. Additionally, some scholars have quantitatively analyzed the impact of homestead withdrawal compensation methods and standards from the perspective of farmers' interaction [59], and farmers' functional cognition [60]. However, few studies have focused on the relationship between the aging of rural families and farmers' homestead withdrawal compensation preferences.

Considering the existing gaps in research, this paper integrates the aging of the rural family population, farmers' value cognition of homesteads, the willingness for homestead withdrawal with compensation, and the compensation preference for homestead withdrawal into a unified analytical framework. Relying on the survey data from 403 rural families in Shenyang, Liaoning Province, China, this study utilizes the binary Logit model and the mediating effect model, based on the theory of neoclassical economics and the theory of cognitive psychology, to empirically analyze the influence and mechanism of rural family aging on the willingness and compensation preference for homestead withdrawal with compensation. Furthermore, this paper explores the role of homestead value cognition throughout this process. This investigation aims to offer a reference for the formulation of homestead withdrawal policies against the backdrop of rural population aging. Meanwhile, China's experiences with land system reform can provide valuable lessons for other countries, particularly those in the developing world.

The remainder of this paper is structured as follows. Section 2 presents the theoretical analysis and research hypotheses. Section 3 introduces the data sources, variable selection, and model design. Section 4 presents and analyzes the empirical results. Section 5 describes the discussion. Section 6 gives the conclusions.

2. Theoretical Analysis and Research Hypothesis

2.1. Characterization of Age Differentiation

In previous studies, scholars have commonly employed a variety of indicators such as the aging rate, the dependency ratio of the elderly population, the proportion of the child population, and the average age to measure the degree of family aging. Among them, the aging rate is the most commonly used indicator to measure the degree of population aging [61]. In this paper, we adopt the population aging rate of families to measure the degree of population aging within families. Defined as the proportion of the elderly population aged 60 and above in the total population of families, the population aging rate of families effectively illustrates family aging. Therefore, the larger the proportion of the elderly population, the greater the degree of family aging, and vice versa.

2.2. The Direct Impact of Family Population Aging on Farmers' Willingness to Withdraw from the Homestead with Compensation and Compensation Preference

The essence of farmers' withdrawal from the homestead is the disposal of homestead assets. According to the theory of neoclassical economics, farmers, acting as "rational economic man", withdraw from their homesteads with compensation primarily to pursue the maximization of economic interests. Only when the risk associated with withdrawal from the homestead falls within the farmers' tolerance, and the benefits derived from the withdrawal outweigh the associated costs, will farmers choose to withdraw from the homestead [62].

This paper constructs a theoretical analysis framework, as depicted in Figure 1. This paper posits that rural families with a high degree of population aging have less of a competitive edge in urban employment. These families often rely on their homesteads to provide a self-sufficient lifestyle, with their existence and productivity largely dependent on agriculture, which effectively minimizes living costs. Farmers' daily living expenses tend to surge when they surrender their homesteads. The compensation offered by the government in exchange for relinquishing the homesteads fails to offset the farmers' long-term livelihood costs. As a result, the benefits derived from surrendering the homesteads are outweighed by the costs incurred, which makes these highly aged rural families more reliant on their homesteads and prone to retain them. In contrast, rural families experiencing a relatively lower degree of population aging tend to carry a smaller family pension burden. Members of these families typically reside in urban areas and towns, exhibiting a lower dependence on their homesteads and incurring fewer costs upon their withdrawal. Simultaneously, the opportunity to monetize their assets through paid withdrawal from homesteads presents itself. The compensation helps alleviate some pressures of urban living for these farmers to a certain extent. The benefits of homestead withdrawal outweigh the costs, leading these families to opt out of their homesteads. The issue of family pensions remains a crucial factor influencing farmers' choice to withdraw and the type of compensation they choose. Farmers with varying degrees of population aging exhibit different sensitivities toward compensation methods. Farmers experiencing a higher degree of population aging bear the significant burden of providing for the aged. Their desire for stability inclines them towards non-monetary compensations such as housing or social security, which offer basic living security. Thus, they tend to favor non-monetary compensation methods. However, families with a relatively lower degree of population aging often have stable residences in cities and towns, and carry a smaller burden of family pensions. Therefore, they tend to opt for monetary compensation methods, which can provide capital for their multiple future choices. This analysis leads us to our hypotheses:

H1: *The aging of the family population inhibits the willingness of farmers to withdraw from the homestead with compensation*.

H2: *The aging of the family population promotes farmers to choose non-monetary compensation methods.*

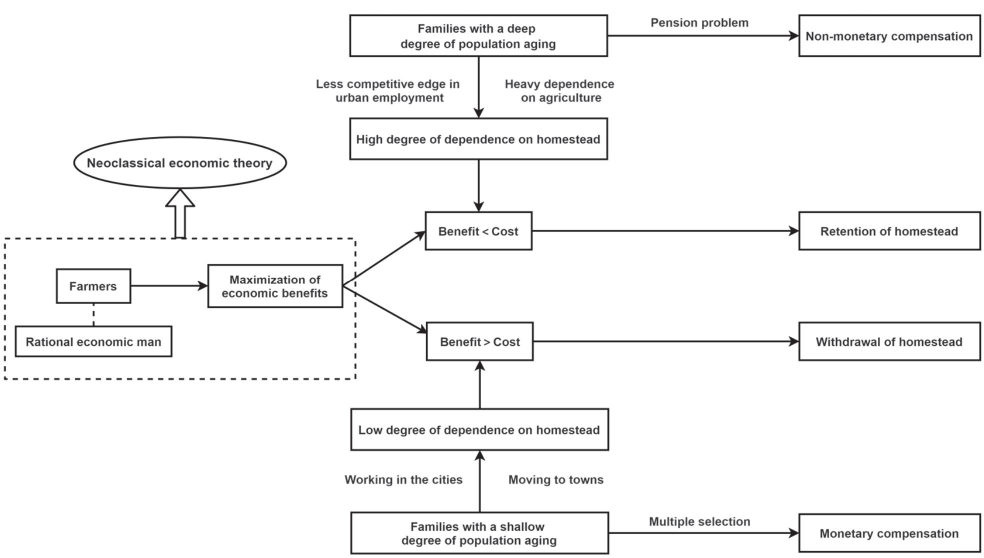

Figure 1. Theoretical Framework of the Influence of Family Population Aging on Farmers' Willingness to Withdraw from the Homestead with Compensation and Compensation Preference.

2.3. The Mediating Role of Homestead Value Cognition

2.3.1. The Impact of Family Population Aging on the Value Cognition of Homestead

The concept of farmers' homestead value cognition is established upon the elucidation of perceived value as observed in the marketing field. Perceived value, as understood from an individual's perspective, enables the customer to assess the value of a product according to their understanding of the product's functionality, quality, economy, etc. [63]. When speaking about farmers' value cognition of homesteads, it predominantly refers to the farmers' holistic evaluation of the multi-functional aspects of a homestead. Reflecting on the current scenario, offering residential and retirement facilities appears to be the most critical function of rural homesteads. Nonetheless, as urbanization rapidly progresses, the function of homestead assets has become increasingly pronounced. There is an observable variance in behavioral cognition among individuals of different ages [54]. This paper creates an analytical framework, as depicted in Figure 2. Families in areas with a pronounced aging population often have a strong demand for homestead security due to their adherence to rural life and lower living costs. As a result, these families possess a deep understanding of the security value of homesteads. When considering asset value cognition, because the realization and security functions of asset functions such as homestead renting, buying, and selling cannot coexist, families with a highly aging population have a weak cognition of this value. For families with a less aged population, a majority of the members gradually transition to urban areas due to reasons such as work and the living environment. Depending primarily on non-agricultural labor in cities for income, they no longer rely on homesteads for survival. This situation leads to a shallow comprehension of the security value of homesteads, shifting their focus towards the value of homestead assets. Therefore, the impact of an aging rural family population on the cognition of homestead value is reflected in the fact that families with a more substantial aging population have a deeper understanding of homestead security functions and a lesser grasp of homestead asset functions. In other words, the aging of the family population positively impacts the cognition of homestead security value and negatively affects the recognition of homestead asset value.

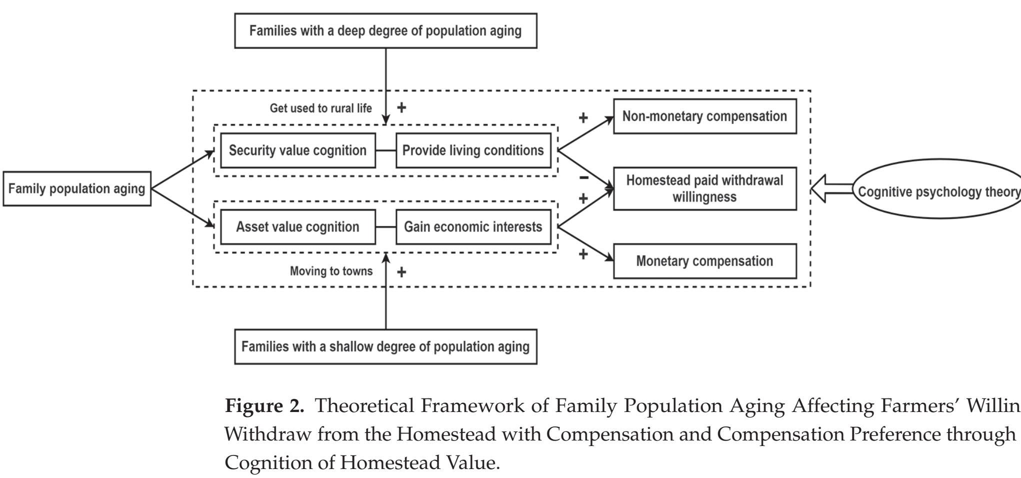

Figure 2. Theoretical Framework of Family Population Aging Affecting Farmers' Willingness to Withdraw from the Homestead with Compensation and Compensation Preference through Farmers' Cognition of Homestead Value.

2.3.2. Impact of Homestead Value Cognition on Farmers' Willingness to Withdraw from the Homestead with Compensation

Cognitive psychology theory underscores that cognition is fundamental to intention and behavior, with individuals' cognition shaping their preferences and thus influencing their decision-making. Consequently, farmers' value cognition of homesteads is bound to exert a certain degree of influence on their willingness to withdraw from the homestead with compensation [54]. As farmers age, their economic expenditure patterns and risk tolerance fluctuate, leading to variations in the cognition of homestead security value and asset value at different ages. The security value of a homestead is demonstrated in its ability to provide basic living conditions for farmers and to effectively lower living expenses. Hence, the deeper a farmer's understanding of the security value of homesteads is, the more likely they are to retain them. On the other hand, the asset value of a homestead is displayed through the potential for descendants to inherit and gain benefits via leasing, selling, or collecting from homesteads. Voluntarily withdrawal from homesteads with compensation is one of the significant methods of realizing this asset value. Therefore, the deeper the farmers' cognition of the value of homestead assets, the more inclined to withdraw from the homestead with compensation. This analysis leads us to our hypotheses:

H3: *The cognition of homestead security value has a negative mediating effect with regard to family population aging affecting farmers' willingness to withdraw from the homestead with compensation*.

H4: *The cognition of homestead asset value has a negative mediating effect with regard to family population aging affecting farmers' willingness to withdraw from the homestead with compensation*.

2.3.3. The Impact of Homestead Value Cognition on Farmers' Homestead Withdrawal Compensation Preference

Individual cognition determines one's preference, and farmers' cognition of homestead value is bound to influence their preference for homestead withdrawal compensation. As a "rational economic man", when farmers choose to withdraw from the homestead, they will choose the compensation method to maximize their interests. The deeper the farmers' cognition of the value of homestead security, the more they pay attention to the basic living conditions that the homestead can provide. The increase in living costs caused by the withdrawal from the homestead will make them tend to choose non-monetary compensation methods such as replacing it with urban housing that can provide more basic living security. The deeper the farmers' cognition of the value of the homestead assets, the more they pay attention to the economic value that the homestead can provide. The economic advantages brought by withdrawal from the homestead can provide strong support for improving the quality of urban life and job selection. Therefore, they tend to choose a more flexible distribution of monetized compensation methods such as one-time capital compensation. This analysis leads us to our hypotheses:

H5: *The cognition of homestead security value has a positive mediating effect with regard to family population aging affecting farmers' homestead withdrawal compensation preference*.

H6: *The cognition of homestead asset value has a negative mediating effect with regard to family population aging affecting farmers' homestead withdrawal compensation preference*.

3. Data Sources, Variable Selection, and Model Design

3.1. Data Sources and Sample Description

3.1.1. Data Sources

Population aging is an undeniable trend in China. Notably, the northeast region is grappling with the country's most severe population aging challenges. Data from the seventh national census reveal that the aging rate of Liaoning Province tops the nation at 25.72%, marking it as the province with the most pronounced population aging. A combination of low birth rates and high net migration rates primarily drives the aging issues in the three provinces of Northeast China. A declining economy, widening of regional differences in urbanization level, aggravation of the contradiction between urban and rural areas, and continuous negative growth of population render the rural development of the three provinces of Northeast China volatile [64]. As the capital of Liaoning Province and the largest central city in Northeast China, Shenyang demonstrates outstanding political, economic, and cultural-center functions. This prominence generates a powerful radiative effect and drive, luring the rural population to migrate to urban areas, and leading to a widespread idleness of surrounding rural homesteads. Shenyang (41.20°~43.04° N, 122.42°~123.81° E) is located in the south of Northeast China and the central part of Liaoning Province, which is the center of the Northeast Asian economic circle and the Bohai economic circle (Figure 3). Shenyang spans a total area of 12,860 square kilometers and encompasses 13 county (district) level administrative regions, including 10 municipal districts, one county-level city, and two counties. By the end of 2020, Shenyang housed a permanent population of 9.073 million, consisting of 7.668 million urban dwellers and 1.405 million rural residents, resulting in an urbanization rate of 84.51%. Approximately 600,000 rural homesteads exist within the city, spanning an area of about 568.7 square kilometers. On average, each homestead covers an area of about 836.7 square meters. Roughly 21,000 homesteads remain idle, occupying an area of about 18.2 square kilometers, yielding an idle homestead rate of 3.5%. In 2020, Shenyang was designated as one of the pilot areas for the new round of rural homestead system reform in the country, which has offered a vast number of samples in support of this research. The data of this study are derived from a sample survey of farmers in Shenyang conducted in July 2021. This research adopts a mixed approach of stratified sampling and simple random sampling to select sample farmers. Firstly, in adherence to the principle of far, middle, and near to the county, three streets were randomly selected at three levels. Secondly, following the principle of high, medium, and low homestead idle rates, each street randomly selected three villages within three tiers. Finally, 12 farmers from differing families were randomly chosen from each village. A total of 405 questionnaires were gathered from four districts, 13 streets, and 35 administrative villages. After eliminating the questionnaires with distorted or missing key information, 403 valid questionnaires were secured, boasting an effective rate of 99.51%. The farmer questionnaire survey primarily employed a method of a "one-to-one" interview between the farmer and the investigator. The main contents of the questionnaire encompass the farmers' family situations, their understanding of homestead value, subjective satisfaction, and so on.

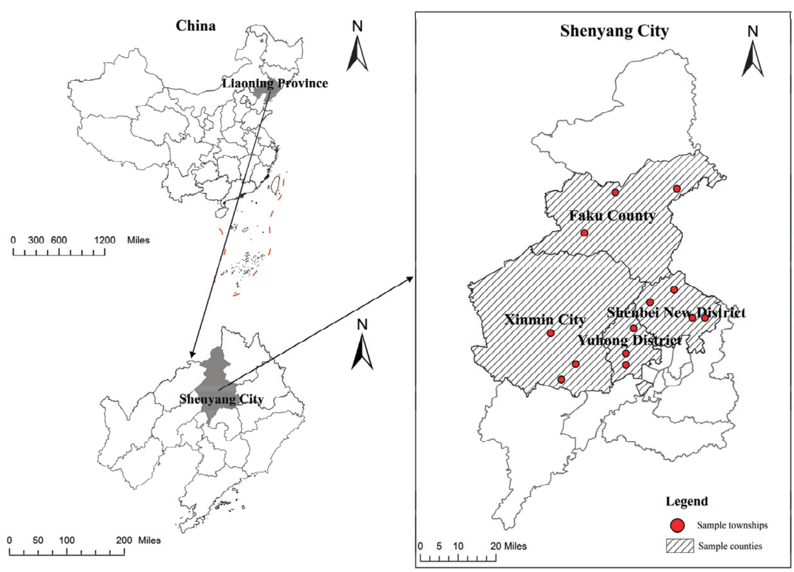

Figure 3. Study area and location of sample townships.

3.1.2. Sample Description

According to the statistical results of the questionnaire, among the 403 surveyed farmers, farmers aged 60 and over accounted for 53.85%, indicating that the rural aging problem in the surveyed areas is serious. The proportion of the labor force in rural families generally exceeds 0.5, representing 86.35% of the total sample size. The ratio of part-time farmers reaches a substantial 99.26%. In the survey on the willingness of farmers to withdraw from the homestead with compensation, 309 families have indicated their willingness to withdraw from the homestead with compensation, accounting for 76.67% of the total sample. Among them, 164 families chose monetary compensation, accounting for 53.07% of the total number of farmers willing to withdraw from the homestead with compensation, and 145 families chose non-monetary compensation, accounting for 46.93% of the total number of farmers willing to withdraw from the homestead with compensation.

3.2. Variable Selection

3.2.1. Explained Variables

In this paper, farmers' willingness to withdraw from the homestead with compensation and compensation preferences are selected as explained variables. To gauge the farmers' willingness to withdraw from the homestead, we designed the questionnaire with the question, "Are you willing to withdraw from your homestead with compensation?" The responses were coded as binary dummy variables: value 1 for willingness to withdraw from their homesteads, and 0 for unwillingness. Similarly, we aimed to understand farmers' compensation preference for homestead withdrawal by posing the question, "Which withdrawal compensation method are you more inclined to choose?" If farmers lean towards monetary compensation, the response was coded as 1. For a non-monetary compensation preference, we assigned a value of 0.

3.2.2. Core Explanatory Variable

This paper selects the aging degree of the rural family population as the core explanatory variable. Referring to the relevant research, in the empirical study, the proportion of the elderly population in the total population, the average age, the elderly dependency ratio, and other indicators are generally used to measure the degree of aging. Based on the international definition of aging, this paper uses the family population aging rate to characterize the degree of family population aging. The family population aging rate refers to the proportion of the elderly population aged 60 and above in the family compared to the total family population.

3.2.3. Mediator Variables

This paper selects the value cognition of farmers' homesteads as the mediator variable, which is subdivided into the security value cognition and the asset value cognition. In the survey, farmers' judgments on the two survey questions of "the homestead can be used to live and reduce the cost of living" and "the homestead can be left as property to future generations" were used to refer to their corresponding homestead value cognition [54]. The index adopts a Likert five-point scale, where 1 means "extremely unimportant", 5 means "extremely important". The higher the score, the deeper the value cognition of farmers.

3.2.4. Control Variables

Considering other factors that may affect farmers' willingness to withdraw from the homestead with compensation and compensation preferences, this paper mainly selects control variables from three aspects: householder characteristics, family characteristics, and farmers' satisfaction: (1) Variables of householder characteristics including gender, age, and education level; (2) Family characteristic variables including the number of the non-agricultural labor force, the total non-agricultural income, the number of left-behind elderly, and the familiarity of the second generation of farmers with agricultural farming; (3) The satisfaction of farmers including their satisfaction with rural infrastructure, their satisfaction with the rural ecological environment and their satisfaction with the rural living consumption level. The descriptive statistical analysis results of the data with farmers' willingness to withdraw from the homestead with compensation and farmers' compensation preference as the explained variables are shown in Tables 1 and 2.

Table 1. Variable selection and descriptive statistical analysis results.

Variable Name			Variable Meaning and Assignment	Average Value	Standard Deviation
Explained variable	Willingness to withdraw		1 = Willing 0 = Not willing	0.767	0.423
Core explanatory variable	Family population aging rate		The number of people over 60 years old in the interviewed families/the total family population	0.361	0.372
Mediator variables	Security value cognition		1 = Extremely unimportant 2 = Not very important 3 = General 4 = More important 5 = Extremely important	3.903	0.830
	Asset value cognition		1 = Extremely unimportant 2 = Not very important 3 = General 4 = More important 5 = Extremely important	4.164	0.827
Control variables	Householder Characteristics	Gender	1 = Male 0 = Female	0.938	0.242
		Age	Actual survey value/person	60.784	10.068
		Education level	1 = Below primary school 2 = Primary school 3 = Junior high school 4 = High school 5 = College degree or above	2.896	0.861
	Family Characteristics	Number of the non-agricultural labor force	Actual survey value/person	1.404	1.103
		Number of left-behind elderly	Actual survey value/person	0.493	0.821
		Total non-agricultural income	Actual survey value/ten thousand yuan	5.624	5.893
		The second generation of farmers' familiarity with agricultural farming	1 = Very familiar 2 = Familiar with a point 3 = Completely unfamiliar	2.501	0.780
Control variables	Satisfaction	Satisfaction with rural infrastructure conditions	1 = Extremely dissatisfied 2 = Not satisfied 3 = Satisfied 4 = Relatively satisfied 5 = Very satisfied	3.717	1.137
		Satisfaction with the rural ecological environment	1 = Extremely dissatisfied 2 = Not satisfied 3 = Satisfied 4 = Relatively satisfied 5 = Very satisfied	3.777	1.095
		Satisfaction with the level of rural living consumption	1 = Extremely dissatisfied 2 = Not satisfied 3 = Satisfied 4 = Relatively satisfied 5 = Very satisfied	3.846	0.957

Note: The explained variable is farmers' willingness to withdraw from the homestead.

Table 2. Variable selection and descriptive statistical analysis results.

Variable Name			Variable Meaning and Assignment	Average Value	Standard Deviation
Explained variable	Compensation preference		1 = Monetary compensation 0 = Non-monetary compensation	0.531	0.500
Core explanatory variable	Family population aging rate		The number of people over 60 years old in the interviewed families/the total family population	0.375	0.371
Mediator variables	Security value cognition		1 = Extremely unimportant 2 = Not very important 3 = General 4 = More important 5 = Extremely important	3.877	0.852
	Asset value cognition		1 = Extremely unimportant 2 = Not very important 3 = General 4 = More important 5 = Extremely important	4.172	0.806
Control variables	Householder Characteristics	Gender	1 = Male 0 = Female	0.945	0.228
		Age	Actual survey value/person	60.598	10.127
		Education level	1 = Below primary school 2 = Primary school 3 = Junior high school 4 = High school 5 = College degree or above	2.906	0.850
	Family Characteristics	Number of the non-agricultural labor force	Actual survey value/person	1.489	1.090
		Number of left-behind elderly	Actual survey value/person	0.492	0.832
		Total non-agricultural income	Actual survey value/ten thousand yuan	6.193	6.081
		The second generation of farmers' familiarity with agricultural farming	1 = Very familiar 2 = Familiar up to a point 3 = Completely unfamiliar	2.518	0.767
	Satisfaction	Satisfaction with rural infrastructure conditions	1 = Extremely dissatisfied 2 = Not satisfied 3 = Satisfied 4 = Relatively satisfied 5 = Very satisfied	3.696	1.167
		Satisfaction with the rural ecological environment	1 = Extremely dissatisfied 2 = Not satisfied 3 = Satisfied 4 = Relatively satisfied 5 = Very satisfied	3.799	1.077
		Satisfaction with the level of rural living consumption	1 = Extremely dissatisfied 2 = Not satisfied 3 = Satisfied 4 = Relatively satisfied 5 = Very satisfied	3.825	0.991

Note: The explained variable is compensation preference.

3.3. Model Design

3.3.1. Binary Logit Model

The Logit model is also a "logistic regression", which is a commonly used method for empirical analysis. In this paper, the dependent variables of "farmers' willingness to withdraw from the homestead with compensation" and "which type of compensation is more favored" are assigned to 0 and 1, so the binary Logit model is selected for regression analysis. The model is defined as follows:

$$Y_i = c_0 + cX_i + \beta_2 Z_i + e_1 \tag{1}$$

In Formula (1), Y_i represents the willingness to withdraw or compensation preference of the farmer's homestead; X_i is the population aging rate of the family; Z_i is the control variable; c_0 is a constant term; c and β_2 are the parameters to be estimated, where the coefficient c is the total effect of the family population aging rate on the willingness to withdraw from the homestead with compensation or the preference for compensation; e_1 is a random error term.

3.3.2. Mediating Effect Model

To further investigate whether the population aging rate of families has an impact on the willingness to withdraw from the homestead with compensation and the compensation preference through the cognition of the value of the homestead, this paper adopts the mediation test procedure proposed by Wen et al. [65]. The mediation effect is examined based on the total effect of the family population aging rate on the farmer's willingness to withdraw with compensation and compensation preferences. The test process is shown in Figure 4, and the specific model is defined as follows:

$$M_i = a_0 + aX_i + \gamma Z_i + e_2 \tag{2}$$

$$Y_i = b_0 + c'X_i + bM_i + \delta Z_i + e_3 \tag{3}$$

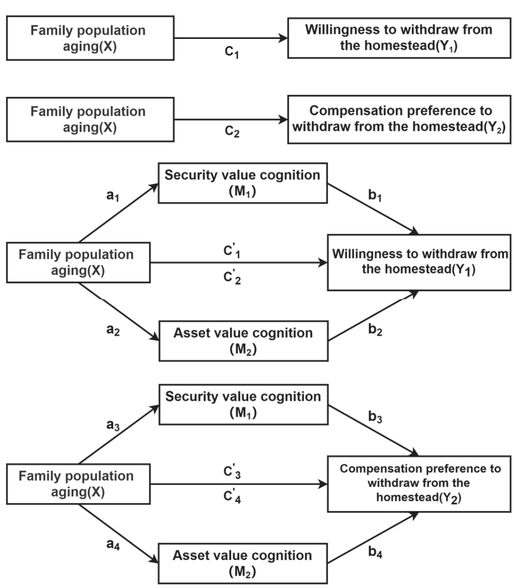

Figure 4. Mediating effect testing process.

In Formula (2), M_i is the value cognition level of the farmer's homestead, and coefficient a is the effect of the aging rate of the family population on the value cognition of the farmers' homestead; in Formula (3), coefficient b is the effect of farmers' cognition of homestead value on the willingness or compensation preference of homestead paid withdrawal; the coefficient c′ is the direct effect of the family population aging rate on the willingness to withdraw from the homestead with compensation or the preference for compensation; e_2 and e_3 are random errors. According to the mediating effect test process proposed by Wen et al. [65], the first test is whether the coefficient c in Formula (1) is significant; secondly, the significance of coefficients a and b in Formulas (2) and (3) is tested in turn, to judge whether the indirect effect ab is significant; finally, if the indirect effect is significant, the c′ significant situation in Formula (3) is judged to be a complete mediating effect or a partial mediating effect. At the same time, it is necessary to compare the direction of ab and c′ symbols. If ab and c′ are the same, the results are explained by the mediating effect. If ab and c′ are different, the results are explained by the masking effect.

4. Empirical Results and Analysis

Considering that there may be multicollinearity among multiple variables, the multicollinearity test is first performed on all explanatory variables. The results show that the VIF values of all explanatory variables are less than 10, and the Mean VIF is less than 2, indicating that there is no multicollinearity among the existing explanatory variables. Then, stata16.0 software is used to empirically test the mechanism of family population aging rate affecting farmers' willingness to withdraw from the homestead and compensation preference. The regression results of the model are shown in Tables 3–5.

Table 3. Regression results of the total effect of family population aging on farmers' willingness to withdraw from the homestead and compensation preference.

Variable Name	Model 1 (Willingness to Withdraw)		Model 2 (Compensation Preference)	
	Coefficient	dy/dx	Coefficient	dy/dx
Family population aging rate	2.072 *** (0.532)	0.335 (0.081)	−0.897 * (0.517)	−0.197 (0.111)
Gender	0.515 (0.476)	0.083 (0.077)	0.348 (0.531)	0.076 (0.116)
Age	−0.037 ** (0.017)	−0.006 (0.003)	0.001 (0.016)	0.001 (0.004)
Education level	−0.083 (0.151)	−0.013 (0.024)	−0.319 ** (0.156)	−0.070 (0.033)
Number of non-agricultural labor force	0.322 ** (0.151)	0.052 (0.024)	−0.458 *** (0.150)	−0.100 (0.031)
Number of left-behind elderly	−0.239 (0.183)	−0.039 (0.029)	0.641 *** (0.183)	0.141 (0.037)
Total non-agricultural income	0.102 *** (0.036)	0.017 (0.006)	0.043 * (0.024)	0.009 (0.005)
The second generation of farmers' familiarity with agricultural farming	0.123 (0.162)	0.020 (0.026)	−0.357 ** (0.165)	−0.078 (0.035)
Satisfaction with rural infrastructure conditions	−0.304 * (0.170)	−0.049 (0.027)	0.256 * (0.155)	0.056 (0.033)
Satisfaction with the rural ecological environment	0.297 * (0.166)	0.047 (0.027)	−0.115 (0.168)	−0.025 (0.037)

Table 3. *Cont.*

Variable Name	Model 1 (Willingness to Withdraw)		Model 2 (Compensation Preference)	
	Coefficient	dy/dx	Coefficient	dy/dx
Satisfaction with the level of rural living consumption	−0.108 (0.136)	−0.018 (0.022)	−0.273 ** (0.127)	−0.060 (0.027)
Log likelihood	−199.098		−194.264	
LR chi^2	39.600 ***		38.670 ***	
Pseudo R^2	0.091		0.090	
Sample size	403	403	309	309

Note: *, **, *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. Robust standard error in parentheses.

Table 4. Regression results of the mediating effect mechanism of farmers' willingness to withdraw from the homestead.

Variable Name	Model 3 (Security Value)	Model 4 (Asset Value)	Model 5 (Willingness to Withdraw)	Model 6 (Willingness to Withdraw)
	Coefficient	Coefficient	Coefficient	Coefficient
Family population aging rate	0.372 ** (0.167)	−0.224 (0.166)	2.170 *** (0.537)	2.086 *** (0.534)
Security value			−0.275 * (0.159)	
Asset value				0.077 (0.156)
Gender	0.065 (0.171)	0.039 (0.170)	0.535 (0.479)	0.513 (0.476)
Age	−0.004 (0.005)	0.002 (0.005)	−0.038 ** (0.017)	−0.036 ** (0.017)
Education level	0.076 (0.050)	−0.006 (0.050)	−0.058 (0.152)	0.083 (0.152)
Number of non-agricultural labor force	−0.037 (0.047)	0.073 (0.047)	0.300 ** (0.151)	0.316 ** (0.151)
Number of left-behind elderly	0.034 (0.058)	0.076 (0.058)	−0.230 (0.183)	−0.244 (0.184)
Total non-agricultural income	0.011 (0.008)	−0.007 (0.008)	0.106 *** (0.036)	0.103 *** (0.036)
The second generation of farmers' familiarity with agricultural farming	0.030 (0.053)	0.061 (0.053)	0.125 (0.163)	0.120 (0.162)
Satisfaction with rural infrastructure conditions	0.043 (0.051)	0.156 *** (0.051)	−0.300 * (0.171)	−0.314 * (0.171)
Satisfaction with the rural ecological environment	0.108 ** (0.054)	−0.007 (0.054)	0.338 ** (0.169)	0.297 * (0.166)
Satisfaction with the level of rural living consumption	0.013 (0.043)	−0.019 (0.043)	−0.104 (0.136)	−0.107 (0.136)
Pseudo R^2			0.097	0.091
R-squared	0.072	0.069		
Sample size	403	403	403	403

Note: *, **, *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. Robust standard error in parentheses.

Table 5. Regression results of the mediating effect mechanism of farmers' homestead withdrawal compensation preference.

Variable Name	Model 7 (Security Value)	Model 8 (Asset Value)	Model 9 (Compensation Preference)	Model 10 (Compensation Preference)
	Coefficient	Coefficient	Coefficient	Coefficient
Family population aging rate	0.433 ** (0.197)	−0.433 ** (0.184)	−1.034 ** (0.527)	−0.779 (0.524)
Security value			0.242 (0.152)	
Asset value				0.288 * (0.163)
Gender	0.096 (0.212)	0.158 (0.198)	0.325 (0.536)	0.291 (0.534)
Age	−0.006 (0.006)	0.002 (0.006)	0.003 (0.016)	0.001 (0.016)
Education level	0.097 (0.060)	−0.026 (0.056)	−0.343 ** (0.157)	−0.310 ** (0.156)
Number of non-agricultural labor force	−0.058 (0.056)	0.027 (0.052)	−0.455 *** (0.151)	−0.469 *** (0.151)
Number of left-behind elderly	0.029 (0.068)	0.140 ** (0.063)	0.644 *** (0.184)	0.605 *** (0.184)
Total non-agricultural income	0.014 (0.009)	−0.010 (0.008)	0.041 * (0.024)	0.047 * (0.024)
The second generation of farmers' familiarity with agricultural farming	0.011 (0.063)	−0.001 (0.059)	−0.371 ** (0.167)	−0.365 ** (0.167)
Satisfaction with rural infrastructure conditions	0.033 (0.059)	0.164 *** (0.055)	0.248 (0.154)	0.214 (0.159)
Satisfaction with the rural ecological environment	0.126 * (0.064)	0.024 (0.060)	−0.142 (0.168)	−0.125 (0.171)
Satisfaction with the level of rural living consumption	−0.009 (0.049)	0.003 (0.046)	−0.277 ** (0.128)	−0.279 ** (0.129)
Pseudo R^2			0.097	0.098
R-squared	0.083	0.105		
Sample size	309	309	309	309

Note: *, **, *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. Robust standard error in parentheses.

4.1. Total Effect Analysis

The regression results are shown in Table 3. In Model 1, the aging rate of the family population has a significant positive impact on the willingness of farmers to withdraw from the homestead with compensation and the coefficient c_1= 2.072. That is, the higher the level of family population aging rate, the more farmers are inclined to withdraw from the homestead with compensation, invalidating Hypothesis 1. The reason is that since the reform and opening-up, with the increasing advancement of China's urban and rural policies, the relationship between urban and rural areas has changed significantly, showing a trend from urban-rural division to gradual integration, and the economic links between urban and rural areas have become closer. Economic development has made most of the current rural farmers become part-time farmers. Family income has increased year by year, and farmers' requirements for quality of life have been increasing. At the same time, young family members tend to settle in cities and towns. The feeling of missing relatives and the inconvenience of leaving their children's lives lead to the desire of farmers to move to cities and towns to live with their children. The relatively sound infrastructure and developed medical level of the town make it convenient for farmers to provide for the aged while improving the quality of life and improving living conditions. The compensation obtained by withdrawing from the homestead can alleviate the pressure of family pensions to a certain extent. Changes in the external environment have changed the willingness of the elderly population to withdraw from the homestead with compensation. Therefore, the greater the proportion of the elderly population in the family, the more farmers are inclined to withdraw from the homestead with compensation.

In Model 2, the aging rate of the family population has a significant negative impact on the compensation preference of farmers' homestead paid withdrawal and the coefficient $c_2 = -0.897$. That is, among farmers who have the willingness to withdraw from the homestead with compensation, the greater the aging of the family population, the more farmers tend to choose non-monetary compensation, and Hypothesis 2 is verified. The results of this study confirm the previous theoretical analysis that long-term and stable housing security is more attractive to the elderly population, and the "stability" mentality makes it more sensitive to non-monetary compensation methods such as housing or social security that can provide basic living security. Therefore, rural families with a large proportion of elderly members tend to choose non-monetary compensation methods.

4.2. Mediating Effect Analysis

4.2.1. The Mediating Effect of Homestead Value Cognition in the Aging of Family Population on Farmers' Willingness to Withdraw from the Homestead

The regression results are shown in Table 4. In Model 3 the aging rate of the family population has a significant positive impact on the farmers' cognition of the value of homestead security and the coefficient $a_1 = 0.372$. That is, the higher the aging rate of the family population, the deeper the cognition of the value of homestead security. In Model 5, the farmers' cognition of homestead security value has a significant negative impact on farmers' willingness to withdraw from the homestead and the coefficient $b_1 = -0.275$. That is, the deeper the cognition of farmers' security value, the weaker their willingness to withdraw from the homestead. The coefficients a_1 and b_1 are significant, indicating that the security value cognition plays a mediating role and Hypothesis 3 is verified. At the same time, the direct effect is significant and the coefficient $c_1' = 2.170$, but its symbol is opposite to a_1b_1. Explaining the results according to the masking effect, the proportion of the effect is calculated to be 4.71%. The cognition of farmers' security value significantly reduces the willingness of farmers to withdraw from the homestead with regard to family population aging rate and willingness to withdraw.

In Model 4, the impact of family population aging rate on farmers' cognition of homestead asset value is not significant and the coefficient $a_2 = -0.224$. In Model 6, the direct effect is significant and the coefficient $c_2' = 2.086$. The influence coefficient b_2 of asset value cognition on farmers' willingness to withdraw from the homestead is 0.077, which is not significant. In summary, it can be seen that Hypothesis 4 is not established, indicating that the aging rate of the family population does not affect the willingness of farmers to withdraw from their homesteads through their cognition of the value of homestead assets.

4.2.2. The Mediating Effect of Homestead Value Cognition in the Aging of Family Population on Farmers' Homestead Withdrawal Compensation Preference

The regression results are shown in Table 5. In Model 7, the aging rate of the family population has a significant positive impact on the value cognition of the farmers' homestead security and the coefficient $a_3 = 0.433$. That is, in the families with the willingness to withdraw from the homestead with compensation, the higher the level of the aging rate of the family population, the deeper the farmers' cognition of the value of homestead security. In Model 9, the direct effect is significant and the coefficient $c_3' = -1.034$, which indicates that the family population aging rate has a significant negative impact on the compensation preference of farmers' homestead withdrawal. That is, in the families with the willingness to withdraw from the homestead with compensation, the higher the level of family population aging, the more farmers tend to choose the non-monetary compensation method. The influence of security value cognition on the compensation preference of farmers' homestead withdrawal is not significant and the coefficient $b_3 = 0.242$. The influence coefficient a_3 is significant and b_3 is not significant. According to the mediating effect test process provided by Wen et al. [65], a Bootstrap method is needed to test a_3b_3. The indirect effect is not significant, that is, the cognition of security value does not play a mediating role, indicating that the aging of the family population does not affect the compensation preference of homestead withdrawal through the cognition of farmers' security value, and Hypothesis 5 is not established.

In Model 8,the influence of the aging rate of the family population on the cognition of the value of farmers' homestead assets is significant and the coefficient $a_4 = -0.433$. This shows that the aging rate of the family population has a significant negative impact on the cognition of the value of farmers' homestead assets. That is, in the families with the willingness to withdraw from the homestead with compensation, the higher the aging level of the family population, the shallower the cognition of the value of farmers' homestead assets. In Model 10, the influence of asset value cognition on farmers' homestead withdrawal compensation preference is significant and the coefficient $b_4 = 0.288$. This shows that farmers' asset value cognition has a significant positive impact on farmers' homestead withdrawal compensation preference, that is, the deeper the farmers' asset value cognition is, the more likely they are to choose the monetary compensation method. The coefficients a_4 and b_4 are significant, indicating that asset value cognition plays a mediating role and Hypothesis 6 is verified. At the same time, the direct effect is not significant and the coefficient $c_4' = -0.779$. Therefore, the value cognition of farmers' homestead assets plays a complete mediating role in the influence of family population aging on the compensation preference of farmers' homestead exit. The mediating effect is calculated to be 16.01%. An aging family population enhances the willingness of farmers to choose non-monetary compensation by inhibiting the value cognition of farmers' assets. The results of this study also confirm the previous theoretical analysis, that is, rural households with a large proportion of elderly members have a heavy burden of old-age care, and old-age security is in the primary position. Therefore, the shallower the farmers' awareness of the value of homestead assets, the more inclined they are to choose non-monetary compensation methods that can provide basic living security.

4.3. Robustness Test

4.3.1. Replace the Core Explanatory Variable

With the advancement of medical standards, the average life expectancy has gradually increased, so the aging age limit will be further tightened. In this section, the proportion of the elderly population over 65 years old is used as the basis for the division of population aging, to verify the impact of family population aging on farmers' willingness to withdraw from the homestead and their compensation preferences. Based on this, Logit regression and mediating effect are used for regression analysis. The empirical results are as shown in Tables 6–8. The results are basically consistent with the results of the population aging model based on the standard statistic of 60 years old, indicating that the stability of the model results is good.

4.3.2. Replacement Model

Since the willingness to withdraw from the homestead with compensation and the compensation preference in this study are two-category variables, the core explanatory variable and control variables are kept unchanged, and the Logit model is replaced with the Probit model for regression analysis to further test the robustness of the model. According to the analysis, the regression results are consistent with the above results in terms of significance and coefficient symbol, which verifies the reliability of the above conclusions. In view of the limitation of space, it is not repeated here.

Table 6. Regression results of the total effect of family population aging on farmers' willingness to withdraw from the homestead and compensation preference.

Variable Name	Model 1 (Willingness to Withdraw)		Model 2 (Compensation Preference)	
	Coefficient	dy/dx	Coefficient	dy/dx
Family population aging rate	1.440 ** (0.562)	0.239 (0.091)	−0.946 * (0.554)	−0.208 (0.119)
Gender	0.345 (0.469)	0.057 (0.078)	0.455 (0.531)	0.100 (0.116)
Age	−0.027 (0.018)	−0.004 (0.003)	0.002 (0.016)	0.001 (0.004)
Education level	−0.050 (0.150)	−0.008 (0.025)	−0.322 ** (0.156)	−0.071 (0.033)
Number of non-agricultural labor force	0.216 (0.144)	0.036 (0.024)	−0.434 *** (0.144)	−0.095 (0.030)
Number of left-behind elderly	−0.036 (0.168)	−0.006 (0.028)	0.570 *** (0.171)	0.125 (0.035)
Total non-agricultural income	0.097 *** (0.035)	0.016 (0.006)	0.044 * (0.024)	0.010 (0.005)
The second generation of farmers' familiarity with agricultural farming	0.095 (0.159)	0.016 (0.026)	−0.337 ** (0.165)	−0.074 (0.035)
Satisfaction with rural infrastructure conditions	−0.315 * (0.162)	−0.052 (0.027)	0.264 * (0.154)	0.058 (0.033)
Satisfaction with the rural ecological environment	0.334 ** (0.160)	0.055 (0.026)	−0.135 (0.168)	−0.030 (0.037)
Satisfaction with the level of rural living consumption	−0.134 (0.133)	−0.022 (0.022)	−0.253 ** (0.127)	−0.056 (0.027)
Log likelihood	−203.905		−194.320	
LR chi^2	29.990 ***		38.560 ***	
Pseudo R^2	0.069		0.090	
Sample size	403	403	309	309

Note: *, **, *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. Robust standard error in parentheses.

Table 7. Regression results of the mediating effect mechanism of farmers' willingness to withdraw from the homestead.

Variable Name	**Model 3 (Security Value)**	**Model 4 (Asset Value)**	**Model 5 (Willingness to Withdraw)**	**Model 6 (Willingness to Withdraw)**
	Coefficient	**Coefficient**	**Coefficient**	**Coefficient**
Family population aging rate	0.447 ** (0.183)	−0.253 (0.183)	1.581 *** (0.571)	1.444 *** (0.562)
Security value			−0.265 * (0.159)	
Asset value				0.054 (0.151)
Gender	0.040 (0.170)	0.054 (0.170)	0.345 (0.473)	0.346 (0.469)
Age	−0.005 (0.006)	0.003 (0.006)	−0.029 * (0.018)	−0.026 (0.018)
Education level	0.078 (0.050)	−0.007 (0.050)	−0.024 (0.151)	−0.049 (0.150)
Number of non-agricultural labor force	−0.040 (0.046)	0.076 * (0.046)	0.199 (0.144)	0.211 (0.145)
Number of left-behind elderly	0.058 (0.055)	0.061 (0.055)	−0.029 (0.168)	−0.039 (0.168)
Total non-agricultural income	0.011 (0.008)	−0.007 (0.008)	0.101 *** (0.035)	0.097 *** (0.035)
The second generation of farmers' familiarity with agricultural farming	0.025 (0.053)	0.064 (0.053)	0.101 (0.160)	0.091 (0.160)
Satisfaction with rural infrastructure conditions	0.032 (0.051)	0.162 *** (0.051)	−0.312 * (0.163)	−0.322 ** (0.163)
Satisfaction with the rural ecological environment	0.122 ** (0.054)	−0.015 (0.054)	0.374 ** (0.163)	0.334 ** (0.160)
Satisfaction with the level of rural living consumption	0.007 (0.043)	−0.015 (0.043)	−0.133 (0.134)	−0.133 (0.133)
Pseudo R^2			0.075	0.069
R-squared	0.075	0.070		
Sample size	403	403	403	403

Note: *, **, *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. Robust standard error in parentheses.

Table 8. Regression results of the mediating effect mechanism of farmers' homestead withdrawal compensation preference.

Variable Name	Model 7 (Security Value)	Model 8 (Asset Value)	Model 9 (Compensation Preference)	Model 10 (Compensation Preference)
	Coefficient	Coefficient	Coefficient	Coefficient
Family population aging rate	0.562 *** (0.216)	−0.454 ** (0.203)	−1.092 * (0.562)	−0.811 (0.558)
Security value			0.243 (0.152)	
Asset value				0.287 * (0.162)
Gender	0.028 (0.212)	0.217 (0.199)	0.453 (0.535)	0.390 (0.537)
Age	−0.008 (0.006)	0.002 (0.006)	0.004 (0.016)	0.001 (0.017)
Education level	0.098 (0.059)	−0.028 (0.056)	−0.347 ** (0.157)	−0.314 ** (0.156)
Number of non-agricultural labor force	−0.059 (0.054)	0.038 (0.051)	−0.427 *** (0.146)	−0.447 *** (0.146)
Number of left-behind elderly	0.058 (0.063)	0.106 * (0.060)	0.559 *** (0.172)	0.542 *** (0.172)
Total non-agricultural income	0.013 (0.009)	−0.009 (0.008)	0.043* (0.024)	0.048 ** (0.024)
The second generation of farmers' familiarity with agricultural farming	0.002 (0.063)	0.008 (0.059)	−0.344** (0.166)	−0.346 ** (0.167)
Satisfaction with rural infrastructure conditions	0.027 (0.059)	0.169 *** (0.055)	0.257 * (0.154)	0.221 (0.159)
Satisfaction with the rural ecological environment	0.136 ** (0.064)	0.014 (0.060)	−0.166 (0.169)	−0.143 (0.171)
Satisfaction with the level of rural living consumption	−0.018 (0.049)	0.011 (0.046)	−0.254 ** (0.127)	−0.261 ** (0.128)
Pseudo R^2			0.096	0.098
R-squared	0.089	0.103		
Sample size	309	309	309	309

Note: *, **, *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. Robust standard error in parentheses.

5. Discussion

5.1. Comparison with Existing Studies on Homesteads

The aging of the population has become an inexorable trend in societal development. In the face of rapidly accelerating urbanization and the increasingly severe aging of the rural population, exploring how the aging of the family population affects farmers' willingness to withdraw from the homestead with compensation and their compensation preferences is crucial. Such an exploration will help the efficient use of homesteads and promote rural revitalization. This paper empirically analyzes the impact of rural family population aging on farmers' willingness to withdraw from the homestead with compensation and their preference for withdrawal compensation and the mechanism of homestead value cognition.

Based on our test results, it was observed that aging in rural families significantly increased the farmers' willingness to withdraw from the homestead with compensation. Interestingly, this finding contradicts the results of research by Sun et al. [51]. We hypothesize that the possible reason for this discrepancy is that, with economic development and improvements in living standards, the elderly's attitude towards their homesteads has evolved. Older farmers often find it difficult to carry out high-intensity agricultural labor, so even the elderly with local support are gradually inclined to withdraw from the homestead and choose to live in cities or towns with a higher quality of life. In general, there is a complex mechanism linking the aging of the family population with farmers' willingness to withdraw from their homesteads. Understanding this mechanism requires a multifaceted approach that takes into account diverse influencing factors. In terms of compensation preference, we found that the greater the aging of the rural family population, the more inclined they are to opt for non-monetary compensation. This is similar to the findings of Wang et al. [56], who suggest that older farmers are more willing to accept resettlement as a form of compensation. Although we conducted separate studies on families and individuals, both of them reveal that the elderly and young people have different life needs and expectations, reflecting the significance of life security for the elderly population. With regard to mediating effect analysis, the method we used is consistent with that of Xie et al. [42]. Both studies employ the causal step method proposed by Baron and Kenny [66], which is effective for testing mediating effects. Unlike Shi et al. [6], who concentrates on the direct impact of farmers' policy cognition on their willingness to withdraw from homesteads, we integrate cognitive psychology theory into our mediating effect analysis. This allows us to reveal both the role of farmers' value cognition of homesteads as a mediator and the underlying psychological mechanisms affecting their withdrawal willingness and compensation preferences. It can be seen that farmers' cognition of homestead value will have a certain degree of influence on their willingness to withdraw from the homestead with compensation and compensation preference, which will provide important enlightenment for the formulation of homestead withdrawal policy.

5.2. Policy Recommendations

Based on the research findings, considering the increasingly aging rural population, this paper proposes the following policy recommendations to enhance farmers' willingness to withdraw from the homestead with compensation: (1) Differentiated compensation policies for homesteads should be devised, aligning with the age structure of farmers' families. A key aspect of this should be developing and improving the social old-age security system for families that withdraw from their homesteads. Having a well-structured security system is crucial to encouraging farmers' compensated homestead withdrawal. Policies must prioritize farmers' interests, ensuring basic security for their housing and economic conditions. It is crucial to acknowledge that highly aged rural families pay greater attention to the security value of homesteads. Thus, public service systems like pensions and healthcare should be further enhanced, improving the quality of life and retirement benefits of the elderly. The provision of diverse employment conditions for farmers withdrawing from homesteads should be promoted to stimulate their employment and income, reducing their pension burdens. The legitimate land rights of urban-settled farmers should be protected, encouraging lawful, voluntary homestead transfers. At present, the majority of Chinese farmers do not have a high-level social security system. Therefore, the current rural homestead reform should not be hasty. (2) Circulation of information resources should be strengthened to guide farmers towards reasonable cognition of homestead value. Relevant departments should routinely organize village officials to explain homestead withdrawal policies to farmers and use the Internet to publicize successful homestead withdrawal cases, helping farmers make more rational decisions. Additionally, establishing and perfecting the mechanisms and systems of compensated homestead withdrawal is a significant prerequisite for promoting such withdrawals. Hence, the government should formulate a stable and legally effective mechanism for compensated homestead withdrawal, standardize transparency in farmers' participation in the withdrawal process, and prevent conflicts of interest and withdrawal concerns due to policy changes, thereby enhancing the efficiency of compensated homestead withdrawal. (3) In designing the homestead withdrawal compensation scheme, the combination of non-monetary and monetary compensations should be considered, catering to farmers' diverse needs. The diversity and complexity of different farmers' homesteads and variations in family economic conditions should be recognized. Compensation methods and standards that meet the actual needs of heterogeneous farmers should be established. Throughout the compensated homestead withdrawal process, farmers' interests should be effectively protected, solving the living needs and development needs of farmers after they withdraw from the homestead, and ensuring housing, livelihood sources, and old-age security for those who withdraw from their homesteads.

5.3. Research Contributions and Limitations

Under the background of population aging, this paper delves into the impact of family population aging on farmers' willingness to withdraw from the homestead with compensation and their compensation preference. This paper extends the existing research on the withdrawal with compensation of farmers' homesteads and introduces a novel perspective on compensation related to farmers' homestead withdrawal. Additionally, it enriches the literature in the field of population aging. While offering valuable insights to the academic realm, it serves as a crucial reference in motivating farmers to withdraw from their homesteads, aiding the development of rural revitalization policies, and crafting a social security system tailored for the elderly. A detailed exploration of the various modes and preferences concerning withdrawal compensation reflects the real needs and expectations of farmers in the face of aging challenges, which helps to ensure that policies and measures are more practical and humane. Internationally, in the context of an aging population around the world, this paper not only provides a reference for China, but also provides unique insights and experiences for other developing countries or countries with similar situations. However, it is worth pointing that our sample is mainly from Shenyang City, Liaoning Province, China, which means that the sample area is relatively single. In the future, with the gradual deepening of the reform of China 's homestead system, the team will further expand the research scope and sample size, consider incorporating samples from other regions of China to test the results of this study, and analyze the regional differences in farmers' willingness to withdraw from rural homesteads. Simultaneously, the team will investigate other factors that might influence the connection between population aging and farmers' willingness to withdraw from homesteads, delving deeper into the underlying dynamics between them.

6. Conclusions

Based on the survey data of 403 rural families in Shenyang, Liaoning Province, China, this paper employs the binary Logit model and the mediating effect model to empirically analyze the impact and mechanism of rural family aging on farmers' willingness to withdraw from the homestead with compensation, and their compensation preference. The study's findings are as follows: (1) The aging of the family population significantly increases farmers' willingness to withdraw from the homestead with compensation. Furthermore, the greater the family population's aging, the more inclined farmers are to opt for non-monetary compensation methods. (2) With regard to family population aging to promoting withdrawal willingness from the homestead with compensation, farmers' cognition of the security value of the homestead presents a masking effect of 4.71%. This effect indirectly suppresses farmers' willingness to withdraw from the homestead with compensation, whereas the farmers' cognition of the asset value of the homestead does not have a mediating effect. (3) With regard to family population aging towards promoting farmers' non-monetary compensation choices for the homestead, farmers' cognition of the value of homestead assets plays a fully mediating role with a magnitude of 16.01%.

This significantly boosts farmers' inclination to choose non-monetary compensation, yet there is no mediating effect on the farmers' cognition of the homestead's security value. According to the characteristics of different farmer groups, measures such as cultivating farmers' reasonable cognition of the value of the homestead and formulating differentiated compensation policies for homestead withdrawal can be taken to enhance farmers' willingness to withdraw from the homestead.

Author Contributions: Conceptualization, H.G.; data curation, Y.H.; funding acquisition, H.G.; methodology, H.G. and Y.H.; project administration, H.G.; resources, F.Q.; software, Y.H. and Y.W.; supervision, H.G.; validation, Y.H.; writing—original draft, Y.H.; writing—review and editing, H.G., Y.H., and B.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Scientific Research Foundation of Liaoning Province (Grant No. WSNZK202002), the China Postdoctoral Science Foundation (Grant Nos 2020T130433 and 2018M631824) and the Liaoning Province Social Science Foundation (Grant No. L19CGL009).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Spatial Correlation between Water Resources and Rural Settlements in the Yanhe Watershed Based on Bivariate Spatial Autocorrelation Methods

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Abstract: The production–living–ecological functions of rural settlements are closely tied to water resources, which are the primary influencing factors of the spatial characteristics of rural settlements. However, the specific relationship between water resources and the spatial characteristics of rural settlements remains unclear. Understanding the interrelationship between the two can better safeguard the ecological pattern of the basin and optimize the living environment of settlements. This study utilized multi-source data to calculate the water yield, water demand, and ecological surplus or deficit of water resources in the Yanhe watershed. We quantified the spatial characteristics of rural settlements and employed bivariate spatial autocorrelation methods to analyze the spatial correlation between water resources and the spatial distribution, scale, and boundary form of rural settlements in the Yanhe watershed. The results show the following: ① Seven sub-basins in the upper reaches exhibit a severe ecological deficit in water resources, with insufficient water resources to support the demands of regional socio-economic development. The middle and lower reaches have achieved a balance between water supply and demand. ② Rural settlements are most densely distributed in the middle reaches, with the smallest area scale, exhibiting a transitional spatial characteristic towards the upstream and downstream ends. ③ The Moran's I values of spatial aggregation and morphological index of rural settlements with respect to the ecological surplus or deficit of water resources are 0.36 and 0.50, respectively, indicating a strong positive correlation. The Moran's I value of the area scale with respect to the ecological surplus or deficit of water resources is −0.60, indicating a significant negative correlation. This research has important practical significance for guiding the spatial layout of rural settlements in the Yanhe watershed and promoting their sustainable development.

Keywords: rural settlements; water resources; Yanhe watershed; bivariate spatial autocorrelation

Citation: Zhang, L.; Hou, Q.; Duan, Y.; Liu, W. Spatial Correlation between Water Resources and Rural Settlements in the Yanhe Watershed Based on Bivariate Spatial Autocorrelation Methods. *Land* **2023**, *12*, 1719. https://doi.org/10.3390/land12091719

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 1 August 2023
Revised: 30 August 2023
Accepted: 1 September 2023
Published: 3 September 2023

1. Introduction

Rural settlements are spatial places where agricultural populations live and work, and their spatial distribution and patterns reflect the comprehensive relationship between human activities and the natural environment [1]. Water resources are fundamental production factors for regional agricultural production and rural development [2], and they are important influencing factors of settlement spatial characteristics [3]. The loess hilly and gully region in the middle reaches of the Yellow River Basin is an area with severe soil erosion. Issues such as the fragile ecological environment and limited construction land restrict the sustainable development of the regional living environment [4,5]. Water resources have a significant impact on this region in various ways. Compared to well-developed urban infrastructure, rural settlements have a higher dependence on local water resources for production, living, and ecological development. Therefore, integrating water resources and optimizing the spatial layout of rural settlements has become an important aspect of achieving high-quality development in the Yellow River Basin.

The main purpose of studying the spatial pattern characteristics of rural settlements is to analyze the regional spatial characteristics and underlying rules of the rural settlement system [6]. As a natural–social integrated entity of human–land–water interaction, the basin is a cluster unit that integrates various elements [7]. Analyzing the spatial pattern characteristics of rural settlements at the basin scale is more conducive to exploring the formation process and differentiation patterns of rural settlements in different regional environments. It has important value and universal significance for the study of human settlements in complex geographical environments [8]. Currently, research on the spatial characteristics of rural settlements mainly focuses on the spatial distribution, scale structure, landscape form, evolution laws, and mechanisms of settlement patterns [6,9,10]. This research adopts a combination of qualitative and quantitative methods and incorporates GIS spatial analysis, landscape pattern index analysis, spatial econometric models, spatial statistical analysis, and other methods into the study of rural settlement spatial characteristics. The research scale mainly focuses on administrative scales such as province [11], city [12], county [13], and township [1], with only a few scholars studying the spatial characteristics of rural settlements at the basin scale [14,15]. Therefore, it is necessary to conduct relevant research at the basin scale to promote the sustainable development of water and human systems and to facilitate regional rural revitalization.

Regarding the research on the impact of water resources on rural settlements, previous studies have shown that as the distance between rural settlements and water systems increases, both the number and area of settlement patches gradually decrease [16]. With improved access to water resources, the shape of settlements tends to become more compact [17]. The total water consumption is a prerequisite for the development of water resource systems, and water conservation and efficiency are key to the healthy and sustainable development of water resource systems [2]. A certain relationship between the acquisition and utilization of water resources and the spatial characteristics of rural settlements is evident. However, there is currently a lack of research on the relationship between water resource quantity and the spatial pattern of rural settlements. The water footprint is one of the commonly used methods in water resource utilization studies, and it has the potential to be applied in research on green water resource utilization efficiency, water resource carrying capacity, and the optimal allocation of water resources [18,19]. This can effectively measure water consumption and sustainable development. Spatial autocorrelation analysis, an important tool for analyzing the interdependence and distribution characteristics of variables within a spatial context, has been widely applied in landscape ecology [20–22], aquatic ecology [23], rural settlements [24] and other fields. Therefore, the water footprint method can be used to measure water resources, and spatial autocorrelation analyses can be employed to examine the relationship between water resources and rural settlements.

Based on this, this study uses landscape metrics to quantify the spatial pattern of rural settlements in the Yanhe watershed. The water footprint and water resource ecological surplus or deficit model are employed to analyze the spatial distribution characteristics of water resources in the basin. With the assistance of the GeoDa platform, bivariate spatial autocorrelation methods are applied to specifically analyze the water yield, water demand, and ecological surplus or deficit of water resources in the Yanhe watershed and their spatial correlation with rural settlements. The aim is to provide a reference and guidance for the sustainable development of rural settlements in the loess hilly and gully region of the basin.

2. Study Area and Data Sources

2.1. Study Area

The Yanhe watershed is located in the northern part of Shaanxi Province and belongs to the loess hilly and gully region of the Loess Plateau (Figure 1). The source of the Yan River is in Jingbian County in the northwest of Shaanxi Province. It flows southeastward along the terrain for a total length of approximately 286.9 km, with a basin area of about 7680 km^2. This is the main water source that sustains local production, life, and ecology. Due to severe hydraulic erosion on the surface, the local area has formed a network of numerous gullies and fragmented loess gully systems, with undulating terrain ranging from 0 to 204 m. The upstream area is characterized by steep loess slopes, with slope gradients mostly exceeding 25°. The middle reaches are dominated by short and narrow loess ridges with relatively lower slopes, while the downstream area is mainly composed of long and wide ridges, gently sloping floodplains, and fragmented narrow terraces. The basin's annual precipitation is approximately 431–523 mm (Figure 2), with a decreasing trend from southeast to northwest. The middle reaches have the highest precipitation, followed by the downstream area, while the upstream area has the lowest. The Yanhe watershed mainly consists of Baota District, Ansai District, and Yanchang County, along with small parts of Zhidan County and Jingbian County. Baota District serves as the political, economic, and cultural center of Yan'an City. The basin contains 995 rural settlements, which are closely distributed along the water system, and mainly concentrated in the high-altitude tableland, ridge and hill areas, which are the central part of the basin. Rural settlements in Yanhe watershed have a high dependence on water resources because of their special climatic conditions and topographic features. The distribution of settlements and cultivated land is closely related to the water system, rainfall and runoff.

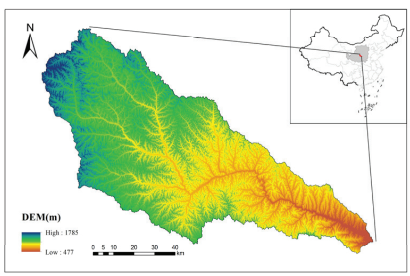


Figure 1. Location map of the Yanhe watershed.

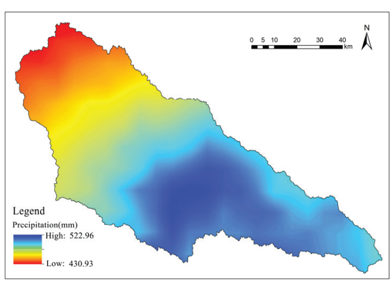


Figure 2. Precipitation map of the Yanhe watershed.

2.2. Data Sources

The data used in this study mainly include satellite remote sensing images, DEM data, land use data, and socio-economic data. The DEM data were obtained from the website of the Geospatial Data Cloud of the Chinese Academy of Sciences (http://www.gscloud.cn, accessed on 20 May 2023). The primary socio-economic data were sourced from the Statistical Yearbooks of Yan'an City and various counties and districts. The land use data used are the 30 m × 30 m land use data for the year 2022. Nighttime light data were obtained from the dataset provided by the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 20 May 2023). Meteorological and hydrological data were sourced from the "Shaanxi Province Water Resources Bulletin", the Ganguyi Hydrological

Station, the "Yangtze River Sediment Bulletin," and the China Meteorological Data Network (http://data.cma.cn, accessed on 20 May 2023).

3. Research Methodology

We focused on the unique climate conditions and regional characteristics of the Yanhe watershed, and followed the methodology of "Spatial heterogeneity, Correlation analysis, Impact relationship". The SWAT model is a spatially distributed and time-continuous hydrological model developed by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA). The model can accurately delineate watershed units and flexibly adjust appropriate parameters [25–28]. Therefore, in this study, the SWAT hydrological model tool divided the Yanhe watershed into 47 sub-basins, which were used as the units for further quantitative analysis. This study quantifies water resource utilization in three aspects, water production, water demand and ecological profit and loss, by constructing a water footprint model of the Yanhe watershed. InVEST is a common model for measuring regional water production, which has been widely used in the Loess Plateau [29–33]. To be more specific, rainfall, runoff, and evapotranspiration are all aspects of water resources that can be fully reflected in terms of water yield. For agricultural production space, rainfall's temporal and spatial distribution is crucial, and runoff may have an impact on where people live. A significant component influencing the growth and development of cultivated land is evapotranspiration. These signs are connected to rural communities that are closely related spatially. The variation in rural settlements' needs regarding water resources across different regions is reflected in the spatial and temporal distribution of water demand. The spatial and temporal distribution of water resource use by WEDS has an impact on the location, size, and borders of rural settlements. Fragstats software was used to measure the landscape index of rural settlement patches in three aspects, namely distribution, scale and form, based on sub-catchment units. Finally, through the ArcGIS planform, the spatial autocorrelation method is used to analyze the spatial correlation between water resources and rural settlement characteristics (Figure 3).

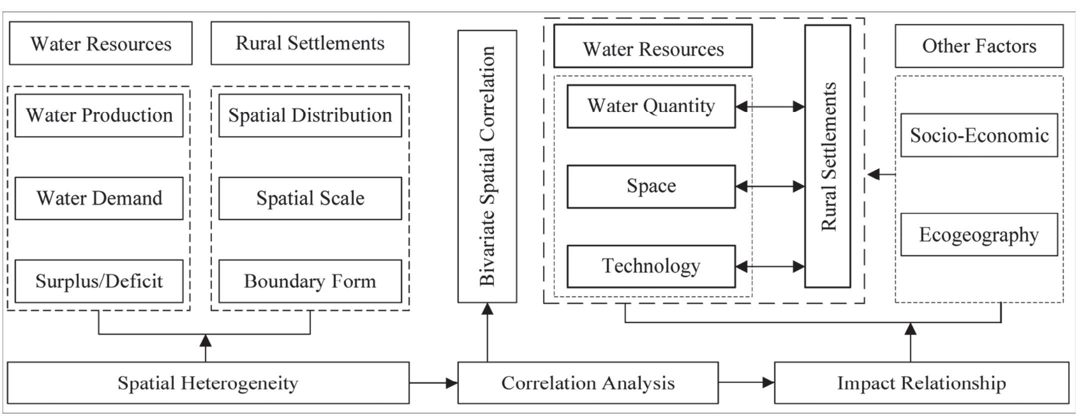


Figure 3. Research methodology.

3.1. Quantification of Water Resources

3.1.1. Water Production

The water production of the entire Yanhe watershed was simulated using the water yield module of the InVEST model. This module estimates the water production in a region based on precipitation data, plant transpiration data, surface evaporation data, root depth, and soil depth, utilizing the principles of the water cycle. The main algorithm of the model is as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \tag{1}$$

In the equation, Y_{xj} represents the water production of type j land use/cover type at grid x. AET_{xj} is the actual evapotranspiration of type j land use/cover type at grid x, and P_x is the annual precipitation in grid x.

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \tag{2}$$

R_{xj} represents the dimensionless aridity index of land use/cover type j at grid x, which is defined as the ratio of potential evaporation to precipitation. ω_x represents the ratio of modified vegetation annual available amount to expected water amount.

$$R_{xj} = \frac{K_{xj} ET_{0x}}{P_x} \tag{3}$$

$$W_x = Z \frac{AWC_x}{P_x} \tag{4}$$

In the equation, ET_{0x} represents the potential evapotranspiration within grid x, measured in mm. K_{xj} denotes the evapotranspiration coefficient of vegetation. AWC_x refers to the plant-available water content, which represents the volumetric water content that can be utilized by vegetation. Z represents the seasonal factor, which represents the parameters related to seasonal rainfall distribution and depth.

$$AWC_x = Min(Max.SoilDepth_x, RootDepth_x) \times PAWC_x \tag{5}$$

In the equation, $PAWC_x$ represents the plant-available water capacity index, which refers to the amount of water that can be effectively used by vegetation. $SoilDepth_x$ represents the soil depth in pixel x, $RootDepth_x$ represents the root depth within pixel x.

3.1.2. Water Demand

Water footprint refers to the amount of water resources required for the consumption of all products and services by a country, region, or individual within a certain period. The actual water use of a country or region includes not only the total amount of local water resources required for local product production or services but also the virtual water content of imported products and services in the region [34]. Based on on-site investigations and local water resources bulletins, in the study area, it has been determined that there is no cross-basin water transfer in the Yanhe watershed. Therefore, in calculating the total water footprint, this study does not consider the virtual water content imported from other countries or regions. The analysis focuses on the complex interactions between production, livelihood, and ecology [35], and the specific formula is given as follows (6):

$$W_{EF} = P_{EF} + L_{EF} + E_{EF} \tag{6}$$

In the equation W_{EF} represents the water footprint within the region; P_{EF} denotes the water demand for production within the river basin; L_{EF} represents the water demand for residential livelihoods; E_{EF} denotes the water demand for ecosystems.

The calculation of water demand for production was divided into the primary sector and the secondary/tertiary sectors. In this study, the spatialization of water demand for production in the Yanhe watershed was achieved based on the water consumption corresponding to the GDP value of each district and county in the basin. According to the ShaanXi water resources bulletin 2018, the per capita water consumption in Shaanxi-Yan'an area in 2018 was 242.5 m^3, the water consumption per 10,000 yuan GDP was 38.3 m^3, and the water consumption per mu of farmland irrigation was 301.1 m^3.

In the Yanhe watershed, agriculture has the highest proportion of the GDP of the primary sector, followed by animal husbandry, while forestry and fisheries have a relatively small proportion. Therefore, in this study, the water demand for the primary sector in the Yanhe watershed was limited to agriculture and animal husbandry, with agriculture occurring only in dryland areas and animal husbandry occurring only in grassland areas. Land use data and grassland livestock capacity were used to calculate the primary industry water demand of each township in the Yanhe watershed in 2018 and allocate it to each sub-watershed.

The calculation formula for the primary sector GDP is as follows:

$$GDP1_{ij} = GDP1_i \times Q_{ij} \div SUM_{ij} \quad (7)$$

In the equation $GDP1_{ij}$ represents the GDP produced in the *j*-th grid of the *i*-th city (in 10,000 RMB); $GDP1_i$ represents the GDP of the primary sector in the *i*-th city in 2018 (in 10,000 RMB); Q_{ij} represents the weight corresponding to the *j*-th grid in the *i*-th city; SUM_{ij} represents the total number of grids with land use type *j* in the *i*-th city [36].

Numerous scholars have conducted research demonstrating a strong correlation between nighttime lights and GDP in the secondary/tertiary sectors [37,38]. Therefore, in this study, the linear regression relationship between nighttime lights and GDP was established using SPSS software to calculate the water demand for the secondary/tertiary sectors. The specific formulas are as follows:

$$GDP23_{ij} = VIIRS_{ij} \times X_i \quad (8)$$

$$GDP23_{ij} = GDP23_i \times GDP_i \div SUM_i \quad (9)$$

In the equation: $VIIRS_{ij}$ represents the nighttime lights value in the *j*-th grid of the *i*-th district/county; X_i represents the conversion coefficient between GDP and nighttime lights in the *i*-th district/county; $GDP23_{ij}$ represents the GDP of the secondary/tertiary sectors in the *j*-th grid of the *i*-th district/county (in 10,000 RMB); GDP_i represents the secondary/tertiary sector GDP of the *i*-th district/county in 2018 (in 10,000 RMB); $GDP23_i$ represents the converted value of GDP in the *j*-th grid of the *i*-th district/county; SUM_i represents the total sum of $GDP23_{ij}$ in the *i*-th district/county.

Ecological water demand in this study was divided into biological water demand and non-biological water demand. The formula used to calculate non-biological water demand is as follows:

$$B_a = W_s + W_e + W_w \quad (10)$$

$$W_s = S_t / C_{max} \quad (11)$$

$$W_e = \begin{cases} A_x E_x - P \ (E_x > P) \\ 0 \qquad (E_x < P) \end{cases} \quad (12)$$

$$W_w = a_s \cdot H_s \cdot A_s \quad (13)$$

In the equation, B_a represents the non-biological water demand, W_s represents the water demand for sediment transport in rivers, W_e represents the water demand for evaporation from rivers and lakes, and W_w represents the soil water content. S_t represents the long-term average sediment transport in rivers, C_{max} represents the average value of the maximum sediment concentration in rivers over the years. E_x represents the long-term average evaporation from rivers and lakes, P represents the long-term average annual precipitation, and A_x represents the area of rivers and lakes. a_s represents the soil water coefficient, H_s represents the soil depth, and A_s represents the land area.

Biological water demand was calculated based on vegetation evapotranspiration, including evapotranspiration from forests and grasslands. The specific calculation formula is as follows:

$$W_p = K_0 \cdot ET_0 \cdot A_p \quad (14)$$

In the equation, W_p represents vegetation evapotranspiration, K_0 represents the evapotranspiration coefficient of vegetation, ET_0 represents the potential evapotranspiration, and A_p represents the vegetation distribution area.

3.1.3. Water Resources Ecological Surplus/Deficit (WRES/D)

The water resource ecological surplus/deficit (W_{ED}) is the difference between the water supply (W_{EC}) and water footprint (W_{EF}) within a region. It can be used to assess the sustainability of water resource utilization in the region. The calculation formula is as follows [19,39,40]:

$$W_{ED} = W_{EC} - W_{EF} \quad (15)$$

If $W_{ED} > 0$, this indicates a surplus of water resource ecological balance in the region, indicating a sustainable utilization state. When $W_{ED} = 0$, this represents an ecological balance state. If $W_{ED} < 0$, this indicates a deficit in water resource ecological balance, implying that the water resources are insufficient to support the demands of regional socio-economic development.

3.2. Spatial Characteristics of Rural Settlements

The landscape pattern indices can reflect the characteristics of rural settlement patterns and spatial configurations [12]. For this study, three indices were selected to assess the landscape patterns of rural settlements in the sub-basins: Patch Density (PD), Mean Patch Size (MPS), and Mean Patch Fractal Dimension (FRAC_MN). Fragstats 4.2 software was used to calculate these landscape indices, allowing for an analysis of the spatial distribution, size, and boundary shape characteristics of rural settlements in the Yanhe watershed.

The Mean Patch Fractal Dimension (FRAC_MN) represents the spatial form of rural settlements, with values ranging from 1 to 2. A value closer to 1 indicates stronger self-similarity of rural settlement patches, with smaller ratios of length to width and more regular patch shapes. This demonstrates that rural settlements are artificial patches; under the conscious intervention of human beings, the nature of rural settlement patches is relatively regular and easy to manage [41]. Therefore, the patches tend to resemble circles or squares, indicating a higher degree of human interference, as patches formed by human activities often have more regular shapes. Conversely, a value closer to 2 indicates more complex shapes of rural settlement patches, with elongated and narrower geometries, suggesting less human interference.

3.3. Bivariate Spatial Autocorrelation

Compared to traditional spatial autocorrelation, which considers only one variable, bivariate spatial autocorrelation characterizes the spatial relationship between different geographic features. The Moran's I index obtained from bivariate spatial autocorrelation is used to evaluate the degree of correlation between a location variable and other variables [42]. The range of Moran's I coefficient is [–1, 1]. The results can be classified into three main situations: ① When the value of Moran's I coefficient is greater than 0, this indicates a positive spatial autocorrelation among the study objects. Specifically, the closer the coefficient value is to 1, the stronger the positive correlation, indicating a stronger spatial clustering of the study objects. ② When the value of Moran's I coefficient is less than 0, this indicates a negative spatial autocorrelation among the study objects. Specifically, the closer the coefficient value is to -1, the stronger the negative correlation, indicating greater spatial dissimilarity among the study objects. ③ When the value of Moran's I coefficient approaches 0, this reflects the random distribution characteristic of the study objects, indicating the absence of spatial autocorrelation [19].

In this study, the global bivariate spatial autocorrelation analysis in Geoda software was used to describe the spatial relationship between the characteristics of rural settlements and water resources in the Yanhe watershed. The local bivariate spatial autocorrelation was employed to identify the differences in this spatial relationship among sub-basins.

4. Analysis Results

4.1. Spatial Distribution Characteristics of Water Resources in the Yanhe watershed

By using Equation (15), the water resource ecological surplus or deficit was calculated for each sub-basin, revealing that the water resource ecological surplus or deficit in the Yanhe watershed ranges from -34265.14×10^4 m^3 to 3841.43×10^4 m^3. Due to differences in geographical environment and area size, there are significant disparities in water resource ecological surplus or deficit among sub-basins. The sub-basin with the highest water resource ecological surplus/deficit is sub-basin 29 (Xichuan), located in the middle reaches, while sub-basin 1 (Maquangou), located in the upper reaches, has the lowest water resource ecological surplus/deficit. Using the natural breaks method in ArcGIS 10.2, the water resource ecological surplus or deficit results were classified into five levels: low, relatively low, medium, relatively high, and high. A distribution map of water resource ecological surplus or deficit in the Yanhe watershed (Figure 4) was obtained. Seven sub-basins located in the upper reaches, namely sub-basins 5 (Yapangou), 6 (Zhoujiawangou), 1 (Maquangou), 4 (Hezhuanggou), 2 (Kangjiahegou), 9 (Gaojiagou), and 10 (Chaluchuangou), have the lowest level of water resource ecological surplus/deficit, indicating a severe water resource ecological deficit. Several larger tributaries in the middle reaches, such as sub-basins 15 (Mudanchuan), 18 (Majiagou), 26 (Fengfuchuan), 17 (Xingzigou), 29 (Xichuan), 35 (Loupingchuan), 40 (Dufuchuan), 45 (Longsigou), and the downstream sub-basin 47 (Gaojiahe, Nanhegou), have the highest level of water resource ecological surplus/deficit. The water supply–demand status is relatively balanced in these areas, indicating a state of supply–demand equilibrium.

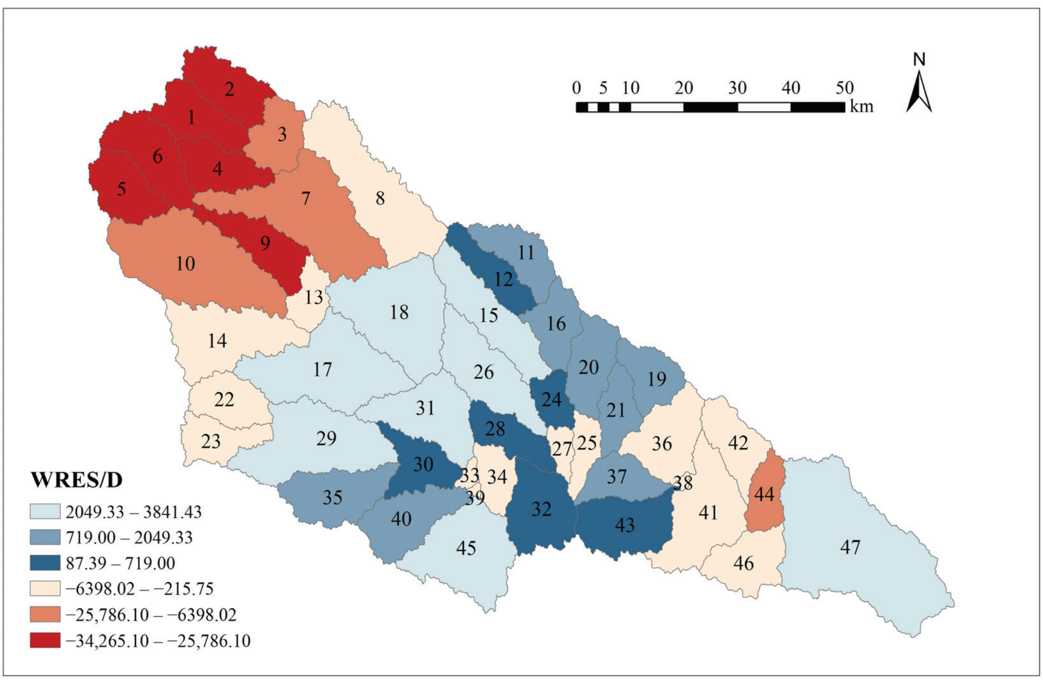
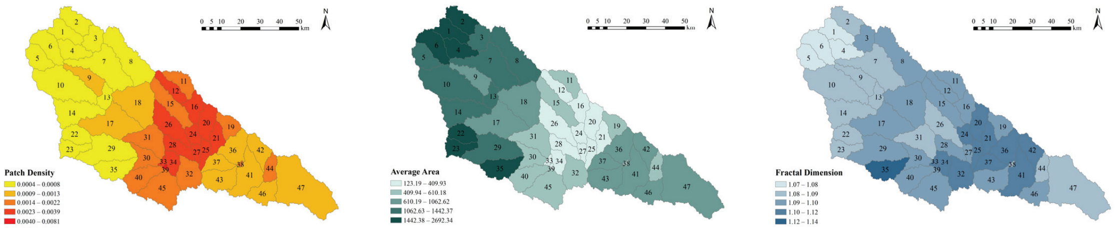


Figure 4. Spatial distribution of water resources in the Yanhe watershed.

4.2. Spatial Layout Characteristics of Rural Settlements in the Yanhe watershed

In order to further explore the spatial layout characteristics of rural settlements in the study area, the landscape index was divided by the natural discontinuity grading method (Jenks) (Figure 5). It can be seen that rural settlements in Yanhe watershed have obvious spatial clustering characteristics in three aspects: spatial distribution, scale characteristics and boundary form.



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

Figure 5. Spatial layout characteristics of rural settlements in the Yanhe watershed. (**a**) patch density; (**b**) average area; (**c**) fractal dimension.

4.2.1. Spatial Distribution Characteristics

The analysis of patch density was used to examine the spatial distribution characteristics of rural settlements in the Yanhe watershed (Figure 5a). The results indicate that the patch density values of rural settlements in the Yanhe watershed range from 0 to 0.39 patches/km^2, showing a pattern of "dense in the central part and sparse at both ends." The density core area in the middle of the Yanhe watershed has a patch density range of 0.20 to 0.70 patches/km^2, including areas such as sub-basins 12 (Guansugou), 16, 20, 24, 25 (Panlongchuan), 26 (Fengfuchuan), and sub-basins 27, 28, 33, 39 (Nanchuan), where the central urban area of Yan'an City is located.

4.2.2. Scale Characteristics

The average area of rural settlements in each sub-basin unit within the Yanhe watershed was calculated (Figure 5b). The results show that the sub-basin unit with the smallest average area of rural settlements is sub-basin 33, with an average area of only 2.30 km^2, located in the central area of Yan'an City. The sub-basin unit with the largest average area of rural settlements is sub-basin 1 (Maquangou), spanning Zhidan County and Jingbian County in the upstream area, with an average area of 20.79 km^2, indicating a larger scale. The central part of the basin has favorable natural conditions, a relatively wide terrain, and abundant water resources, which is why rural settlements in this area have smaller and more concentrated areas. The standard deviation of average settlement area within sub-basins 29 (Xichuan), 1 (Maquangou), 2 (Kangjiahegou), 10 (Chaluchuan), 43 (Zhengzhuanggou), and 37 (Guoqishugou) ranges from 5.15 km^2 to 12.76 km^2. Among them, sub-basin 29 (Xichuan) has the highest standard deviation of average settlement area, at 12.76 km^2, indicating significant differences in the development scale of rural settlements within the sub-basin. Sub-basin 33 has a standard deviation of only 0.85 km^2, indicating a relatively similar development scale of rural settlements within the sub-basin.

4.2.3. Boundary Form Characteristics

The fractal dimension of each sub-basin unit in the Yanhe watershed was calculated (Figure 5c). The fractal dimension shows an increasing trend from the northwest to the southeast, with the minimum value of 1.07 in sub-basin 6 (Zhoujiawangou) at the upstream end and the maximum value of 1.14 in sub-basin 35 (Loupingchuan) in the Baota District of the middle reaches. This indicates that there is a tendency for the shape of rural settlements to become more complex from upstream to downstream. However, the fractal dimension in the Yanhe watershed ranges from 1.07 to 1.14, with an average value of 1.09, which is close to 1.10, with small variations. This suggests that the overall shape of rural settlements in the Yanhe watershed is relatively regular and block-like.

4.3. Influence of Water Resources on the Spatial Characteristics of Rural Settlements in the Yanhe watershed

4.3.1. Global Spatial Association between Water Resources and Spatial Characteristics of Rural Settlements

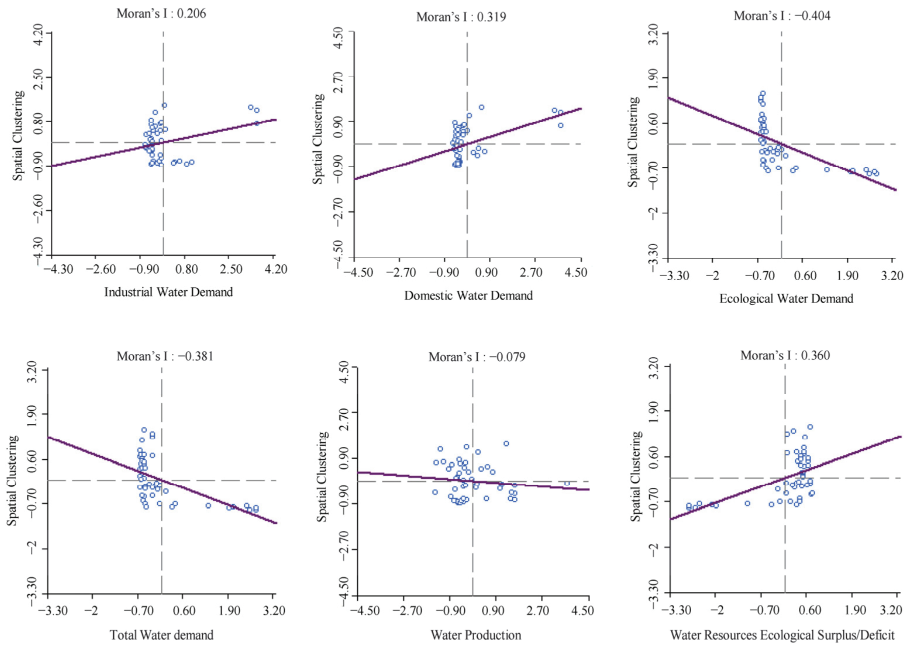
Using GeoDa spatial analysis tool, a spatial weight matrix was established to calculate the Moran's I global spatial autocorrelation index between water resources' ecological surplus/deficit and the different spatial characteristics of rural settlements (Table 1). From Table 1, it can be observed that the bivariate Moran's I value for spatial clustering and spatial form with a water resource ecological surplus/deficit is greater than 0, while the bivariate Moran's I value for the area scale of rural settlements with a water resource ecological surplus/deficit is less than 0. All three indicators passed the significance test at the 1% level, indicating a significant spatial correlation between the three types of rural settlement spatial characteristics and water resource ecological surplus/deficit. Specifically, the Moran's I value for spatial clustering and the water resources ecological surplus/deficit is 0.36, indicating a strong positive correlation. This suggests that, as the availability of water resources improves, rural settlements tend to cluster together. The positive correlation between spatial form and water resources' ecological surplus/deficit is even stronger, with a Moran's I value of 0.50. This indicates that when water resource utilization is more sustainable, rural settlements are less likely to be disturbed, resulting in more complex and elongated patches. There is a significant negative correlation between area scale and water resources' ecological surplus/deficit, with a Moran's I value of −0.60. This implies that when water conditions are favorable, rural settlements tend to have smaller area scales. This is because, in areas with better water conditions, rural settlements are more concentrated, leaving less land available for expansion and resulting in smaller area scales.

Table 1. Bivariate Moran's I statistics of water resources and spatial characteristics of rural settlements in the Yanhe watershed.

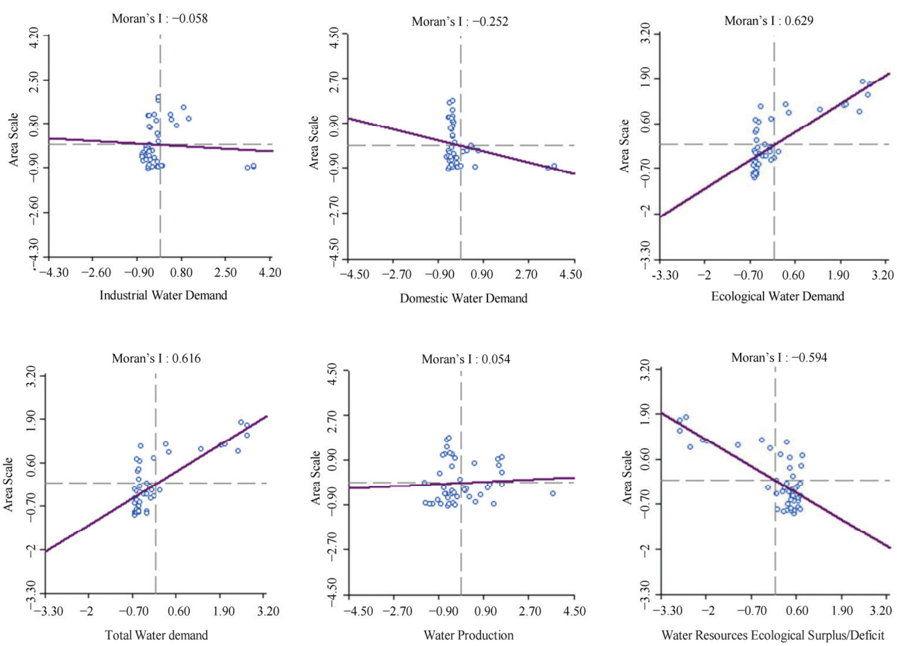
	Industrial Water Demand	**Domestic Water Demand**	**Ecological Water Demand**	**Total Water Demand**	**Water Production**	**Water Resources Ecological Surplus/Deficit**
Spatial Clustering	0.21 ***	0.32 ***	−0.40 ***	−0.38 ***	−0.08	0.36 ***
Area Scale	−0.06	−0.25 ***	0.63 ***	0.62 ***	0.05	−0.60 ***
Spatial Form	0.01	0.19 ***	−0.54 ***	−0.53 ***	−0.16 ***	0.50 ***

Note: The superscripts *** indicate significance at the 1% levels.

Examining the bivariate spatial autocorrelation of different types of water resources with spatial characteristics of rural settlements, it can be seen that the correlation between different spatial characteristics of rural settlements and ecological water demand is generally stronger than their correlation with other water resource elements. This indicates that ecological water demand has a more significant impact on the spatial characteristics of rural settlements. As the ecological water demand increases, it encroaches more on the production and living space of rural settlements, leading to higher fragmentation, more dispersed spatial distribution, larger area scales, and more regular spatial forms of rural settlements. Industrial water demand only exhibits a weak positive spatial correlation with the spatial clustering of rural settlements, with a Moran's I value of 0.21, indicating that, in sub-basins with a higher industrial water demand, rural settlements tend to exhibit more clustered distributions. Water production only shows a weak negative spatial correlation with the spatial form of rural settlements, with a Moran's I value of −0.16, indicating that as the water yield improves, the patch spatial morphology index becomes smaller, which means that the rural settlements are subjected to more human intervention (Figure 6).

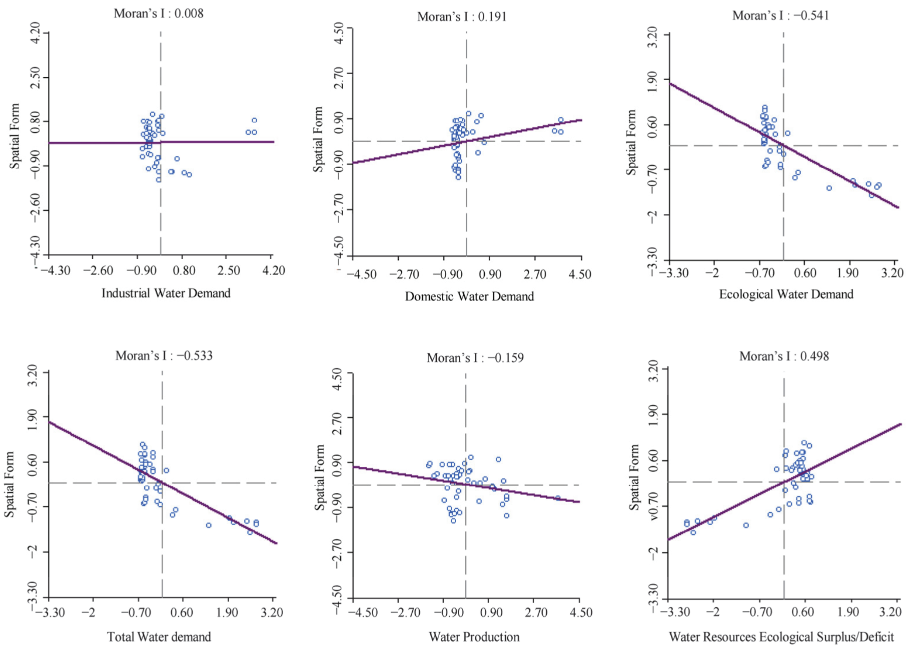


(**a**)



(**b**)

Figure 6. *Cont*.



(**c**)

Figure 6. The Moran scatter plot of spatial autocorrelation between rural settlement spatial characteristics and water resources. (**a**) The Moran scatter plot of spatial autocorrelation between spatial clustering index and water resources. (**b**) The Moran scatter plot of spatial autocorrelation between area scale index and water resources. (**c**) The Moran scatter plot of spatial autocorrelation between spatial form index and water resources.

4.3.2. Local Spatial Association between Water Resources and Rural Settlements Characteristics

Based on the bivariate local spatial autocorrelation analysis, the Local Indicators of Spatial Association (LISA) cluster maps were generated to represent the spatial relationship between water resources ecological surplus/deficit and the spatial clustering, area scale, and spatial form of rural settlements in the Yanhe watershed (Figure 7). The LISA cluster maps show whether there is a high–high (H-H)/low–low (L-L) positive spatial correlation, low–high (L-H)/high–low (H-L) negative spatial correlation, or no significant spatial correlation (i.e., spatial randomness) between water resources ecological surplus/deficit and rural settlement spatial characteristics. From Figure 6, it can be observed that there are more L-L-correlated regions between water resources ecological surplus/deficit and spatial clustering, mainly located in the upstream area of the basin. The H-H-correlated regions are found around the Baota District in the middle reaches of the basin, while the H-L-correlated regions are less prominent and mainly located in the upstream area near Xingzigou. In the LISA cluster map of water resources ecological surplus/deficit and area scale, the L-H-correlated regions are also located in the upstream area, while the H-L-correlated regions are observed in the sub-basins of Mudanchuan, Fengfuchuan, Panlongchuan, Nanchuan, Masichuan, Dufuchuan, Longsigou, and other major tributaries in the middle reaches. These regions are surrounded by sub-basins with smaller area scales and exhibit a higher ecological surplus/deficit in water resources. The H-H-correlated region is only present in the Xichuan sub-basin. The LISA cluster map of water resources' ecological surplus/deficits and spatial form reveals three types of local spatial heterogeneity. The upstream area shows an L-L correlation consistent with the spatial clustering. This further confirms the strong spatial heterogeneity between water resources' ecological surplus/deficit and the rural settlement spatial characteristics in this region. A small portion of upstream sub-basins forms H-L clusters, while H-H clusters are distributed at the junction of the middle and lower reaches.

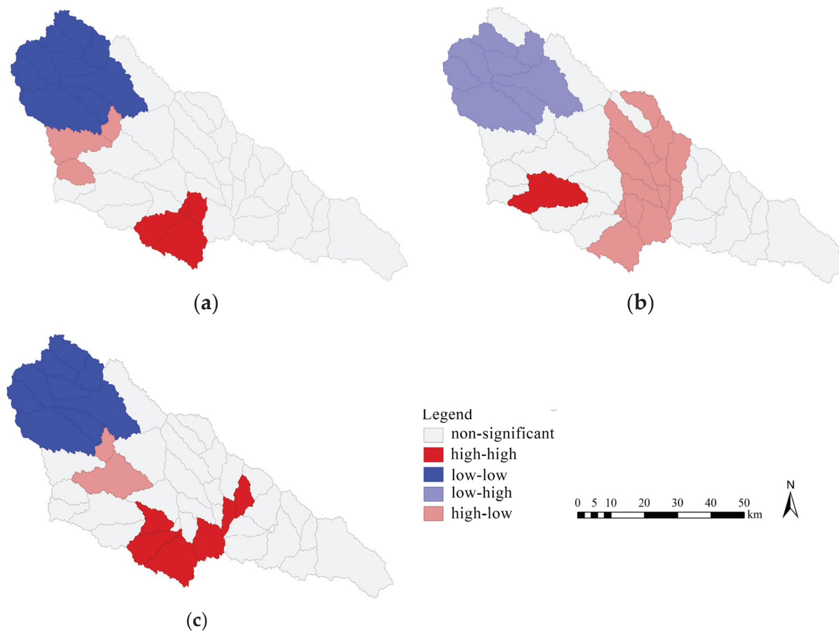


Figure 7. LISA cluster maps of the water resources ecological surplus/deficit and rural settlements spatial characteristics. (**a**) WRES/D and patch density. (**b**) WRES/D and patch area. (**c**) WRES/D and patch shape.

Although there are specific characteristics in the local spatial associations between water resources' ecological surplus/deficit and different rural settlement spatial characteristics, overall, there is a certain degree of spatial similarity. The upstream area and the surrounding Baota District in the Yanhe watershed exhibit significant clustering features. The upstream area of the Yanhe watershed is characterized by steep loess slopes, higher slope gradients, more surface runoff, faster flow velocity, and more severe soil erosion. The sustainable utilization of water resources is more challenging in this area, imposing greater limitations on the spatial development of neighboring rural settlements. The Baota District serves as the core area for urban development in the Yanhe watershed, attracting a large population and many industries. The high demand for water resources in daily life and industrial development in this area leads to a more strained water resource utilization status and a more prominent contradiction with the development of rural settlements. Therefore, it exhibits pronounced spatial clustering characteristics.

4.4. The Relationship between Water Resources and Rural Settlements in the Yanhe watershed

By summarizing and integrating the relationships between various elements of rural settlements and water resources in the Yanhe watershed, we can understand the overall relationship between the two. Water resources in the Yanhe watershed can mainly be categorized into three aspects: quantity, spatial distribution, and technology. Quantity and spatial distribution are inherent characteristics of water resources in the Yanhe watershed, while technology refers to the means of improving the sustainable utilization of water resources for rural settlements. Figure 8 shows that the form, distribution, and scale characteristics of rural settlements are directly linked to water resources in terms of quantity and spatial distribution, and indirectly linked to water resource technologies. Specifically, the spatial form of rural settlements is negatively correlated with the distribution of water resources. The spatial distribution of rural settlements is negatively correlated with ecological water demand and industrial water demand. The spatial scale of rural settlements is positively correlated with domestic water demand and industrial water demand, but negatively correlated with domestic water demand and river network density. Additionally, in terms of water resource technologies, the capacity of domestic wastewater treatment is positively correlated with water environmental quality. Water abundance, as an indicator of water resource quality attributes, reflects the value of water resource utilization for humans. Water abundance is an important indicator for measuring the quality of water resources and their value for human use. This indicator is positively related to both water production and water demand, and can help to evaluate the efficiency of water resource utilization in human activities. Directly adjusting the utilization efficiency and methods of water resources can have an impact on the size and spatial distribution of rural settlements.

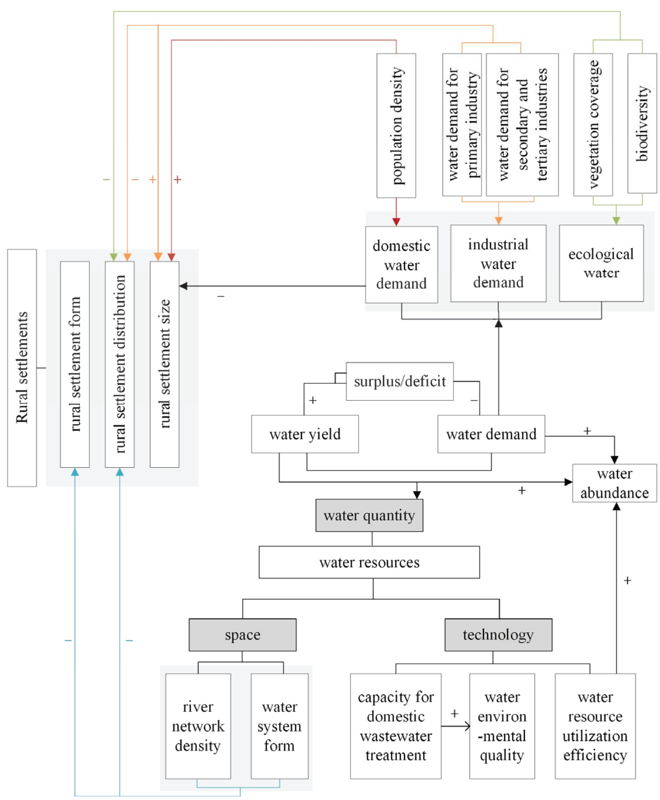


Figure 8. Mechanism of interaction between rural settlements and water resources in the Yanhe watershed. "−" indicates negative influence, "+" indicates positive influence.

As shown in Figure 9, the socio-economic system, as a human factor variable, has a significant impact on both water resources and the development of rural settlements. Policy support, infrastructure, and social support can greatly influence various aspects, such as water quantity, water quality, water cost, wastewater treatment, irrigation methods, and water system landscapes, thereby affecting the quality of life, industrial development, and ecological environment of rural settlements.

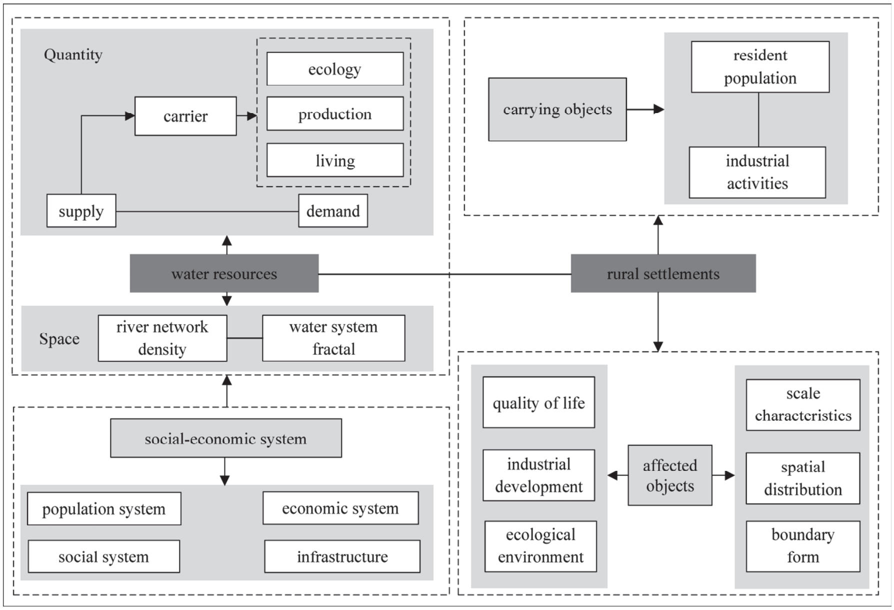


Figure 9. Relationship between rural settlements and water resources in the Yanhe watershed.

Water resources have important impacts on various aspects of rural settlements. In terms of the quantity characteristics of water resources, the development of production, livelihood, and ecological spaces relies, to some extent, on water resources. The supply–demand relationship of water resources can influence the daily life and production activities of rural settlements. In terms of the spatial characteristics of water resources, the density of river networks and the distribution of water systems can affect the scale characteristics, spatial distribution, boundary forms, and internal structures of rural settlements.

The positive and negative effects generated by human water resources' development during the process of rural settlement development also directly influence the water changes in the quantity of water resources. The spatial layout, development patterns, functional positioning, and internal structures of rural settlements lead to changes in water ecological environment and waterfront land use nature, and the combined effects of positive and negative effects vary in different regions. The upstream area of the Yanhe watershed is characterized by a fragmented terrain, sparse vegetation, and scattered farmland. Severe soil erosion is the main cause of ecological deficits in regional water resources. The impact of rural settlement developments on water resources is manifested in negative effects such as excessive water exploitation. In the middle reaches of the basin, the river valley is broad, the channels are flat, agricultural irrigation conditions are good, and facility agriculture is developed. Moreover, the infrastructure in this region is relatively complete, and water resource utilization efficiency is high. Therefore, the impact of rural settlement development on water resources is mainly characterized by positive effects such as efficient water resource utilization. In the downstream region, which is a fragmented tableland area, rural settlements are concentrated and larger in scale. The industrial scale and mechanization level are high, and the dominant vegetation type is forestland. The impact on water resources is mainly positive, with good water and soil conservation conditions, among other positive effects.

4.5. Discussion

Rural settlements, as complex systems, possess various characteristics, and relying on a single indicator alone is insufficient to accurately and comprehensively reflect the spatial development features of rural settlements in a region [43]. Therefore, the study of rural settlement spatial characteristics requires the selection of multiple indicators from multiple aspects for comprehensive measurement in order to more fully and completely depict the spatial features of rural settlements in a region. In this study, indicators such as rural settlement patch density, average patch size, and average patch fractal dimension were employed to analyze and reveal significant regional differences in the spatial characteristics of rural settlements in the Yanhe watershed. Research conducted by Dong Xiaopu and others also found that the density of rural settlements in the Baota District was relatively high, while the density in the Ansai District was generally low [44]. Consistent with previous studies [2,16,17], this research identifies the middle reaches of the Yanhe watershed as high-value areas in terms of water resources' ecological surplus/deficit. The region features a gentle terrain, convenient transportation, and small-sized and clustered rural settlements. On the other hand, the tableland, ridge and hill areas in the upper reaches exhibit a higher elevation and transportation difficulties, forming clusters of low-value water resource ecological surplus/deficits characterized by larger-sized settlements with lower density.

At present, the quantification method of water footprint is mainly used to determine the consumption of water resources by calculating the water consumption of various products or economic sectors [45]. Due to the complexity of the water use process of various products, the data acquisition caliber, type, and structure are different, resulting in a certain degree of error in the calculation of water volume. In addition, from the perspective of the scale of land use in the Yanhe watershed, rural settlements and agricultural land account for a large proportion and are widely distributed, and rural residents are mainly engaged in agricultural production [46]. Therefore, in the rural human–land system, the proportion of agricultural water is relatively large, and the proportion of industrial water is relatively small, with little impact on rural settlements. However, in the process of urbanization in the future, industry will play an increasingly important impact on the development of local villages, so it is necessary to further study the impact of industrial water demand and water use on rural settlements in future research.

Bivariate spatial autocorrelation analysis reveals the spatial correlation between water resources and the spatial characteristics of rural settlements, providing a scientific basis for land use decision-making, ecosystem management, and industrial development guidance in the Yanhe watershed. Research by Yue Bangrui and others concluded that the development of rural settlements in arid areas must coordinate with the relationship with water resources. The spatial form of rural settlements should facilitate the intensive use of limited water resources and reduce the loss of long-distance water transport [47]. Gao Kai and others emphasized the importance of qualified water quality, diverse water resource utilization methods, and a good ecological environment for the sustainable development of rural settlements [48]. Due to the limited land and water resources and rugged terrain, it is necessary to strictly control the scale of construction land and the development of villages, optimize the spatial layout of villages, allocate vegetation types reasonably, adjust industrial structure, improve water resource utilization efficiency, and promote the use of water-saving facilities. These measures are the most feasible approach to improving the ecological environment quality and enhaninge the sustainable development of water resources and rural settlements in the Yanhe watershed while maintaining the living standards of rural residents and actively promoting ecological protection. In the process of rural settlement evolution, attention should be paid to the increasing pressure on water resource utilization caused by the growth in rural scale, as well as the significant increase in water pressure due to the expansion of ecological land and the promotion of reforestation. Additionally, based on the spatial local heterogeneity characteristics of water resources and rural settlements at different levels, in the upper reaches of the basin, it is necessary to regulate ecological governance efforts, improve ecological environmental quality, strictly control the amount of ecological water use, and gradually achieve coordinated development between rural settlements and water resources. In the middle reaches of the basin, rural settlement construction should be carried out in an orderly manner while maintaining the relatively good water resource utilization status at present, and minimizing the disturbance and destruction of water resources caused by rural settlement development. These spatial heterogeneity characteristics provide an important basis for the implementation of differentiated rural settlement construction and water resource regulation measures in the basin, and can provide a reference when optimizing the layout of rural settlements. However, due to the limitations of the article's length, it is difficult to systematically discuss the regional planning and resource governance in the basin, which requires further in-depth research.

5. Conclusions

This study quantitatively measured the sustainable utilization of water resources in the Yanhe watershed using the water resource ecological surplus/deficit method. This reveals the spatial characteristics of rural settlements in the Yanhe watershed from three perspectives: spatial distribution, scale characteristics, and boundary forms. Finally, the bivariate spatial autocorrelation method was used to analyze the correlation between water resources and the spatial characteristics of rural settlements. The main conclusions of the study are as follows:

(1) The water resource ecological surplus/deficit in the Yanhe watershed show an overall spatial pattern of being low in the west and high in the east. The seven sub-basins in the upstream region exhibit a low level of water resource ecological surplus/deficit, indicating a severe deficit in water resources. The sub-basins in the middle and lower reaches, as well as the larger tributaries, show a relatively balanced supply–demand status of water resources.

(2) The spatial characteristics of rural settlements in the Yanhe watershed exhibit a spatial differentiation pattern, with the middle reaches as the highest-value zone and a gradual transition in a stepped manner towards the upstream and downstream ends. The distribution of rural settlements is most dense in the middle reaches, with the smallest area and more regular spatial forms.

(3) The Moran's I values of spatial clustering and spatial forms in relation to water resource ecological surplus/deficit are 0.36 and 0.50, respectively, indicating a strong positive correlation. This suggests that as the sustainability of water resource utilization improves, rural settlements tend to cluster more, and patches become more complex and elongated. The Moran's I value of the area scale in relation to water resource ecological surplus/deficit is -0.60, showing a negative correlation, indicating that when water conditions are better, the size of rural settlements tends to be smaller.

(4) The bivariate LISA maps of water resource ecological surplus/deficit and different spatial characteristics of rural settlements have their own characteristics, but overall, they exhibit certain spatial similarities. In the upstream region of the Yanhe watershed, soil erosion is more severe, the state of sustainable water resource utilization is more challenging, and greater restrictions are imposed on the spatial development of neighboring rural settlements. The residents' daily lives and industrial development in the Baota District have higher demands for water resources, and the water resource utilization is more strained, leading to more pronounced conflicts with the development of rural settlements.

Although this study has identified the spatial correlation between water resources and rural settlements in the Yanhe watershed, further research is needed to explore the driving factors behind this correlation. With the acquisition of more data and in-depth research, future studies will delve into the driving factors to better guide the optimization of rural settlement layout.

Author Contributions: Conceptualization, L.Z. and W.L.; methodology, W.L.; software, L.Z.; investigation, W.L.; resources, Y.D.; writing—original draft preparation, L.Z. and Q.H.; writing—review and editing, Y.D. and L.Z.; project administration, Y.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under Grant 52178030, the National Key Research and Development Program under Grant 2022YFC3802803, the Fundamental Research Funds for the Central Universities, CHD under Grant 300102412723, and the Philosophy and Social Science Research Project in Shaanxi under Grant 2023ZD0622.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The authors gratefully acknowledge the supports of various foundations. The authors are grateful to the editor and anonymous reviewers whose comments have contributed to improving the quality of this study.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

The Spatial Pattern Evolution of Rural Settlements and Multi-Scenario Simulations since the Initiation of the Reform and Opening up Policy in China

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Abstract: Since the inception of China's reform and opening-up policy, the rapidly advancing process of urbanization and the primacy accorded to urban development policies have imparted increasingly profound ramifications on rural domains. Nonetheless, antecedent research has predominantly fixated on urban sprawl, overlooking the spatial metamorphosis of rural settlements and the prospective developmental trajectories within the policy paradigm. Consequently, this inquiry endeavors to scrutinize the evolution of the spatial configuration of rural settlements in She County from the advent of reform and opening-up (1980–2020) utilizing remote sensing data. In tandem, through scenario delineation and the utilization of the CLUE-S model, it aspires to prognosticate the evolving trends in the spatial arrangements of rural settlements in She County by 2035. The empirical findings divulge that (1) The temporal progression of rural settlement spatial configurations in She County over the preceding four decades can be delineated into two discernible phases. From 1980 to 2000, alterations in the number, extent, and spatial morphological attributes of rural settlements remained circumscribed. While the count of rural settlements registered a diminution (by 3), the aggregate extent experienced a marginal augmentation (by 8.45%), concomitant with a gradual gravitation towards regular boundaries, manifesting a stochastic distribution throughout the investigation expanse. Conversely, from 2000 to 2020, the quantity and extent of rural settlements in She County underwent a precipitous augmentation (92 and 36.37%, respectively), characterized by irregular peripheries. (2) The CLUE-S model achieved an overall precision of 0.929, underscoring its applicability in emulating fluctuations in rural settlements. (3) Within the new-type urbanization scenario, the cumulative expanse of rural settlements witnessed a decline of 35.36% compared to the natural development scenario, marked by substantial conversions into grassland and urban land usage. Furthermore, orchestrated planning and directive measures have propelled the consolidation of rural settlements in She County, engendering a more equitable and standardized layout. Under the aegis of the ecological conservation scenario, the total rural settlement area recorded a 0.38% reduction vis-à-vis the natural development scenario, primarily entailing competitive coexistence with arable land, grassland, and urban land usage in spatial terms.

Keywords: rural settlements; spatial pattern evolution; scenario simulation; CLUE-S Model

Citation: Sheng, S.; Lian, H. The Spatial Pattern Evolution of Rural Settlements and Multi-Scenario Simulations since the Initiation of the Reform and Opening up Policy in China. *Land* **2023**, *12*, 1763. https://doi.org/10.3390/land12091763

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 24 August 2023
Revised: 8 September 2023
Accepted: 10 September 2023
Published: 11 September 2023

1. Introduction

Inappropriate land utilization practices are currently imperiling the global trajectory toward sustainable development, thereby compounding the intricacies associated with realizing the objectives of SDG13 (Addressing Climate Change) and SDG16 (Preserving, Restoring, and Promoting Sustainable Land Ecosystems) [1,2]. Within the intricate tapestry of our planet's ecological dynamics, land emerges as a finite and non-renewable resource, pivotal in the intricate interplay of human societal and economic dynamics [3]. However, the prevailing landscape is marred by a series of suboptimal land usage paradigms that not only upset ecological equilibrium but also cast shadows upon the tenets of socio-economic sustainability [4]. The convergence of rational and systematically orchestrated land utilization patterns assumes an eminent significance in the face of global climate fluctuations, eroding biodiversity, and the pressing matter of food security, among others [5,6]. Through prudent land apportionment, the reduction of carbon emissions and the preservation of biodiversity can be harmonized with the provisioning of ample arable land to satiate humanity's nutritional requisites [7,8]. Nevertheless, as the global populace continues its relentless expansion, the scarcity of land resources is destined to escalate, further exacerbating the tensions between burgeoning human needs and the limited expanse of the land [9]. Hence, it becomes imperative to recalibrate our vantage point and embrace the pivotal role of land utilization metamorphosis in elevating the quality of our habitation and propelling sustainable human advancement.

Rural settlements, the foundational units of rural production and subsistence, are pivotal in upholding familial bonds and facilitating social interactions [10]. However, the rapid global march of urbanization has spawned the unremitting expansion of urban areas, imparting profound repercussions on the trajectory of rural settlements and the associated challenges they confront [11]. For instance, in advanced economies, certain nations like France and Athens have prioritized urban expansion, inadvertently disregarding the excessive encroachment of urban sprawl upon rural settlements, leading to a fragmentation of rural settlement distributions [12,13]. Conversely, during Poland's urban economic metamorphosis, rural settlements experienced similar flourishing, giving rise to diverse village typologies encompassing domains such as tourism, entertainment, and agriculture [14]. However, Lithuania's swift urban development has triggered an excessive outflow of rural populations, culminating in the rapid vanishing of rural settlements [15]. In a parallel vein, China, as the world's most populous developing nation, has placed a distinct emphasis on the expansion of urban areas after economic reforms [16].

Nonetheless, this rural-urban developmental disbalance has bred a litany of pressing concerns, encompassing the sluggish socioeconomic progress of rural regions, inadequate preservation of cultural heritage, exacerbated population outmigration, and the conspicuous lack of unified governance and strategic planning for rural settlements [17,18]. This scenario has crystallized into the emergence of a distinctive dual urban-rural paradigm [19]. Acknowledging the profound historical heritage of rural China, rural settlements wield a critical role in nurturing their inhabitants' spiritual and material cultural lives [20]. Hence, it is imperative that we accord paramount attention to rural development concerns, particularly those entwined with rural settlements.

Recognizing the dynamic spatial transformations of rural settlements assumes profound significance in pursuing rational configurations and efficacious planning for these habitation clusters [21]. However, methodological and data disparities emerge among scholars across different national contexts. Drawing upon conventional survey data, Polish scholars unearth that within the ambit of 15 villages encompassing Lublin city, a conspicuous trend of settlement expansion is discerned in closer proximity to the urban core and major transportation arteries. This expansion, nevertheless, correlates with a reduction in the proportion of agricultural expanse, accompanied by architectural nuances diverging from traditional rural motifs [14]. In the context of Lithuania, the diminishing demographic sway of rural denizens prompts a recalibration of rural settlements within suburban peripheries or adjacency to agrarian enterprises, with extant rural dwellings subject to a comprehensive spatial blueprint to regiment developmental trajectories [15]. Harnessing remote sensing-derived land use data, Slovenian investigations underscore the interval from 1991 to 2005, wherein rural settlements exhibit an augmenting central functional locus, correspondingly accompanied by an ascent in density within proximate hinterlands [22]. An exploratory foray into the Indian province of West Bengal spanning 1975 to 2020 divulges an uneven spatial distribution and variable pace of rural residential domain expansion. Concurrently, the fortification of public utilities embracing education, healthcare, communication, and commercial infrastructure facilitates the confluence of rural habitats and attains a harmonized scale, concurrently attenuating reliance on urban nuclei [23]. Worth underscoring is that while the trove of antecedent research on rural habitat transmutations furnishes a diverse spectrum of insights and pragmatic solutions, the unique tapestry of China's rural fabric, characterized by historical profundity, demographic amplitude, and pronounced economic heterogeneity across regional demarcations, necessitates nuanced consideration. When juxtaposed against orthodox data modalities germane to examining rural settlements, remote sensing datasets offer heightened visual lucidity and proffer more conspicuous patterns, thus exhibiting an enhanced alignment with the mandate of discerning spatial evolution within the contours of Chinese rural settlements [24]. Furthermore, the judicious calibration of bespoke policies and pragmatic measures tailored to the developmental trajectory of rural settlements mandates an in-depth grasp of their protracted evolution [25].

Simulating land use changes under diverse scenarios assumes a pivotal role in the formulation of empirically grounded decisions, fostering the tenets of sustainable development, and orchestrating resource management strategies [26]. For instance, within land use dynamics intertwined with global urbanization, scholars in the United States undertook simulations encompassing the intricate tapestry of land cover patterns across an expansive spectrum of 2000 urban agglomerations [27]. In the context of the East African Rift Valley Basin, researchers diligently sought to simulate the metamorphosis of land use patterns within the Matenchose watershed, therein affording a quantification of its manifold ramifications upon the finite troves of natural resources [28]. Across the topography of Romania, scholars embarked upon an intellectual odyssey of simulating the transformative contours of land use, thereby probing the latent underpinnings underpinning environmental stewardship and the dynamics of land management paradigms [29]. This investigative expanse was further enriched by manifold cross-scenario simulations orchestrated to discern the optimal vantages within the mosaic of land utilization strategies. Japanese scholars, for instance, judiciously deliberated upon the cascading consequences that divergent climatic and land use scenarios visited upon the aqueous resources of watersheds, therein illuminating their intricate interplay [30]. In concert, a constellation of research endeavors proliferated, adorning the landscape of inquiries spanning the gamut from simulating the vicissitudes of land use under the aegis of climatic transmutations to addressing the imperatives of food security and confronting the frangible precincts of ecological vulnerability [31–33].

Nonetheless, while this corpus of scholarship coalesces around the liminal realm of land use transitions, a discernible lacuna in the annals of research pertains to the prognostication and simulation of developmental trajectories intrinsic to rural settlements. Concurrently, prevailing inquiries that dissect the prospects of simulation and prognostication inherent to rural settlements predominantly gravitate toward the troposphere of natural expansion, with scant consideration afforded to the entwined narrative of rural settlement evolution as it exists within the interplay of policy incentives and spatial governance dynamics [34]. Functioning as enclaves of paramount importance, rural settlements constitute the crucible within which the alchemy of policy determinism and socioeconomic dynamics coalesce [35]. Hence, the harmonious integration of policy levers into the ambit of scenario formulations, as they traverse the landscape of prognosticating and simulating the spatiotemporal choreography of rural settlements amid varying policy interventions, assumes profound salience. Within this intellectual precinct, the rubric of assessing nascent rural settlement paradigms and the sculpting of judicious developmental templates stands poised at the precipice of significance. In tandem, this intellectual pursuit serves as a vanguard, proffering the blueprints and directives that underpin the trajectory of rural spheres, instilling them with foresight and navigational clarity.

Against the backdrop of policy imperatives and human activities, the spatial configuration of rural habitation within She County has traversed a trajectory of evolvement. In their predictive and simulated manifestations, divergent scenarios expound the potential permutations that might be engendered within She County's rural habitation landscape. Nevertheless, prevailing research exhibits a proclivity toward urban dynamics, leaving the study of rural settlements relatively marginalized. Concomitantly, the orchestration of scenarios often disregards the nuances of regional contexts and the dynamic flux inherent within planning policies. Within this framework, the objectives of this study are threefold: firstly, to scrutinize the mutational trends underpinning the dimensions of rural habitation within She County across the temporal span from 1980 to 2020; secondly, to unveil the distinctive characteristics and patterns underpinning the spatial evolution of rural habitation during this period; lastly, employing simulation and projection methodologies, to dissect the trajectories and pivotal attributes of rural habitation dynamics across varying scenarios. By traversing this intellectual terrain and filling a lacuna in scholarship, this study aspires to proffer a more comprehensive vista, thereby affording a deeper comprehension of the intricate interplay engendering the relationship between urbanization and rural developmental paradigms.

2. Study Area and Data Sources

2.1. Study Area

Situated in the Hebei Province of China, precisely at coordinates 36°17′ N–36°55′ N and 113°26′ E–114° E, She County holds a strategic location within the city of Handan. Nestled on the eastern foothills of the Taihang Mountains, this county occupies the southwestern realm of Hebei Province, forming a nexus at the confluence of the Shanxi, Hebei, and Henan provinces. Reverberating as an essential hinge, She County exemplifies its significance as a pivotal juncture connecting the prominent Jing-Jin-Ji (Beijing-Tianjin-Hebei) region with the heart of the Central Plains, thereby assuming a distinctive locus (see Figure 1). Notably, She County boasts the distinction of being included in the third tranche of comprehensive national pilot areas for pioneering new urbanization endeavors—a designation conferred in December 2016 [36]. Its topographical tapestry predominantly comprises rugged terrain, with an average elevation cresting at 1000 m, punctuated by a zenith at 1562.9 m. Distinguished by a warm temperate continental monsoon climate, the annual precipitation quantifies to 571.7 mm, painting the climatic canvas. As of the terminus 2020, She County encompassed a total populace of 432,754 souls, with an urbanization quotient marking 65.11%. In 2020, the county's gross domestic product (GDP) scaled 17.282 billion yuan, encapsulating a year-on-year escalation of 4.5%. A facet warranting attention resides in the per capita disposable income for denizens of urban provenance, constituting 26,630 yuan, bearing witness to a 4.9% augmentation, whereas, for their rural counterparts, this metric stood at 15,676 yuan, manifesting a 6.6% augmentation [37].

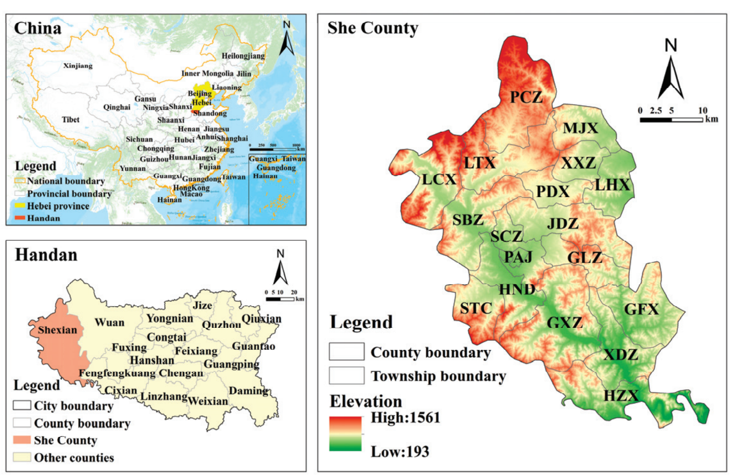

Figure 1. Location map of She County in Hebei Province, China. JDZ stands for Jingdian Town; PCZ stands for partial town; PDX stands for Bidian Township; PAJ stands for Ping An Street; GFC stands

for Guanphong Township; MJX stands for Mujing Township; GXZ stands for Guxin Town; GLZ stands for Gengle Town; SBZ stands for Soburg Town; SCZ stands for involved town; LCX represents Liaoning urban and rural areas; STC stands for Shentou Township; XXZ stands for Xixu Town; LTX stands for Lutou Township; HND stands for Henan Branch; HZX stands for Hezhang Township; LHX stands for Longhu Township.

2.2. Data Sources

The data utilized in this study can be categorized into two main types: natural geographic data and socio-economic data (Table 1). The natural geographic data encompass land use, digital elevation model (DEM) data, and water bodies. The socio-economic data encompass population density, gross domestic product (GDP), railway networks, road networks, and nocturnal luminosity data. Details regarding these data's temporal scope, resolution, sources, and intended applications are provided below.

Table 1. Data Sources and Explanation of Usage.

	Data	Time	Resolution	Data Sources	Data Sources
Physical geographic data	land use data	1980–2020	30 m	China Resources Environment Science and Data Center [38]	Extraction and simulation of rural settlements
	DEM	2005	30 m	China Resources Environment Science and Data Center [39]	Extraction and simulation of rural settlements
	Water area	2005	—	China Resources Environment Science and Data Center [40]	Extraction and simulation of rural settlements
Socioeconomic data	Population density	2005	1000 m	WorldPop [41]	Extraction and simulation of rural settlements
	GDP	2005	1000 m	China Resources Environment Science and Data Center [42]	Extraction and simulation of rural settlements
	Railway	2005	—	China Resources Environment Science and Data Center [43]	Extraction and simulation of rural settlements
	Highway	2005	—	NASA [44]	Extraction and simulation of rural settlements
	Nocturnal Luminosity Data	2005	1000 m	Global Change Research Data Publishing & Repository [45]	Extraction and simulation of rural settlements

3. Research Methodology

In this study, we employed several methods to achieve our objectives. Firstly, we extracted rural settlement data in She County using land use data. Subsequently, we employed the spatial rhythm index and average nearest neighbor index to ascertain the spatial patterns and evolutionary characteristics of rural settlements in different periods. Lastly, we utilized the Markov model and CLUE-S model to predict and simulate the spatial distribution of rural settlements under various developmental scenarios.

3.1. Measurement of Spatial Landscape Patterns

3.1.1. Spatial Rhythm Index

The utilization of the Spatial Rhythm Index commonly elucidates the dynamic evolution of land utilization patterns, thereby encapsulating pertinent insights into the configuration of landscapes and the spatial arrangement of elements. Within the scope of this study, the selection of indices is poised to be both focused and comprehensive, strategically capturing the multifaceted attributes pertaining to the spatial disposition and developmental scale of rural settlements [46]. Consequently, we have judiciously chosen density indicators (reflecting patch count), land use indicators (pertaining to patch area), scale indicators (encompassing average patch size and the largest patch index), and shape indicators (encompassing the landscape shape index) to aptly delineate the evolutionary traits of the spatial pattern exhibited by rural settlements. The computation of all selected indices can be adeptly performed using the Fragstats software suite, which draws upon land utilization data germane to rural settlements. A comprehensive elucidation of the meanings and mathematical formulations for each index is elucidated in Table 2.

Table 2. Spatial Rhythm Indices and Their Significance.

Primary Indicators	Secondary Indicators	Index Interpretation	Formula	Formula Specification
Density index	Number of Patches (*NP*) [47]	Number of landscape patches of a certain class.	$NP = n_i$	Where, n_i represents the number of patches containing a specific patch type within the landscape, measured in "units".
Land use index	Patch Area (*CA*) [47]	The class area (*CA*) reflects the size of a specific patch type within the landscape and serves as the basis for calculating other indicators.	$CA = \sum_{j=1}^{n} a_{ij} \times \frac{1}{1000}$	Where a_{ij} represents the area of patch *ij*, with values falling within the range $CA \geq 0$, measured in hectares (hm^2).
scale merit	Mean patch area (*MPS*) [47]	The Mean Patch Size represents an average condition, indicating the degree of landscape fragmentation. A smaller *MPS* value indicates a more dispersed patch type.	$MPS = \frac{CA}{NP}$	Where, *CA* refers to the total area in hectares (hm^2), and *NP* represents the total number of patches.
	Largest Patch Index (*LPI*) [48]	The Maximum Patch Index is used to identify the dominant patch type within the landscape.	$LPI = \frac{a}{CA}$	In this context, a stands for the maximum area of a patch within a certain patch type, measured in hectares (hm^2); *CA* represents the total area of patches of a specific type within the landscape, also measured in hectares (hm^2).
Shape index	Landscape Shape Index (*LSI*) [48]	The Landscape Shape Index (*LSI*) is employed to reflect the irregularity or complexity of a given patch. A higher *LSI* value indicates greater irregularity and elongation in the shape of the corresponding patch.	$LSI = \frac{0.25 \sum_{i=1}^{n} c_i}{\sqrt{\sum_{i=1}^{n} a_i}}$	Where, c_i denotes the perimeter of the ith patch, measured in meters (m), while a_i represents the area of the ith patch, measured in hectares (hm^2).

3.1.2. Average Nearest Neighbor Index

The Average Nearest Neighbor Index (*NNA*) offers a lens to illuminate the spatial disposition and clustering propensities of rural settlement patches [49]. This method entails gauging the mean distance between each patch's centroid and that of its closest neighbor. This average distance is subsequently juxtaposed against the expected average distance derived from a hypothetical random distribution model. This comparison aims to discern whether the arrangement of patches showcases tendencies towards spatial clustering, thereby shedding light on the clustering tendencies of settlements. Calculating the *NNA* value can be facilitated using the spatial analysis capabilities within ArcGIS 10.8 software, with the formula presented as follows:

$$NNA = \frac{\sum_{i=1}^{n} d_i / m}{\sqrt{n/R}/2}$$

where d_i represents the distance between the centroid of the ith rural settlement patch and the centroid of its nearest neighboring rural settlement patch, measured in meters (m). n denotes the total count of rural settlement patches, while R signifies the area of the minimum bounding rectangle that encompasses all rural settlement patches within the study area, expressed in square meters (m^2). A *NNA* value of 1 indicates a random distribution pattern of rural settlement patches. Conversely, if *NNA* < 1, it reflects an aggregated spatial distribution of rural settlement patches. On the other hand, values exceeding 1 suggest a dispersed distribution of rural settlement patches.

In addition, a significance test is required to be conducted. Further assessment of the significance of the *NNA* values is accomplished by calculating standardized *Z* scores [49]. In this study, we utilized ArcGIS 10.8 software to extract the rural settlement patches of She County as points. Subsequently, the ArcGIS spatial statistics tool was employed to calculate the *Z* scores for the years 1980, 2000, and 2020, aiding in determining the spatial distribution pattern of rural settlement patches in She County, whether they exhibit clustering or dispersion. The formula employed is provided below:

$$Z = \frac{\overline{d_i} - E(d)}{\sqrt{var\left(\overline{d_i} - E(d)\right)}}$$

where d_i represents the distance between the centroid of the ith rural settlement patch and the centroid of its nearest neighboring rural settlement patch, measured in meters, and the average nearest neighbor distance is denoted as $E(d)$. If Z exceeds 1.96 or falls below -1.96, it signifies a statistically significant d value. Conversely, if the Z value falls within the range of -1.96 to 1.96, no statistically significant difference is observed.

3.2. Simulating and Predicting the Spatial Evolution of Rural Settlement Patterns

The simulation of land use dynamics, informed by driving factors and the competitive interactions among different land use categories, is executed through the iterative spatial allocation methodology of the CLUE-S model [50]. This model encompasses two principal modules: the non-spatial demand and spatial allocation modules. The former determines the composition and quantities of land use types under various scenarios, while the latter employs binary logistic regression to allocate these demands to suitable spatial locations within the study area based on the cumulative probability of land use requirements across scenarios. This intricate process replicates the evolving spatial configuration of land use changes. Notably, CLUE-S is a refined adaptation of the original CLUE model, meticulously tailored to simulate land use transitions within smaller geographic regions. The operationalization of the CLUE-S model necessitates an array of input files, encompassing the baseline land use map of the study area for the initial simulation year, datasets related to land use demands, transition matrices for land use conversions, driver-specific data, and the central parameter configuration files integral to the model's functioning.

The choice to set the year 2035 as the focal point of our simulation holds significance due to a well-considered rationale. We projected future land use changes over a two-decade span (2015–2035) based on the land use change rates observed during the preceding ten years (2005–2015). Given the formal designation of She County as a pilot zone for new urbanization initiatives by national authorities in 2015, our decision to utilize data predating that year was motivated by a desire for a more accurate portrayal of the county's forthcoming land use dynamics. Furthermore, in harmony with local governance strategies, the She County government has ratified the "Overall Land Spatial Planning for She County (2021–2035)", henceforth referred to as the "She County Land Spatial Plan". This plan articulates 2035 as the ultimate target year, with an interim milestone in 2025 [37]. In alignment with these strategic guidelines, our study strategically adopts 2035 as the designated target year.

3.2.1. Non-Spatial Demand Module

In the context of simulating the 2035 land use changes, the non-spatial demand module assumes a critical role in quantifying alterations in land use types driven by diverse factors or demands within distinct scenarios. In this study, we have delineated three scenarios:

Natural Development, New Urbanization, and Ecological Conservation, each designed to encapsulate the evolving patterns of rural residential settlements in She County.

(1) Natural Development Scenario

The Natural Development Scenario unveils the impending landscape of land use changes and the trajectory of rural residential settlement evolution in She County. In this scenario, the change rates for different land cover categories adhere to historical trends. This scenario is a foundational reference point, illuminating the nuanced developmental trajectories of land use and rural residential settlements within She County. Accordingly, the land use areas for each land cover category in 2035 are projected based on the observed land use change rates from 2005–2015. Furthermore, the land use type areas for each year between 2015 and 2035 are derived through linear interpolation techniques.

(2) New Urbanization Scenario

The New Urbanization Scenario primarily focuses on the prospective patterns of land use and the evolution of rural residential settlements following the implementation of the New Urbanization Plan.

In December 2016, She County was designated one of China's third National Comprehensive Pilot Zones for New Urbanization [36]. The future developmental trajectory of She County is intricately tied to the contours of China's New Urbanization policy. To quantitatively assess the policy's impact, an in-depth analysis of its specifics and distinctive features is essential. This serves as the foundation for allocating scales and spatial distributions to various land use types, ultimately formulating the requirements for different categories of land utilization. The essence of the New Urbanization policy revolves around placing people at the heart of urbanization, necessitating the transformation of rural inhabitants into urban citizens. This transformation is epitomized by the migration of rural residents to urban areas. Accordingly, using projected urban and rural population figures for 2035 and employing Primary Indicator Drivers (PID), we delineate the demand for urban and rural habitation. Moreover, as New Urbanization mandates coordinated industrial growth, emphasizing the harmonious development of urbanization alongside the respective economic and industrial foundations, we can ascertain the requisites for other construction land based on the migration patterns of the rural labor force.

Regarding population data and land use change values, the Primary Indicator Drivers (PID) approach can deduce the increments in target land use types resulting from population growth and subsequently compute the corresponding land use quantities for future urban and rural populations of She County. The formula for this process is as follows [21]:

$$U(t) = A(t)$$

Taking the rural registered population as an example, in the equation, $U(t)$ represents the increase in the quantity of land occupied by rural settlements within a specific period in the study area; $\frac{dp}{dt}$ signifies the growth of rural population during the same period; $A(t)$ denotes the increase in the quantity of land occupied by rural residential areas due to the rise in per capita population.

Moreover, within the context of the current intermediate urbanization rate (65.11%) prevailing in the study area, the realization of this process necessitates the continual expansion of urban land to accommodate the urbanization of the populace and the augmentation of other construction land for industrial advancement. The Land Use Spatial Planning of She County outlines that by the year 2035, the total permanent population of the county is projected to reach 712,100, with an urban population of 526,900 and an urbanization rate of 74%. The total area allocated for construction land across the entire jurisdiction is estimated at approximately 178.81 square kilometers. Within this expanse, urban construction land is earmarked for 92.74 square kilometers, while rural residential land covers 30.8 square kilometers. Hence, drawing on the PID methodology, it becomes feasible to compute the anticipated demands for urban and rural residential land by 2035.

Furthermore, due to the imperative of ecological conservation stipulated by the new paradigm of urbanization, there arises the need for a commensurate increase in ecologically designated lands, such as forests and grasslands. In tandem, the expansion of urban areas may inevitably lead to a concomitant reduction in arable land. In sum, juxtaposed with the scenario of natural growth, the trajectory of new-model urbanization underscores the necessity for augmenting areas dedicated to urban spaces, other construction purposes, as well as forested and grassland areas while concurrently scaling back the allotment of land for rural residential use. Grounded in these considerations, the imperatives for land allocation across various categories in 2035 can be effectively ascertained.

(3) Ecological Protection Scenario

The ecological protection scenario incorporates ecological security constraints into the natural development scenario, aiming to safeguard the ecological environment and restrain unregulated conversions of existing natural ecological land. Accordingly, this scenario intensifies the emphasis on conserving forested areas, grasslands, and water bodies while rigorously constraining the expansion of arable and construction land. Concurrently, the likelihood of converting ecologically functional grasslands, forests, and water bodies in She County into construction and arable land is diminished within the purview of this ecological scenario.

3.2.2. Spatial Allocation Module

The spatial allocation module encompasses the allocation of land use data from distinct scenarios into appropriate spatial locations, with the objective of simulating the spatial arrangement of land use changes [51]. Throughout the spatial allocation process, we integrate spatial policies as a foundational element, establishing designated restricted conversion zones to guide the spatial distribution of land use.

(1) Restricted Conversion Zones

Establishing policy-driven restricted conversion zones is primarily predicated upon the actual transformation patterns of land use types. In conjunction with China's Third National Land Survey, we have delineated distinct prohibited conversion zones for varying development scenarios (Figure 2). In conventional urbanization, where land use changes adhere to natural developmental trajectories and encompass unrestricted conversions of land use types, no explicitly defined restricted zones are designated. Conversely, within the ambit of the new urbanization scenario, we meticulously adhere to directives outlined in documents such as the "National New Urbanization Plan (2021–2035)", "Handan City New Urbanization Plan (2021–2035)", and She County's Land Spatial Plan. The crux of the new urbanization policy lies in eschewing any compromise vis-à-vis agriculture, food security, ecology, and the environment.

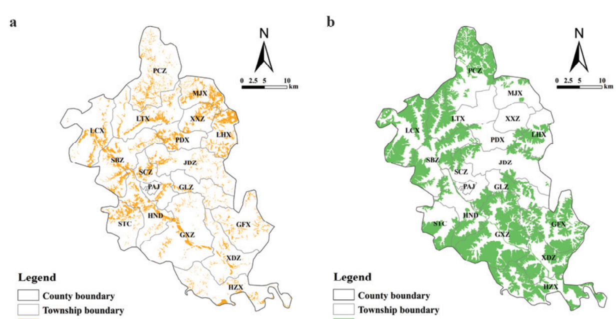

Figure 2. Restricted Conversion Zones. (**a**) Represents Essential cropland, and (**b**) Depicts Ecological Protection Red Line; JDZ stands for Jingdian Town; PCZ stands for partial town; PDX stands for Bidian

Township; PAJ stands for Ping An Street; GFC stands for Guanphong Township; MJX stands for Mujing Township; GXZ stands for Guxin Town; GLZ stands for Gengle Town; SBZ stands for Soburg Town; SCZ stands for involved town; LCX represents Liaoning urban and rural areas; STC stands for Shentou Township; XXZ stands for Xixu Town; LTX stands for Lutou Township; HND stands for Henan Branch; HZX stands for Hezhang Township; LHX stands for Longhu Township.

Furthermore, She County's Land Spatial Plan ensures the safeguarding of arable land and guarantees the security of staple food and vital agricultural products. Henceforth, the essential cropland areas in She County's Land Spatial Plan are marked as restricted conversion zones (Figure 2a). Within the framework of ecological protection, we hew closely to the ecological protection red line policies enunciated in She County's Land Spatial Plan. Areas encircled by the ecological protection red line shall be stringently managed, with an unequivocal prohibition on development, implementation of stringent access controls, and rigorous oversight of construction activities. A phased withdrawal strategy, contingent on real-world contingencies, is concurrently instated. Beyond the ecological protection red line, a classification-driven management approach is adopted. With a paramount emphasis on conservation, imperative ecological restoration initiatives are undertaken while safeguarding ecological functionality and preserving ecosystems. This approach, underpinned by planning and control precepts, facilitates judicious development. Consequently, areas demarcated within She County's ecological protection red line are demarcated as restricted conversion zones (Figure 2b).

(2) Driver Analysis

Distinct driving factors exert varying influences on both land use changes and the evolution of rural settlements. To effectively elucidate the nuanced impacts of these factors, we draw upon research findings pertaining to rural settlements and judiciously select a comprehensive set of nine driving factors for the evolution of rural settlements. These factors encompass elevation, slope, aspect, distance to water bodies, distance to roadways, distance to railways, GDP, population density, and nocturnal luminosity data (depicted in Figure 3) [10,21,52]. Notably, slope and aspect data are derived from the Digital Elevation Model (DEM) dataset, and all distance metrics are calculated as Euclidean distances utilizing ArcGIS 10.8. These driving factors are meticulously resampled to a spatial resolution of 30 m × 30 m and converted into ASCII files, which are pivotal input factors for the CLUE-S model.

Before conducting simulations, it is imperative to assess the compatibility of all driving factors with the simulation prerequisites. Employing the Convert module within the CLUE-S model, we transformed all driving force files into a txt format, subsequently inputting them into the SPSS software for binary logistic stepwise regression analysis, yielding regression coefficients (β values) [53]. This approach was deployed to scrutinize the driving factors, providing insight into the quantitative relationship between the spatial distribution of distinct land-use types and the driving forces influencing their spatial allocation, as elucidated by the ensuing equation:

$$log\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1\ X_{1,i}\ + \beta_2 X_{2,i} + \ldots\ldots + \beta_m X_{m,n}$$

where P_i (ranging between 0 and 1) denotes the likelihood of the spatial distribution (suitability) of land-use type i at each grid unit. X_i represents the influencing factors on land-use type *i*, and β_i corresponds to the coefficient linked with the driving factors specific to land-use type *i*.

The validation of the Logistic regression results is assessed using the ROC (relative operating characteristics) analysis. A ROC value below 0.5 indicates a weakened explanatory capacity of the driving factor for the specific land class. Conversely, when the ROC surpasses 0.7, the selected driving factors demonstrate strong explanatory capabilities, rendering them suitable for simulation within the study area. Regression coefficients calculated from the driving force files with ROC values exceeding 0.7 are then selected for simulation.

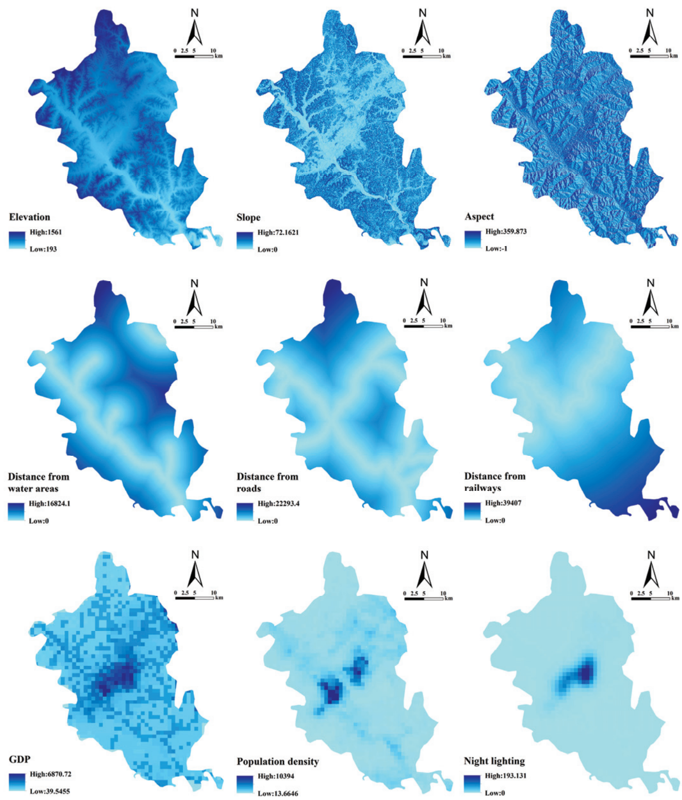

Figure 3. Driving Factors of Spatial Patterns Evolution in Rural Residential Areas of She County in 2005.

3.3. Spatial Iterative Computation

The CLUE-S model utilizes spatial iterative computation to determine the total probabilities of each land use type, primarily through the spatial allocation module for simulating the spatiotemporal patterns of land use [54]. The formula for spatial iteration is as follows:

$$TPROP_{i,u} = P_{i,u} + ELAS_u + ITER_u$$

where $TPROP_{i,u}$ denotes the comprehensive probability associated with land use type u on grid i, while $P_{i,u}$ signifies the probability of the spatial distribution (suitability) of land use type u, computed through the logistic regression equation for grid i. The term $ELAS_u$ represents the elasticity transformation coefficient specific to land use type u, and its inclusion is contingent upon grid unit i already belonging to land use type u during the considered year. Additionally, $ITER_u$ serves as an iterative variable that conveys the relative competitive dynamics of the land use type.

3.4. Evaluation of Simulation Accuracy

Before applying the CLUE-S model to project future land use dynamics across various scenarios, a preliminary evaluation of its simulation accuracy is essential. The *Kappa* index, commonly employed for assessing classification image precision, is our chosen metric for this evaluation [52]. In this study, we employ the *Kappa* index to quantitatively gauge the simulation performance of the CLUE-S model. Specifically, the reference year of 2005 forms the baseline, against which we simulate land use changes for 2015 through the model application. Subsequently, the simulated outcomes are juxtaposed with actual land cover data from 2015, enabling a thorough appraisal of the simulation accuracy. The *Kappa* index formula, central to this assessment, is articulated as follows:

$$Kappa = \frac{P_m - P_n}{P_p - P_n}$$

where P_m represents the proportion of accurately simulated outcomes; P_n denotes the anticipated proportion of accurate simulations under random circumstances; and P_p signifies the proportion of accurate simulations under ideal classification scenarios. It is generally acknowledged that *Kappa* values within the range of 0.41 to 0.60 indicate viable model simulation outcomes, reflecting a moderate level of concordance. *Kappa* values falling between 0.61 and 0.80 suggest favorable model simulation results, showcasing a substantial degree of concurrence.

4. Research Results

4.1. Evolution of Rural Settlement Size from 1980 to 2020

The cumulative expansion of rural settlement extents in She County demonstrated a sustained growth trajectory spanning 1980 to 2020. Over this temporal span, the collective augmentation of rural settlement areas aggregated to 1448.19 hectares, as depicted in Table 3. Significantly, distinct developmental phases emerged, each marked by its characteristic features. During the initial period encompassing 1980 to 2000, the enlargement of rural settlement dimensions in She County exhibited a restrained progression. The alteration in patch areas amounted to 255.21 hectares, characterized by an annual growth rate of 0.42%. Notably, the year 2000 witnessed a reduction in the number of patches compared to 1980, presenting a negative growth rate of −0.1%. This stage indicated a comparatively gradual development of rural settlements, marked by constrained size escalation. In the subsequent era spanning 2000 to 2020, the rural settlement domain in She County underwent a substantial expansion, accruing 1192.68 hectares. Within this timeframe, the aggregate number of patches reached 149, demonstrating an annual growth rate of 3.1%, while the patch areas experienced an average annual growth rate of 1.82%. In stark contrast to the 1980–2000 phase, this period was characterized by an accelerated pace of rural settlement development and a notable surge in size. Notably, despite reaching their pinnacle in terms of patch count and cumulative area by 2020, rural settlements in She County exhibited the smallest average patch area during this juncture, measuring 18.56 hectares. In juxtaposition, the zenith of the average patch area occurred in 2000, registering at 22.01 hectares.

Table 3. Spatial Rhythmic Indicators of Rural Settlements in She County from 1980 to 2020.

Primary Index	Secondary Indicators	1980	2000	2020
Density index	NP	152	149	241
	Average annual change ratio		−0.1%	3.1%
Land use index	CA (ha)	3023.73	3279.24	4471.92
	Average annual change ratio		0.42%	1.82%
Scale merit	MPS (ha)	19.89	22.01	18.56
	LPI	7.30	7.41	3.68
Shape index	LSI	15.22	15.08	22.65

4.2. Evolution of Spatial Patterns of Rural Settlements

Between 1980 and 2020, the spatial distribution of rural settlements in She County exhibited a progressive shift towards irregularity and fragmentation. Taking the years 1980, 2000, and 2020 as pivotal instances, the landscape shape index of rural settlements in She County registered values of 15.22, 15.08, and 22.65, respectively. These values indicate a pattern where the landscape shape index of rural settlements initially declined before experiencing an upward trend. Notably, post-2000, there was a noticeable intensification of irregularity in the external configuration of rural settlements. The landscape morphology of rural settlements in She County appeared to reach a turning point around the year 2000. Before 2000, rural settlements displayed a tendency towards spatial regularity. However, from 2000, irregular tendencies became more pronounced, leading to a greater degree of irregularity and fragmentation in the landscape morphology of rural settlements. Moreover, the proportion of the largest contiguous rural settlement patch relative to the total landscape area in She County for 1980, 2000, and 2020 stood at 7.30%, 7.41%, and 3.68%, respectively. This metric underscores the escalated fragmentation of rural settlements post-2000, accompanied by a diminishing area of the largest contiguous patch.

Moreover, from 1980 to 2020, the *NNA* (Nearest Neighbor Analysis) values for rural residential points in She County consistently remained below 1, indicating a tendency towards spatial agglomeration in Table 4. Furthermore, the corresponding *Z*-values for these rural residential points consistently fell below -1.96, underscoring a statistically significant spatial clustering pattern. In addition, the *NNA* (Nearest Antecedent Analysis) values for 1980, 2000, and 2020 exhibited a progressive increase (0.2453, 0.2554, 0.2822). This trend suggests that the degree of spatial aggregation among rural residential points in She County has gradually lessened since 1980.

Table 4. Nearest Neighbor Index (*NNA*) and Clustering Characteristics (*Z*) of Rural Residential Points in She County from 1980 to 2020.

Year	1980	2000	2020
NNA	0.2453	0.2554	0.2822
Z	−264.651071	−271.905351	−306.1088

From 1980 to 2020, the evolution of the spatial pattern of rural residential points in She County can be delineated through four distinct modes: the expansion of preexisting settlements outward (termed individual expansion), the spontaneous amalgamation of smaller and dispersed settlements into larger entities (referred to as agglomeration), the removal of existing rural residential points (characterized as disappearance), and the emergence of new rural residential points (labeled as an addition) (Figure 4). During the period spanning 1980 to 2000, the spatial configuration of rural residential points in She County predominantly exhibited a pattern of overall expansion intertwined with localized disappearance (Figure 4a). This epoch was marked by the expansion of rural settlements largely in an individualistic manner, occasionally accompanied by instances of merging (for example, in Henandian Town). The phenomenon of individual expansion was widely distributed across diverse townships within She County. Between 2000 and 2020, the spatial arrangement of rural residential points underwent a transformation towards heightened occurrences of overall addition and expansion concurrently with instances of localized disappearance (Figure 4b). Freshly established rural residential points were noted to have been dispersed extensively across various townships, with particularly significant instances observed in Pei Town, Shentou Township, and Jingdian Town. Individual cases of expansion were primarily concentrated in Henandian and Mujing Township. However, the disappearance of rural residential points was mainly concentrated in Jingdian Town and Gengle Town, primarily attributed to urban land expansion.

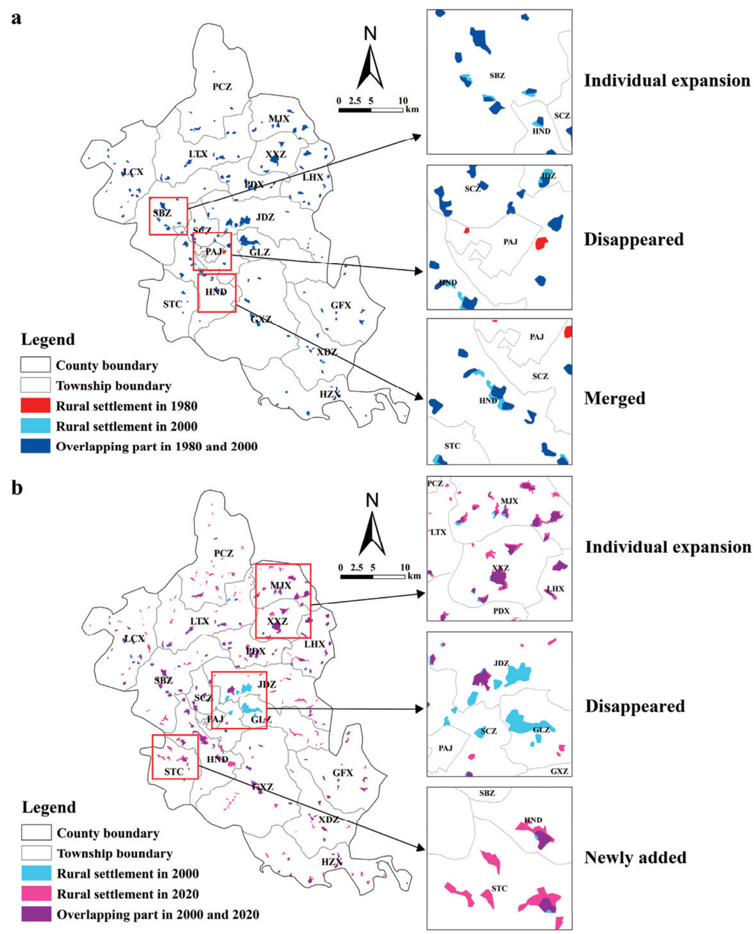

Figure 4. Evolution model of rural settlements in She County from 1980 to 2000 (**a**), and evolution model of rural settlements in She County from 2000 to 2020 (**b**). JDZ stands for Jingdian Town; PCZ stands for partial town; PDX stands for Bidian Township; PAJ stands for Ping An Street; GFC stands for Guanphong Township; MJX stands for Mujing Township; GXZ stands for Guxin Town; GLZ stands for Gengle Town; SBZ stands for Soburg Town; SCZ stands for involved town; LCX represents Liaoning urban and rural areas; STC stands for Shentou Township; XXZ stands for Xixu Town; LTX stands for Lutou Township; HND stands for Henan Branch; HZX stands for Hezhang Township; LHX stands for Longhu Township.

4.3. Simulation of Rural Settlements

4.3.1. Verify the Accuracy of Simulation Results

We conducted a simulation of land use changes in She County from 2005 to 2015 and assessed the accuracy of these simulations by applying the kappa index. The kappa index values for all simulated land types were calculated at 0.929, while for simulating rural residential points, the corresponding kappa index value was computed as 0.879. These values exceeded the threshold of 0.8, demonstrating the capability of the CLUE-S model to generate robust simulation outcomes, thus rendering it suitable for predicting the trajectory of rural residential points in the year 2035.

The results from the ROC test indicated that the fitness of each land class exceeded 0.7, underscoring the robust explanatory capability of the selected driving factors for elucidating land use dynamics in She County. Consequently, these findings can be effectively leveraged to simulate and forecast the probabilistic distribution of future land use patterns and rural residential point allocations within the county.

4.3.2. Evolution Analysis of Rural Settlements under Multi-Scenario Simulation

We have undertaken simulation and projection exercises to assess She County's prospective land utilization scenarios in 2035, considering varying developmental contexts. We have utilized land-use transition matrices (Tables 5–7) to quantify the transitions between distinct land categories during the timeframe spanning 2020 to 2035.

Table 5. Land use transfer matrix from 2020 to 2035 under natural development scenario (km^2).

	Cropland	**Forest Land**	**Grassland**	**Other Construction Land**	**Rural Settlement**	**Urban Land**	**Water Area**	**Area in 2020**
Cropland	373.15	0.56	42.25	0.00	8.08	44.57	2.25	470.87
Forest land	0.39	64.12	12.46	0.00	0.01	1.45	0.25	78.68
Grassland	31.38	9.87	766.85	0.03	3.60	14.74	0.63	827.11
Other construction land	3.68	0.00	4.17	0.00	1.31	3.36	0.16	12.68
Rural settlement	19.09	0.06	1.64	0.00	21.65	1.76	0.51	44.71
Urban land	9.03	0.00	0.39	3.36	12.88	11.60	0.04	37.30
Water area	2.90	0.00	0.58	0.00	0.15	0.14	21.32	25.09
Area under ND	439.63	74.61	828.34	3.39	47.68	77.63	25.17	1496.44

Table 6. Land use transfer matrix from 2020 to 2035 under the new urbanization scenario (km^2).

	Cropland	**Forest Land**	**Grassland**	**Other Construction Land**	**Rural Settlement**	**Urban Land**	**Water Area**	**Area in 2020**
Cropland	127.79	19.75	254.94	1.04	5.43	53.37	8.54	470.87
Forest land	0.03	66.00	12.40	0.00	0.01	0.00	0.24	78.68
Grassland	4.37	11.62	807.33	0.09	0.38	2.68	0.65	827.11
Other construction land	0.51	0.25	8.24	0.10	0.02	3.40	0.16	12.68
Rural settlement	2.62	1.90	13.34	0.12	19.95	5.01	1.78	44.71
Urban land	0.28	0.01	1.89	9.80	4.97	20.31	0.04	37.30
Water area	0.62	0.11	1.62	0.00	0.00	0.78	21.90	25.09
Area under NTU	136.21	99.64	1099.75	11.14	30.82	85.55	33.32	1496.44

Table 7. Land use transfer matrix from 2020 to 2035 under ecological protection scenario (km^2).

	Cropland	**Forest Land**	**Grassland**	**Other Construction Land**	**Rural Settlement**	**Urban Land**	**Water Area**	**Area in 2020**
Cropland	329.94	2.30	74.52	0.00	7.90	52.94	3.27	470.87
Forest land	0.18	66.04	12.04	0.00	0.01	0.16	0.25	78.68
Grassland	23.13	10.51	782.15	0.03	0.83	9.84	0.63	827.11
Other construction land	3.52	0.07	5.35	0.00	1.37	2.20	0.16	12.68
Rural settlement	18.18	0.08	2.46	0.00	21.55	1.79	0.64	44.71
Urban land	7.21	0.00	0.79	2.88	15.77	10.61	0.04	37.30
Water area	2.72	0.02	0.69	0.00	0.08	0.11	21.47	25.09
Area under EP	384.89	79.02	878.00	2.91	47.50	77.65	26.47	1496.44

Within the framework of the natural development scenario, it is anticipated that by the year 2035, She County will witness an expansion in the geographical extent of rural residential areas, urban land parcels, and grassland tracts, corresponding to an augmentation of 2.97 square kilometers, 40.33 square kilometers, and 1.23 square kilometers, respectively (Table 5). Simultaneously, there will be a decline in cropland, forest land, and other constructed areas by an estimated 31.24 square kilometers, 4.07 square kilometers, and 9.29 square kilometers, while the expanse of aquatic bodies will remain relatively stable. Delving into the spatial distribution patterns (Figure 5a), the trajectory of rural residential expansion within the natural development scenario will be interwoven with competition for cropland and urban territories. This predictive model posits that approximately 8.08 square kilometers of rural residential domains are poised to metamorphose into cropland, while 12.88 square kilometers are poised for conversion into urban precincts. Conversely, around 19.09 square kilometers of cropland and 1.76 square kilometers of urban zones are projected to undergo a transformation into rural residential zones. The geographic expansion of rural residential locales in She County will be predominantly concentrated within the central region, encompassing locales such as Jingdian and Gele towns. This expansion phenomenon owes its impetus primarily to the encroaching impact of the adjacent urban expanse.

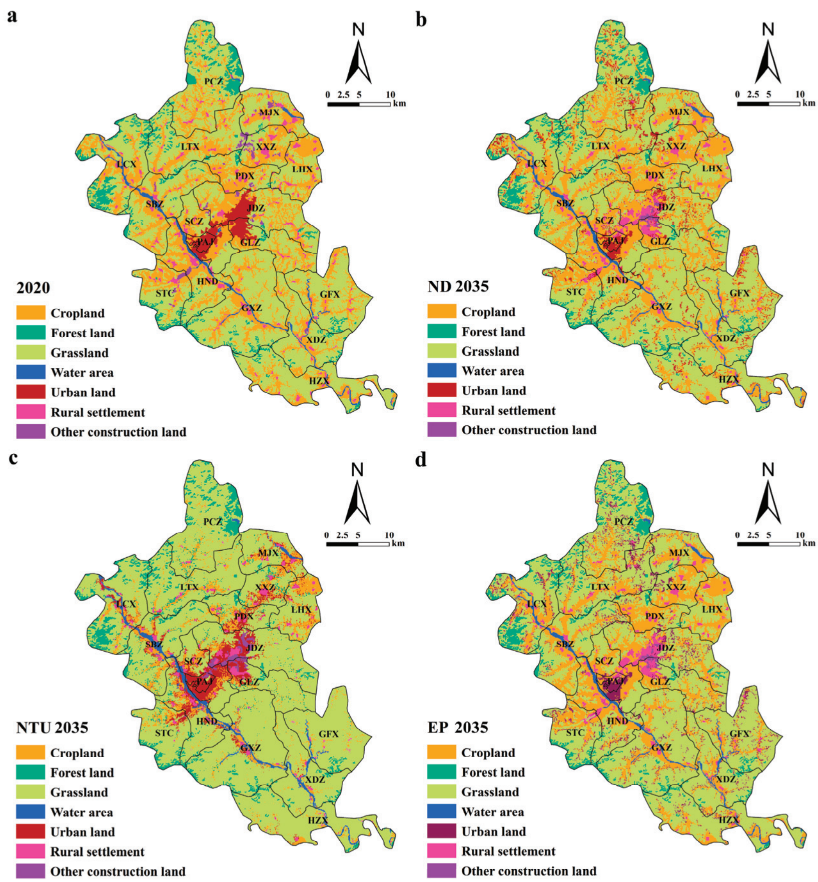

Figure 5. Land use status in 2020 (**a**); Land use simulation in 2035 under natural development scenario (**b**); New urbanization scenario (**c**) and ecological protection scenario (**d**). JDZ stands for Jingdian Town; PCZ stands for partial town; PDX stands for Bidian Township; PAJ stands for Ping An Street; GFC stands for Guanphong Township; MJX stands for Mujing Township; GXZ stands for Guxin Town; GLZ stands for Gengle Town; SBZ stands for Soburg Town; SCZ stands for involved town; LCX represents Liaoning urban and rural areas; STC stands for Shentou Township; XXZ stands for Xixu Town; LTX stands for Lutou Township; HND stands for Henan Branch; HZX stands for Hezhang Township; LHX stands for Longhu Township.

Within the context of the new-type urbanization development scenario, it is envisaged that by the year 2035, She County will experience a reduction in the expanse of rural residential zones, other constructed areas, and croplands, amounting to 13.89 square kilometers, 1.54 square kilometers, and 334.66 square kilometers, respectively. In contrast, urban land, forested areas, grasslands, and aquatic bodies are poised to expand, encompassing 48.25 square kilometers, 20.96 square kilometers, 272.64 square kilometers, and 8.23 square kilometers, respectively (Table 6). Scrutinizing the spatial distribution within the new-type urbanization development scenario framework, the decline in rural residential areas is primarily intertwined with the competition for grasslands, urban land parcels, and croplands. Approximately 13.34 square kilometers of rural residential expanses are anticipated to transition into grasslands, with 5.01 square kilometers earmarked for urban land conversion and 2.62 square kilometers poised for transformation into croplands. Moreover, around 4.97 square kilometers of urban land and 5.43 square kilometers of croplands are predicted to metamorphose into rural residential enclaves (Figure 5c). While the impact of the new-type urbanization policy is notably pronounced within the central zones of She County, such as Shetown, Jingdian, and Gele, leading to a concentrated and contiguous expansion of urban land in these areas, the phenomenon of rural residential expansion within the central region of She County is even more remarkable, engrossing substantial extents of urban territories. Notably, the northern (e.g., Pianzhen) and southern (e.g., Hezhang Township) parts of She County exhibit a conspicuous decline in rural residential locales, primarily transitioning into grasslands.

Under the ecological conservation scenario, it is projected that by the year 2035, She County will witness an expansion in various land use categories, including rural residential areas, forested zones, grasslands, urban land, and aquatic bodies, with increments of 2.79 square kilometers, 0.34 square kilometers, 50.89 square kilometers, 40.3 square kilometers, and 1.38 square kilometers respectively (Table 7). However, this comes alongside a reduction in cropland and other constructed areas, estimated at 85.89 square kilometers and 9.77 square kilometers, respectively. Upon scrutinizing the spatial distribution, the ecological conservation scenario reveals that the expansion of rural residential areas correlates predominantly with the competition for croplands, grasslands, and urban land. Notably, an anticipated 18.18 square kilometers of rural residential regions are poised for conversion into croplands, with an additional 2.46 square kilometers earmarked for the transformation into grasslands and 1.79 square kilometers designated for urban land transition. Simultaneously, approximately 7.9 square kilometers of cropland and 15.77 square kilometers of urban land are foreseen to be repurposed into rural residential zones (Figure 5d). This scenario accentuates the pronounced expansion of rural residential areas within pivotal central regions of She County, such as Jingdian and Gele, which, in turn, absorb substantial portions of urban territories.

4.3.3. Analysis of Rural Residential Spatial Pattern Evolution Trends

We will juxtapose the simulated outcomes against the spatial distribution of rural residential zones in 2020 (Figure 6) to ascertain the evolutionary trajectories of rural residential spatial patterns across distinct developmental scenarios.

Within the ambit of the natural development scenario (Figure 6a), the morphological dynamics of rural residential areas in She County exhibit a binary scheme: accretion and attrition. Throughout this epoch, the central precincts of She County (encompassing Jingdian Town, Gele Town, Shecheng Town, and Ping'an Street) experienced marked augmentations in rural residential domains, largely predicated on the repurposing of preexisting urban tracts. Simultaneously, rural residential areas undergo cessation across multiple townships within She County.

Conversely, under the purview of the new-type urbanization scenario (Figure 6b), an overarching descent tendency characterizes rural residential acreages in She County, interspersed with localized augmentations. The diminution of rural residential domains permeates across diverse townships, while emergent additions are concentrated proximate to the urban precincts of Jingdian Town and Gele Town. Within this framework, She County's rural residential expanses predominantly coalesce along the banks of the Clear Zhang River.

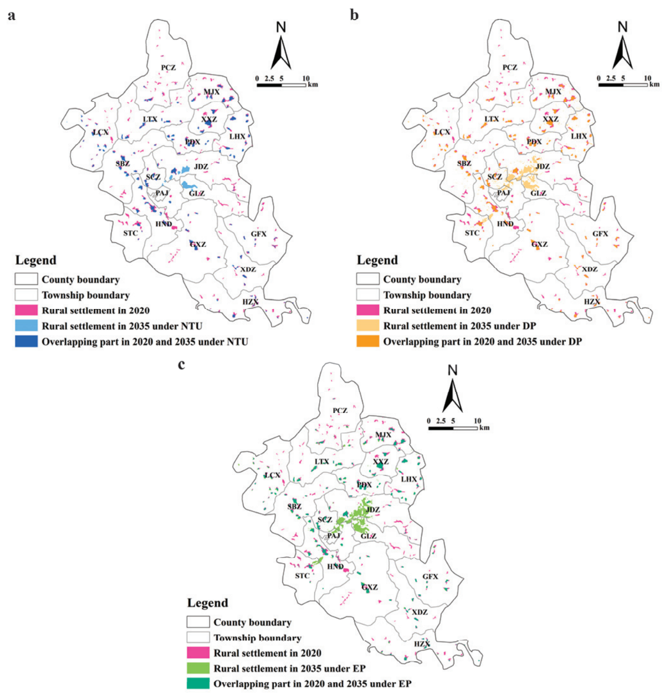

Figure 6. Rural areas in 2035 under natural development scenario (**a**), new urbanization scenario (**b**) and ecological protection scenario (**c**). JDZ stands for Jingdian Town; PCZ stands for partial town; PDX stands for Bidian Township; PAJ stands for Ping An Street; GFC stands for Guanphong Township; MJX stands for Mujing Township; GXZ stands for Guxin Town; GLZ stands for Gengle Town; SBZ stands for Soburg Town; SCZ stands for involved town; LCX represents Liaoning urban and rural areas; STC stands for Shentou Township; XXZ stands for Xixu Town; LTX stands for Lutou Township; HND stands for Henan Branch; HZX stands for Hezhang Township; LHX stands for Longhu Township.

In the ecological conservation scenario (Figure 6c), rural settlements' spatial pattern evolution trend follows a similar pattern to that of the new urbanization scenario. However, in the central region of She County County (including Jingdian Town and Gele Town), the phenomenon of new rural settlements is even more pronounced.

5. Discussion

5.1. Analysis of the Driving Forces behind the Spatiotemporal Evolution of Rural Residential Patterns

5.1.1. Analysis of the Driving Forces behind Rural Residential Scale Changes

The spatial dynamics of rural residential settlements in She County are profoundly influenced by policy and institutional factors. Simultaneously, different temporal stages reveal distinct predominant drivers of spatial transformations in these settlements. The enactment of the reform and opening-up policy has catalyzed rapid economic advancement in She County, subsequently inducing significant shifts in the spatial magnitudes of rural residential domains.

The primary propellants steering the expansion of rural residential areas in She County emanate from swift economic growth and the persistent rise in population. During 1980–2000, rural residential settlements in She County experienced a modest overall expansion, albeit with a reduced numerical count. This epoch bore witness to the ascendancy of township enterprises, which significantly bolstered industrial progress within the county.

By 1996, the tally of township enterprises had surged to 11,830, boasting a workforce of 69,000 and a total output valuation of 3.354 billion yuan. Fiscal revenue for the county eclipsed the billion yuan threshold in 1995 [55]. Following the restructuring state-owned enterprises after 1998, the private sector emerged as a vibrant growth engine [55].

Consequently, since the 1990s, the proliferation of employment avenues in townships, augmented earnings for farmers, and the subsequent metamorphosis of rudimentary abodes into capacious brick-and-mortar structures have propelled the magnification of rural residential settlements. However, industrial advancement also encroached upon select settlements, prompting migration, dissolution, or amalgamation of certain rural residential domains. From 2000 to 2020, rural residential settlements in She County demonstrated a tendency toward clustered expansion in scale and quantity. In the post-2000 era, improved living conditions for farmers resulted in a surge of brick-and-concrete constructions, coupled with a shift from one-story dwellings to multi-story edifices. Affluent households undertook the expansion of existing settlements and even embarked on constructing villas. This phenomenon propelled the ceaseless expansion and sprawl of rural residential precincts. By 2012, She County's Gross Domestic Product had reached 24.846 billion yuan, with total social fixed asset investment reaching 1.143 billion yuan and fiscal revenue amounting to 2.041 billion yuan [55]. The swift economic progress substantially elevated farmers' living standards, fostering material aspirations, and accelerating the acquisition and construction of residential properties.

5.1.2. Analysis of the Driving Forces behind the Spatial Pattern Evolution of Rural Residential Settlements

The period from 1980 to 2000 witnessed a distinctive spatial transformation in the rural residential settlements of She County. During this period, the distribution pattern of these settlements displayed a trend towards stochastic dispersion, gradually transitioning towards a more ordered arrangement. This spatial phenomenon can be attributed to two prominent factors that exerted significant influence. Foremost among these factors is She County's endowed resource abundance. Rural inhabitants historically settled along the picturesque banks of the Qingzhang River, seamlessly integrating their way of life with the watercourse and arable lands. This settlement pattern predominantly clustered along the north-south axis of the river, mirroring its natural flow. Throughout this phase, the expansion of rural residential areas remained largely confined within their existing boundaries, avoiding uncontrolled sprawl encroaching upon cultivable terrain.

Furthermore, the county's southwestern and northeastern zones boasted fertile cropland, creating an environment conducive to rural habitation. However, due to the limited extent of plains, the augmentation of these settlements occurred in measured increments. By contrast, the northwest and southeast regions, characterized by sprawling wetlands and verdant forests, featured topographic undulations unsuitable for prolonged rural settlement. Consequently, these areas exhibited restrained expansion and minimal establishment of new rural residential locales.

However, after the year 2000, She County proactively embarked on the development of new urban areas, giving rise to a frequent occurrence of rural settlement construction in the suburban zones of the new city [56]. Commencing in 2004, concomitant with the impetus of poverty alleviation initiatives and the robust advancement of socialist rural reconstruction, the trajectory of rural residential settlements assumed an accelerated trajectory. Of seminal significance, the year 2009 marked the inauguration of the formulation of the "She County Urban Actual Control Zone Construction Plan", an administrative imperative that instigated a consequential augmentation in the tally of administrative villages, transitioning from 30 to 44 [56]. This administrative pivot, in tandem with the proactive deployment of the Beijing-Tianjin-Hebei coordinated development framework, culminated in the continual elevation of vital transport corridors, including the Taihang Mountain Expressway segment within She County, the Wangjinzhuang connector of the Taihang Mountain Expressway in Handan, and the G234 National Highway segment (formerly known as the Ping She Road) in She County. This infrastructural impetus engendered a heightened interplay of human mobility across regions, thus facilitating the burgeoning proliferation of rural residential settlements [56].

Furthermore, She County orchestrated a sustained ascent along the trajectory of the "Taihang Red River Valley High-Quality Tourism Economic Belt" in its western expanse, propelling the dynamic vitality of the tourism sector. Paradoxically, the ascendancy of tourism-driven enterprises, notably the profusion of agritourism ventures, inadvertently wrought perturbations upon the extant structural tapestry of rural areas. As this burgeoning trend unfolds, a discernible elevation of the fragmentation phenomena manifests, rendering the rural residential settlement milieu increasingly ensnared within the intricate weave of emergent developments.

5.2. Reasons for the Evolution of Spatial Pattern of Rural Settlements under Different Scenarios

In the natural development scenario context, the shifts in land use patterns within She County and the evolving spatial configurations of rural settlements echo patterns akin to those observed during the 2005–2015 timeframe. This alludes to the ongoing urbanization thrust within the rural settlements surrounding urban peripheries, progressively metamorphosing them into urbanized land parcels. However, this trajectory is concomitant with a set of consequential trends and intricacies. With the elevation of residents' living standards, an escalating aspiration for more capacious and comfortable residential environs among rural denizens ensues. This, in turn, culminates in the proliferation of new rural settlements upon arable lands, meticulously crafted to cater to the burgeoning housing requisites of the populace. Nonetheless, this trajectory necessitates judicious equilibrium within the context of territorial spatial planning, assiduously safeguarding the integrity of food production and the enduring sustainability of agriculture.

In the context of the new-type urbanization scenario, it is anticipated that the scale of rural settlements in She County will be diminished compared to the natural development scenario, as illustrated in Tables 5 and 6. The development and growth trajectory of She County will be meticulously aligned with the principles and directives of the new-type urbanization policies, as outlined in the 'She County Territorial Spatial Plan 2021–2035'. Positioned as one of China's comprehensive pilot areas for new-type urbanization, She County's strategic location in close proximity to the Beijing-Tianjin-Hebei region, nestled within the heart of the central plains, confers upon it a pivotal role in facilitating synergistic connections between the Beijing-Tianjin-Hebei region and the central plains. This favorable geographic positioning is poised to generate a wealth of employment opportunities, catalyzing rural-to-urban migration in the surrounding regions. Consequently, within the framework of the new-type urbanization scenario, it is plausible that the scale of rural settlements may contract while the allotment of land for urban development and other developmental purposes will expand.

Furthermore, rural settlement land will predominantly witness competition and transformation vis-à-vis grassland, forestland, and urban land uses. This shift is primarily attributable to the objectives delineated in the 'She County Territorial Spatial Plan 2021–2035', which accentuate the attainment of notable progress and environmental aesthetics in constructing characteristic small towns by 2035 [37]. Additionally, the new-type urbanization policy espouses a resolute commitment to a 'people-centered' approach, with arable land acknowledged as a pivotal cornerstone supporting food production. Consequently, under the new-type urbanization scenario, measures will be undertaken to safeguard the integrity of basic farmland, resulting in relatively tempered competition between rural settlements and arable land.

In the ecological conservation scenario, She County's rural settlement scale remains at parity with the natural development scenario, as detailed in Tables 5 and 7. This outcome stems from She County's steadfast commitment to fostering high-quality ecological development and the harmonious coexistence of rural habitats with their surrounding environment. Within this context, there is a paramount focus on amalgamating She County's natural conservation areas, ecologically significant zones, highly vulnerable regions, and ecologically valuable spaces, all systematically encompassed within the purview of the ecological protection redline. Moreover, within the precincts of the ecological protection redline in the study area, the pre-existing scale and extent of rural settlements consistently dwindle and gradually shift. Consequently, heightened competition ensues between rural settlements and arable land, as well as grasslands. This strategic endeavor is grounded in reinforcing ecosystem functionality, ensuring the sustainability and robust development of the ecological environment.

Additionally, it contributes significantly to preserving ecological equilibrium, safeguarding endangered species and natural resources, thereby strengthening the long-term ecological health and sustainable development of rural habitation areas. It is crucial to underscore that within the ecological conservation scenario, the aspiration to achieve harmonious coexistence between humanity and nature is unwaveringly upheld without compromising residents' living space and quality of life. Consequently, a substantial portion of urban land is transitioned into rural settlements to fulfill these objectives.

5.3. Comparison with Other Studies

The New Urbanization Policy represents a pivotal guiding framework for shaping the future landscape of urban development in China. Within the scope of this research, She County, designated as one of the comprehensive trial areas for China's New Urbanization Initiative, serves as an illustrative case study, epitomizing the dynamics of rural settlement spatial pattern evolution within the context of the New Urbanization paradigm [36]. Furthermore, this study bears considerable significance as it transcends the examination of rural settlement spatial patterns, delving deeper into the ramifications they entail for future societal, economic, and environmental interplays [57]. Its substantive import lies in its capacity to furnish us with nuanced insights into the plausible trajectories and complexities that lie ahead. By simulating rural settlement evolution under diverse scenarios, we are better poised to formulate strategic land-use plans, safeguard ecological systems, foster sustainable rural progress, and provide policymakers with empirically grounded foundations to navigate an increasingly intricate and unpredictable future [58]. The influence of this research extends far beyond rural domains, resonating profoundly with critical imperatives such as urbanization dynamics, environmental conservation imperatives, food security, and the quest for social equity, thereby furnishing indispensable support for the cultivation of a more sustainable tomorrow.

However, previous simulation studies, despite accounting for the driving factors behind settlement spatial pattern evolution, have regrettably failed to consider the influence of actual spatial policy variables [10,21,52]. As a result, the outcomes produced by these studies may not comprehensively reflect the implications of forthcoming policies, thus introducing a considerable degree of uncertainty. Consequently, we have considered and seamlessly integrated She County's most recent designations of "permanent basic farmland" and "ecological protection redlines" into the New Urbanization and Ecological Conservation scenarios, incorporating them as pivotal constraints within our simulation research. This astute incorporation guarantees the future food security of urban and rural inhabitants within the New Urbanization scenario while safeguarding the integrity of ecological functions and environmental stability within the Ecological Conservation scenario. Therefore, our study bears notable practical significance in guiding the future developmental trajectory of She County.

5.4. Policy Implications

Reasonable planning policies and context-specific planning strategies stand as the foremost determinants shaping the urban-rural development pattern [59]. Historical planning policies often fell short of comprehensively considering regional contexts, resulting in an undue skew of resources towards urban areas and a disregard for the aspirations of rural residents [60]. Hence, governmental authorities should adopt an encompassing perspective, integrating various development models, preempting potential challenges in forthcoming urban-rural development, and devising bespoke development policies suited to each locale [61].

The paradigm of new urbanization policy demands a judicious equilibrium between urban and rural development while orchestrating a harmonious urban-rural layout. It is imperative to underscore that the essence of new urbanization policy extends far beyond a mere pursuit of "urban intensification". To this end, it is paramount to steer urban progress away from the indiscriminate depletion of rural assets and to eschew any compromise that jeopardizes the welfare of agricultural sectors, rural regions, and the farming populace [62]. Anchored within the contours of the new urbanization policy, the demographic landscape of She County is poised for further recalibration. Thus, a sagacious calibration of urban and rural populations is essential, with an appropriate allocation of optimal urban and rural scales tailored to their distinct demographic requirements. A corollary concern centers on ensuring food security as a bedrock of human safety, which mandates vigilant safeguards against urban expansion that impinges upon arable lands.

Meanwhile, vigilance must be maintained over the concomitant challenge of idle arable lands stemming from rural emigration. In a culminating reflection, She County, as a pivotal bridge uniting the urban nexus (Handan) and rural domains, can strategically introduce enterprises uniquely attuned to the tapestry of characteristics across its varied townships. This proactive measure can catalyze rural employment prospects, tempering the inflow of rural denizens into urban settings and stemming the outflux of agrarian communities.

Similarly, the ecological scenario entails a harmonious blend of economic advancement and ecological preservation, effectively striking a balance between human activities and the natural world. This involves a comprehensive approach to planning that considers the intricate interplay of human endeavors, resource management, and environmental safeguarding. Emphasis is placed on safeguarding She County's natural reserves, including the She County Qingta Lake Wetland Park, the provincial-level forest park, and the ecologically sensitive areas flanking the Taihang Mountain Expressway. Within these designated ecological protection zones, a rigorous framework is established to curtail the unchecked expansion of rural settlements. This measure is aimed at preserving the pristine ecological equilibrium of the region. The retention of settlements posing a minimal ecological threat is deemed essential while simultaneously addressing potential risks posed by settlements that could disrupt ecological stability. In cases necessitating relocation, the government will play a proactive role in orchestrating the process, ensuring the seamless transition of affected communities. In this relocation strategy, residents will receive appropriate compensation, safeguarding their well-being and interests during the transition. This concerted effort fortifies the resilience and continuity of the ecological environment and upholds the quality of life for the local populace. By embracing these proactive measures, She County is poised to uphold the integrity of its ecological landscape and ensure the sustainable coexistence of both the natural environment and human settlements.

The future spatial development planning of rural settlements must holistically consider external factors. In recent years, factors such as the COVID-19 pandemic, energy crises, and geopolitical dynamics have introduced severe housing crises and elements of social instability [63]. The COVID-19 pandemic has fundamentally altered people's living and working habits, potentially leading to an increased number of individuals seeking rural resettlement. As a result, planning needs to account for potential population influx and societal service requirements [64]. Energy crises and the trend toward sustainable energy necessitate rural communities to contemplate the accessibility and cost implications of energy supply, advocating for green energy solutions to reduce energy dependence. Factors related to geopolitical stability necessitate the consideration of the security of food and resource supply chains. To effectively address these challenges, rural area planning can encompass digital infrastructure, support for remote work, healthcare and medical services enhancements, and the promotion of diversified economic development [65]. This approach will ensure that the future spatial development of rural settlements exhibits greater resilience and adaptability to the ever-changing external environment.

6. Conclusions

Between 1980 and 2020, the scale of rural settlements in She County exhibited a continuous expansion. During the timeframe spanning 1980 to 2000, She County's rural settlement dimensions exhibited a comparatively subdued expansion, evidenced by a cumulative augmentation in patch surface area amounting to 255.21 hectares; subsequently, from 2000 to 2020, the scale of rural settlements witnessed substantial expansion, with an increase of 1192.68 hectares. Over the entire span from 1980 to 2020, the spatial configuration of rural settlements in She County exhibited an escalating trend toward irregularity and fragmentation. Notably, the pivotal year of 2000 marked a significant turning point, transitioning from an orderly development trajectory to a more chaotic evolution of settlements. This transformation was notably shaped by the advancement of urbanization processes and the notable influence of anthropogenic activities, which substantially shaped the spatial dynamics of rural settlements.

In light of this context, three distinct scenarios—natural development, new urbanization, and ecological conservation—have been formulated to simulate and forecast potential trends in rural settlement dynamics under diverse policy interventions. The principal aim of these scenarios is to offer practical recommendations and strategies for governmental authorities and urban planners, with the overarching goal of fostering rational land planning and utilization practices. These endeavors are poised to contribute to environmental preservation and the safeguarding of ecological systems and to creating healthier and more habitable human habitats. In the forthcoming years, through optimising land utilization practices and harmonising human developmental demands with ecological preservation imperatives, the profound impact of these efforts is anticipated to resonate in alignment with global sustainable development goals.

Author Contributions: S.S.: Methodology, Software, Data curation, Writing—original draft; H.L.: Conceptualization, funding acquisition; Writing—review & editing; S.S.: investigation, validation; H.L.: proofreading. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Study on the pattern evolution and regulation of rural residential areas for new urbanization (Grant No. 41671177).

Data Availability Statement: The majority of the datasets used in this study are publicly available and can be accessed through public repositories. All used data repositories are cited either in the main text. Land use Data, DEM data, water area data, GDP data and road data come from the Resource and Environment Science and Data Center (https://www.resdc.cn/ accessed on 20 May 2023). This website allows real-name applications. Population density data from wordpop (https://hub.worldpop.org/geodata/summary?id=39778). This website allows open access. Highway data from NASA (https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1). This website allows open access. Night light data from Global Change Data Warehousing electronic journal (English and Chinese) (https://doi.org/10.3974/geodb.2022.06.01.V1). This website allows open access.

Conflicts of Interest: The authors declare no conflict of interest.

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Identify Optimization Type of Rural Settlements Based on "Production–Living–Ecological" Functions and Vitality: A Case Study of a Town in Northern China

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Abstract: Rural settlements are developing in the direction of functional diversification, driven by rapid urbanization, but also leading to a decline in their vitality as a result of the rapid concentration of rural population in cities. Therefore, this study proposed a theoretical framework to refine the optimization approach for rural settlements from the perspective of "production–living–ecological" functions (PLEF) and vitality. Taking a town in the farming–pastoral ecotone in northern China as a case, we evaluated the level of the PLEF of rural settlements. After exploring the functional requirements of villagers, we revealed the vitality of rural settlements based on social network analysis. The Tapio decoupling model was used to identify the optimization type of rural settlements considering the PLEF and vitality. The results showed that the PLEF of rural settlements was higher in areas with flat terrain, convenient transportation, and rich economies. Rural settlements closer to the central town were stronger in vitality. The PLEF of rural settlements was generally correlated with vitality, which means that rural settlements with a higher level of PLEF also had a stronger vitality. Rural settlements were classified into five types: suburban integration, characteristics protection, agglomeration and upgrading, general survival, relocation, and merger, according to the characteristics of a combination of PLEF and vitality. This study contributes to a deeper comprehension of the functional and structural characteristics of rural settlements and will be beneficial in guiding rural spatial reconstruction.

Keywords: rural settlements; "production–living–ecological" functions; vitality; the farming–pastoral ecotone; Tapio decoupling model

Citation: Zou, Y.; Yi, C.; Rao, Y.; Luo, F.; Lv, C.; Wu, P. Identify Optimization Type of Rural Settlements Based on "Production–Living–Ecological" Functions and Vitality: A Case Study of a Town in Northern China. *Land* **2023**, *12*, 1905. https://doi.org/10.3390/land12101905

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 22 September 2023
Revised: 7 October 2023
Accepted: 9 October 2023
Published: 10 October 2023

1. Introduction

Rural settlements are essential carriers of the "production–living–ecological" spaces in the countryside, which provide villagers with the requirements of agricultural production, living services, ecological conservation, and other functions [1]. Urban and rural constructing land has continued to encroach on rural arable land, woodland, and grassland as a result of the rapid urbanization process [2]. This has limited production space, fragmented living space, and unbalanced ecological space in rural areas. Furthermore, the substantial outmigration of young laborers to urban centers has resulted in the hollowing out and getting older of rural areas [3]. This rural decay, characterized by rural depopulation, cultural dissipation, and ecological degradation, is a global problem. In response to the phenomenon of rural decline, various nations have embraced distinct strategies to revitalize the countryside, such as Liaison Entre Actions de Développement de l'Economie Rurale (LEADER) in the European Union, the One Village One Product (OVOP) Movement in Japan, the Saemaeul Movement in South Korea, the Rural–Urban Integration in the

United States, and Rural Revitalization in China [4–6]. The function of the countryside has gradually diversified from the basic agricultural production function to industrial production, livelihood security, ecological tourism, and other functions under the dual impetus of urbanization and rural revitalization [7]. As a result, the countryside finds itself amidst a rapid and dynamic phase of change.

Function is one of the attributes of rural space, and its change and evolution are essential characteristics of the rural land use pattern [8]. The traditional agricultural production function has been gradually degraded because of the non-cultivation of arable land and the non-farming of the population [9]. The pursuit of material and spiritual requirements of people has led to the growing prominence of rural living and ecological functions. The complex relationship among rural production, living, and ecological functions, which mutually reinforce and constrain, has a significant impact on the development and evolution of rural space [10]. Rural settlements, as an integral part of rural areas, have a "domino effect" in the process of countryside transformation and development in that they are an essential source of countryside development [11]. Throughout the course of rural transformation, the size, structure, and layout of rural settlements have changed dramatically [12]. The challenges are gaining greater prominence, which includes the scattered layout of settlements and the disorganized structure of production, living, and ecological land [13]. The countries have adopted different measures to optimize the land use layout of rural settlements in order to improve the level of PLEF. For example, in the Saemaeul Movement, the South Korean government improved the living quality of villagers by reorganizing the rural living environment [14]. In the OVOP Movement, the Japanese government enhanced the overall function of the countryside by fully utilizing local advantages [15]. And in 2012, the Chinese government initially proposed the goal of optimizing national land planning, which is to build an intensive and efficient production space, a livable and moderate living space, and a clear and beautiful ecological space. With its policy of revitalizing the countryside, the Chinese government has emphasized building a beautiful and harmonious countryside that is desirable to live and work in. This puts forward new requirements for the production, living, and ecological land use pattern of rural settlements in the new era. However, different rural settlements do not have a uniform demand for productive and ecological land due to differences in resources, culture and society. Therefore, clarifying the positioning of rural settlements and identifying the optimization type of rural settlements is an important means of realizing the comprehensive coordination and enhancement of "production–living–ecological" functions (PLEF) of settlements.

Identifying the optimization type of rural settlements is a crucial project for the spatial reconstruction of the countryside, as well as an important way of judging the current development condition and future development trends of rural settlements [16]. This approach serves as a potent remedy to counter rural decay, playing a pivotal role in integrating land resource elements, improving rural habitat, and fostering rural economic growth [17]. In the early twentieth century, French scholars such as Paul Vidal de la Blache and Jean Brunhes explored the types of rural settlements in terms of natural conditions and local geography [18]. They used historical methods to study the types of rural settlements, including fieldwork, comparative analysis, and systematic analysis. Subsequently, Albert Demangeon researched the forms of rural settlements in France and classified villages into four types: long, block, star, and scattered [19]. Scholars have devoted substantial research to identifying the optimization type of rural settlements. The majority of the literature evaluates rural settlements and classifies optimization types from the perspective of single factors, such as population density, location conditions, economic level, cultivation radius, and willingness of farmers [20–23]. Alternatively, scholars construct an evaluation index system from the perspective of multiple factors as a way of identifying the optimization type of settlements, such as PLEF, residential suitability, security resilience, and comprehensive influence [24–27]. Generalized matrix models, coupled coordination models, decoupled models, mutually exclusive combinatorial matrices, and hierarchical analysis are used in identification studies [28,29]. It is noteworthy that the intricate diversity and complexity exhibited by rural settlements impose limitations on the efficacy of classifying them through a single factor. Such an approach fails to facilitate a comprehensive grasp of their intricate form and underlying structural characteristics. The trend of settlement development is characterized by diversification of production functions, humanization of living functions, and rigidity of ecological functions [30]. Presently, both government and scholars are directing their focus toward evaluating rural settlements through the perspective of PLEF. PLEFs are the product of the interaction between the spatial environment and spatial elements. Scholars mostly evaluate rural settlements in terms of overall level, coupling degree, and coordination degree by utilizing the concept of PLEF [31–33]. However, current research commonly analyzes the PLEF of rural settlements by taking settlement patches or administrative villages as the evaluation unit. The natural village area is rarely considered as the evaluation unit. It also ignores the functional requirements of villagers as the main body, which lacks the combination of vitality to identify the optimization type of rural settlements.

The rural territorial system encompasses a geographical framework with distinct structures, functions, and interregional connections influenced by factors such as population mobility, resource endowment, and ecological environment [34,35]. Within this framework, the natural village area, comprising the settlement and surrounding land types, forms the fundamental component. The PLEF of rural settlements is cultivated through an ongoing process of adjustments in response to the available territorial resources and ecological environment of the natural village area [36]. PLEF serves as the cornerstone for meeting the material and societal needs of local inhabitants. Therefore, we evaluate the PLEF of rural settlements considering all the land within the natural village area. Regional variations, however, have led to rural settlements that vary in natural environments and resource endowment conditions [37]. Rural settlements characterized by infertile land, limited resources, and degraded ecological environments tend to exhibit low levels of PLEF [38]. Consequently, these circumstances render the sustenance of essential daily production and living standards challenging for the local villagers. In this case, villagers may seek to satisfy their specific requirements by traveling to adjacent settlements, guided by individual preferences and level of PLEF. To purchase daily necessities, for example, villagers travel to rural settlements with established living conditions, which reflects the phenomena of population mobility. This phenomenon can be construed as rural settlements catering to the functional requirements of non-local villagers. This research describes it as the vitality of rural settlements [39]. The attractiveness of settlements in the region where they are situated, which can satisfy villagers' multiple functional requirements, is denominated as vitality. It includes the attractiveness of the production function, the attractiveness of the living function, and the attractiveness of the ecological function [40]. Currently, the evaluation of PLEF is usually classified on the basis of the settlement's own conditions. It seldom considers the status and role of settlements in the region as a whole. As early as 2007, Woods proposed that the rural territory is a system of multiple settlements with intricate and dynamic rural networks, connecting rural to rural and rural to urban [41,42]. The vitality can reflect the influence of residential areas in the rural network system. Furthermore, the spatial travel behavior exhibited by villagers can be perceived as indicative manifestations of population mobility [43]. The functional requirements of villagers are quantitatively examined to indicate the vitality of settlements in the rural social network based on the spatial travel behavior of villagers. Therefore, this study evaluates rural settlements from the perspective of PLEF and vitality, which can assist the identification of the optimization type of rural settlements.

The farming–pastoral ecotone of Northern China is one of the four major farming–pastoral ecotones in the world. It is predominantly located in a transitional area characterized by dry and semi-arid climatic conditions, with a primary focus on the Inner Mongolia Autonomous Region [44]. This area serves as an important ecological defensive line in northern China, providing wind shelter and sand consolidation while also restricting desertification progress eastward and southward [45]. The biological environment in this region is sensitive and fragile, prone to changes in land use, and plagued by substantial population loss and rural hollowing-out issues.

Therefore, this study selected a town located within the farming–pastoral ecotone in China as a case study. We aimed to propose a theoretical framework from the perspective of PLEF and vitality to comprehensively understand the optimization path of rural settlements. To achieve this, an evaluation index system for rural settlements was constructed based on PLEF, and the vitality of rural settlements was assessed using social network analysis (SNA). The Tapio decoupling model was applied to identify the optimization types of settlements. The following questions will be addressed in this study: (1) What sort of decoupling relationship exists between PLEF and vitality in rural settlements? (2) How can the PLEF and vitality be used to identify the optimal types of rural settlements? The purpose of this work is to provide a scientific foundation for the implementation of rural revitalization strategies for the farming–pastoral ecotone.

2. Theoretical Framework

The functions of rural settlements are gradually developed in the process of continuously adapting to regional environmental endowments and requirements of local villagers, which reflect the results of the interaction between the natural village area and local villagers [46]. Land use, as the "spatial projection" of economic and social development, is an important tool for recognizing the functional spatial differentiation of rural settlements [47]. The land use types within the natural village area collectively provide for the production, living, and ecological multi-functional requirements of the villagers, including settlement land, arable land, grassland, woodland, and so on [48]. These functions are subject to constant change as the socioeconomic level develops, with some functions fading away while others develop new ones (Figure 1).

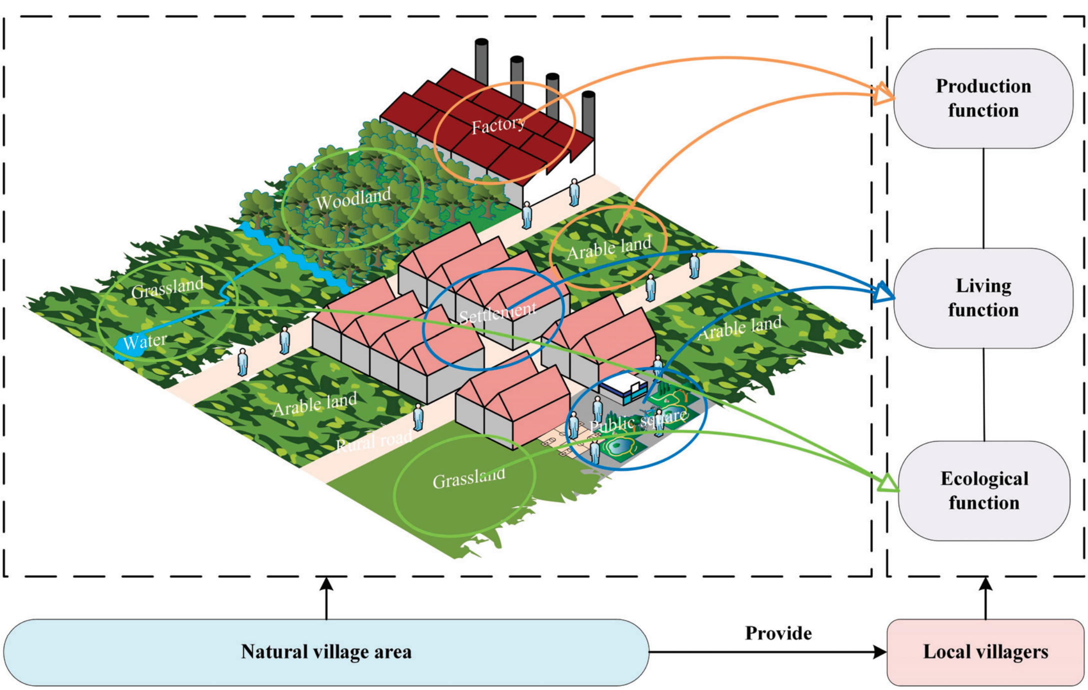

Figure 1. Schematic of the natural village area (note: the figure is drawn by authors).

During the pre-industrialization period, the level of social productivity was low. The land within the natural village areas was not exploited. Rural settlements were carriers of living accommodations for villagers as well as spaces for developing the agricultural production economy [49]. Functions of rural settlements show a naturally dominant and harmonious coexistence, mainly provided by arable land and settlement land within the natural village area [50]. During this period, the total volume of functions of rural settlements was small; the production function was based on agricultural production, the living function was mainly to provide living space for human beings, and the ecological function had not yet been damaged by human activities [51]. At the time of the industrialization period, accompanied by rapid urbanization, the countryside transitioned from a small peasant economic society to a modern industrial society [52]. Land within the natural village area is gradually being replaced by commercial and industrial land. The evolving structure of rural industries has resulted in changes in villagers' modes of production, living, and employment. The continuous transfer of rural labor to the cities has led to the abandonment of huge areas of arable land. The agricultural production function of the countryside has been relatively weakened [53]. Furthermore, with the increased frequency of exchanges and interaction between urban and rural areas, the trend of non-agriculturalization and diversification of rural industries is becoming more and more obvious. The rural areas that are relatively economically developed have spontaneously generated township enterprises while taking over urban industries, and the function of rural industrial production has been significantly enhanced. In the post-industrialization period, ecological problems have been associated with industrial development in the process of urbanization, such as waste of resources, environmental pollution, etc. [54]. Under the guidance of ecological concepts such as green development and sustainable development, the ecological conservation function of the countryside has been increasingly emphasized. People have also become more concerned about their living environment [55]. The government departments have provided villagers with livelihood security functions by improving public service facilities and building leisure and recreational areas. At the same time, the production, living, and ecological activities of each region are guided according to spatial planning and management model innovation [56]. It regulates the development and utilization behaviors of the stakeholders, and the multiple functions of rural areas are becoming increasingly coordinated (Figure 2).

It can be seen that with the development of the social economy, the agricultural production function of rural settlements has been gradually weakened, the living function has been prominent, and the ecological function has been increasingly valued. The PLEF has been running through the evolutionary development of rural settlements. It is an essential perspective for judging the development potential of rural settlements [57]. The level of PLEF of rural settlements varies owing to disparities in location, resource endowment, and development environment [58]. The high level of PLEF implies a rational land-use structure, comprehensive infrastructure, and flourishing industries. In this case, rural settlements cater to a spectrum of functional requirements for villagers, concurrently exhibiting elevated levels of attractiveness and vitality. Conversely, the low level of PLEF implies a single land use structure dominated by residential land use and the lack of industrial land use. And rural settlements are constrained in their capacity to address merely fundamental functional necessities for villagers, resulting in diminished levels of attractiveness and vitality. Hence, this research concludes that an increase in the level of PLEF within rural settlements corresponds to an augmented level of their vitality.

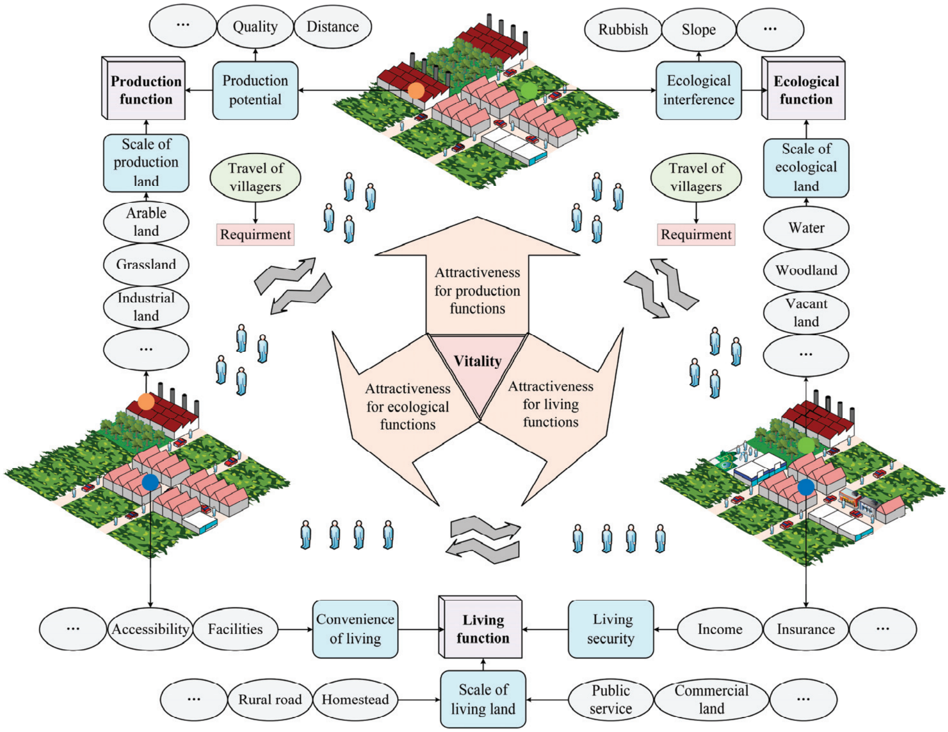

Figure 2. Theoretical framework for PLEF and vitality in rural settlements (note: the figure is drawn by authors).

3. Materials and Methods

3.1. Study Area

Kekeyiligeng Town (Ke Town) is located in the Inner Mongolia Autonomous Region of China and serves as a representative farming–pastoral ecotone (Figure 3). Ke Town has high topography in the north and low topography in the south, with an average altitude of around 1500 m, a temperate continental monsoon climate, with 290~330 mm of annual precipitation. Ke Town was originally a nationwide poverty-stricken area but succeeded in escaping poverty in 2019 with an economy characterized by agriculture and animal husbandry. As of 2019, the rural population of Ke Town amounted to 4883 individuals, reflecting a decline of 7594 individuals compared to 2009. This reduction signifies a decrease of more than 60% within this decade, underscoring the notable diminishment in the vitality of settlement. Water scarcity, sparse vegetation, and poor infrastructure in Ke Town have resulted in low productivity, poor quality of life, and a terrible natural environment in rural settlements, making it impossible to accommodate the requirements of villagers for normal production and living. As a result, an urgent imperative exists to conduct a comprehensive assessment of the present condition of PLEF and the vitality of rural settlements. This research is pivotal for identifying the optimization type that can effectively foster robust and sustainable rural development.

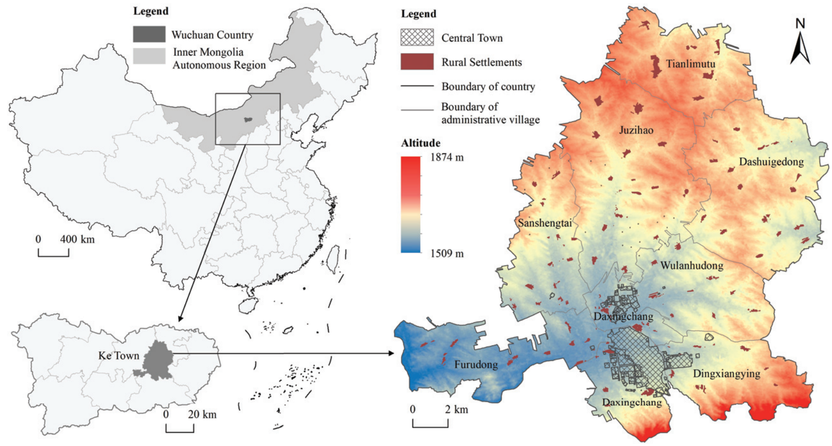

Figure 3. Map of the geographical location of Ke Town (note: the figure is drawn by authors).

3.2. Data Sources

In this study, remote sensing image data were used to delineate natural village areas and slope extraction, including 1 m resolution remote sensing images (https://livingatlas.arcgis.com/wayback/ (accessed on 10 May 2023)) and 30 m resolution DEM (http://www.gscloud.cn/ (accessed on 12 May 2023)). Land use data (the Natural Resources Bureau, Wuchuan, Inner Mongolia Autonomous Region, China) were provided by the Wuchuan Country Natural Resources Bureau. ArcGIS software was used to obtain data on evaluation indicators based on land use data, such as the grassland area index, cropland area index, industrial and mining land area index, accessibility to town centers, and distance from main roads. Socioeconomic data (the Bureau of Statistics, Wuchuan, Inner Mongolia Autonomous Region, China) were collected from the Wuchuan Country Statistical Yearbook, including average annual household income, number of information and communication facilities, number of public service facilities, share of agricultural insurance insured, etc. Field census data were obtained using participatory rural appraisal (PRA), such as quality grade of arable land, rate of new houses built in the last five years, intensity of fertilizer application, residential travel, etc.

Several government documents have been used to identify optimization types of rural settlements, including the National Rural Revitalization Strategic Plan (2018–2022), the Overall Planning of Land Use in Kekeyiligeng Town (2009–2020), the Chinese Traditional Villages List, and the Wuchuan County Traditional Villages List. The National Rural Revitalization Strategic Plan (2018–2022) was proposed in September 2018 by the Chinese government. This is the first planning document that responds to China's rural revitalization strategy. The document makes it clear that rural revitalization will be promoted in categories according to the development status, location conditions, and resource endowments of different villages and in accordance with the ideas of suburban integration, characteristics protection, agglomeration and upgrading, and relocation and merger. The Overall Planning of Land Use in Kekeyiligeng Town (2009–2020) is the land use restructuring, regional land use regulation, and the major tasks of land use formulated by the Ke Town government based on the natural geography and socioeconomic situation. The document established the expansion boundaries for urban construction in Ke Town. The Chinese Traditional Villages List is a list of ancient villages with rich historical information and cultural backgrounds compiled by the Chinese government in 2012, with six batches now published. The villages on this list are national conservation units. The Wuchuan County Traditional Villages List is a county-level list of villages for protection compiled by the Wuchuan County Government. This list of villages has a lower level of protection but covers a wider area.

3.3. Research Idea

Rural settlements are spatial carriers that serve certain functions and connections in rural areas. PLEF represents the comprehensive capacity of rural settlements, whereas vitality characterizes the attractiveness of rural settlements. Both dimensions intricately intertwine, directly impacting and reflecting the socioeconomic progress within rural settlements. Therefore, this study proposed a theoretical framework from the perspective of PLEF and vitality. We took Ke Town of farming–pastoral ecotone as a case study and constructed an evaluation index system of PLEF of rural settlements based on the concept of PLEF. The entropy weight method (EWM) was employed to assign weights to each index to evaluate the level of PLEF in rural settlements. PRA was used to collect data on the spatial travel behavior of villagers, and SNA was used to assess the vitality of rural settlements. The Tapio decoupling model was used to identify the combined characteristics of the PLEF and the vitality of rural settlements. Based on the combined characteristics of both, the optimization type of rural settlements in Ke Town was defined with reference to the National Rural Revitalization Strategic Plan (2018–2022), as well as local plans and other documents (Figure 4).

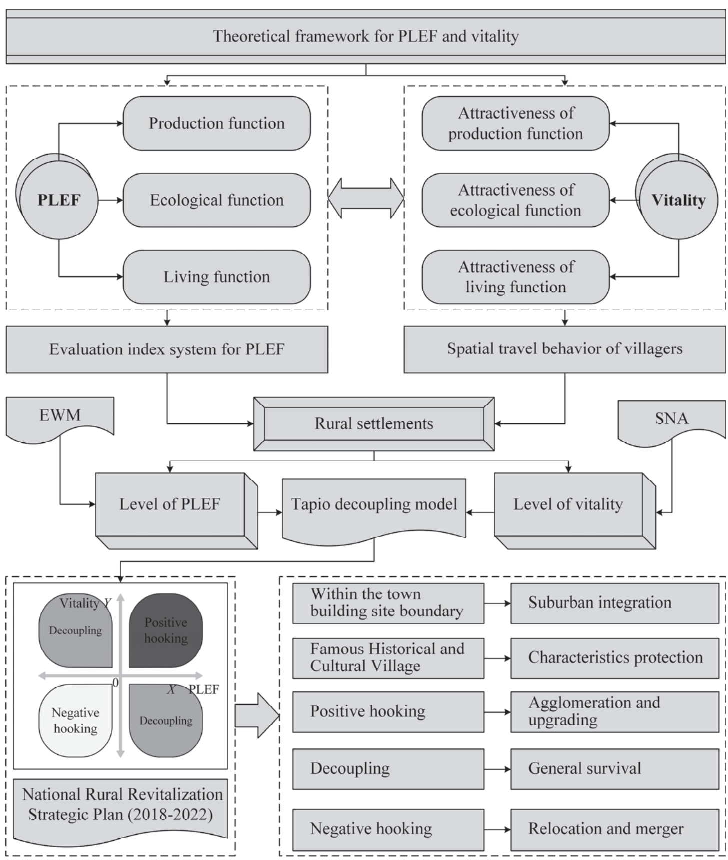

Figure 4. Technology roadmap (note: the figure is drawn by authors).

3.4. Methodology

3.4.1. Participatory Rural Appraisal (PRA)

PRA is a method of gaining information on local realities through informal interviews with villagers [59]. This study mainly used a combination of questionnaires and semi-structured interviews [60]. In the actual survey, we adopted the open-ended questioning method and conducted the interviews according to the survey topic and the survey outline prepared in advance. Moreover, we enabled the surveyed villagers to express their views and wishes on agricultural production, the condition of human habitats, and the relocation of migrants in a harmonious atmosphere.

In August 2019, we conducted a full census of Ke Town. We first visited the village council of each administrative village to obtain basic information about the village to fill out the questionnaire designed in advance. Afterward, we consulted the villagers at their homes and communicated with them face-to-face according to the interview outline to obtain their most realistic ideas. We mainly used this method to obtain data on the indicators in the evaluation index system of PLEF, including the number of information and communication facilities, the number of public service facilities, the average annual household income, the percentage of insured persons in agricultural insurance, the diversity of income sources of villagers, the ecological facilities completeness, the rubbish and wastewater outflow, and the fertilizer application intensity. Furthermore, we obtained data on the spatial travel behavior of villagers during a week through interviews.

3.4.2. Delineation of Natural Village Areas Based on a Remote Sensing Image

The natural village area is developed naturally as a result of the production and living process of villagers. It is the basic unit that provides for the multiple functional requirements of villagers [61]. Hence, this study took the natural village area as the evaluation unit to analyze the PLEF of rural settlements. In the current system of classification of land use status, there is no specific scope of natural village areas. Furthermore, the various types of land within the rural settlements are coarsened into a whole plot. This leads to difficulties in revealing the various land use types and their functions within the natural village area. So, we first need to define the scope of the natural village area. At present, the local villagers have ownership of the land within the natural village area. Conversely, they do not have the ownership of land in other natural village areas [62]. Therefore, we delineated the scope of the natural village area and interpreted the internal land use of rural settlements, which was helped via remote sensing images and PRA.

In Ke Town, rural settlements are characterized by a single mode of production and living and a bad ecological environment. The natural village area is defined by a huge area and a small number of settlements. Arable land and grassland within the natural village area are the main production land for villagers. Residential land and vacant land within settlements are the living land of villagers. All land within the natural village area, including woodlands, grasslands, and rivers, provides ecological space for villagers. The scope of the natural village area includes production land, living land, and ecological land. Mountains, water systems, highways, and other features played a significant role in defining the scope of natural village areas in previous studies. But now that there is a clear ownership relationship among each land, the natural village area can be delimited by acquiring data on ownership of each category through PRA. Therefore, visual interpretation of the geomorphology of Ke Town is performed with the help of remote sensing images. The scope of the natural village area was delineated based on on-site investigation data. Finally, the ArcGIS program was utilized to outline the natural village area with clear land class differentiation using data from the land use change survey (Figures 5 and 6).

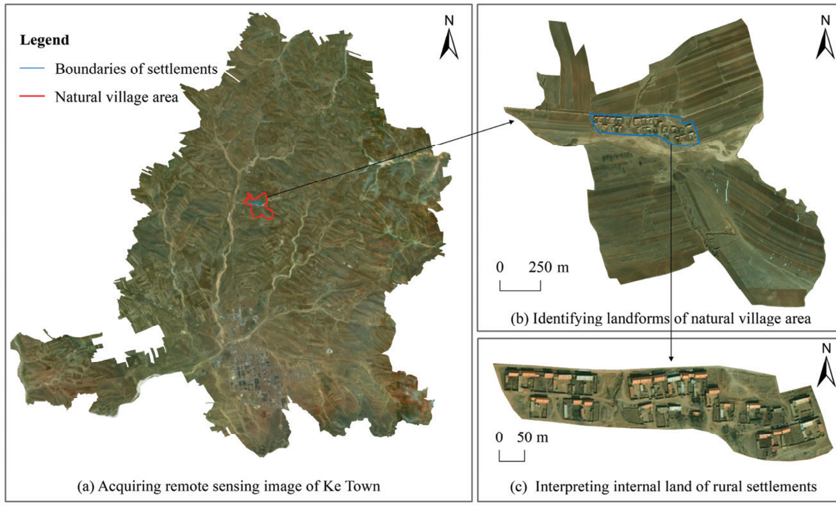

Figure 5. Visual interpretation of land use types (note: the figure is drawn by authors).

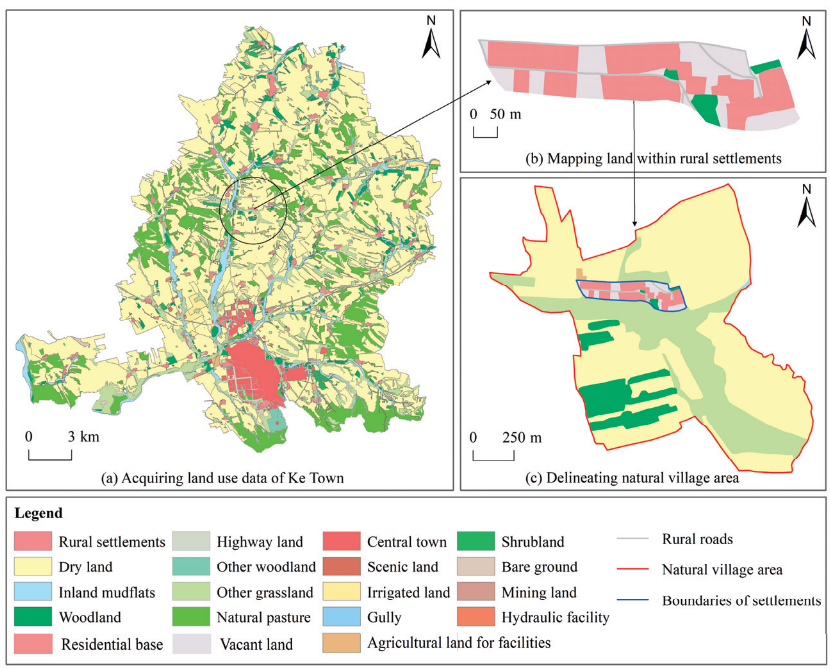

Figure 6. Delineation of Ke Town natural village area (note: the figure is drawn by authors).

3.4.3. Construction of the Evaluation Index System for the PLEF of Rural Settlements

After referring to the existing research results and combining them with the characteristics of the natural villages in Ke Town, this study constructed the evaluation index system of PLEF of rural settlements from three dimensions of the production function, living function, and ecological function [1,13,31,48], as follows (Table 1).

Table 1. Evaluation index system of PLEF of rural settlements (Note: The table is drawn by authors).

Target Layer	Guideline Layer	Indicator Layer	Calculation Instructions	Properties	Weights
Production function	Scale of production land	Area of grassland	Size of grassland in natural village	Positive	0.0145
		Area of arable land	The size of arable land in natural village	Positive	0.0400
		Area of industrial and mining land	The size of industrial and mining land in natural village	Positive	0.0674
	Production potential	Quality grade of arable land	Quality of arable land	Positive	0.0288
		Quality grade of grassland	Quality of grassland	Positive	0.0084
		Distance from mining sites	Distance from rural settlements to mining sites	Negative	0.0756
Living function	Scale of living land	Per capita homestead area	Total homestead area/total population	Positive	0.0290
		Percentage of traffic area	Area of roads/area of settlement	Positive	0.0534
		New housing construction rate in the past five years	New houses in the past five years/total houses of settlement	Positive	0.0289
		Housing utilization rate in the past five years	Houses used in settlements in the past five years/total houses of settlement	Positive	0.0170
	Convenience of living	Accessibility of central town	Distance from central town to settlement	Negative	0.0459
		Distance to main roads	Distance from the main road to settlement	Negative	0.0636
		Number of information and communication facilities	Number of telecommunications, cable TV, and computer within settlement	Positive	0.0249
		Number of public service facilities	Number of clinics, fitness facilities, cultural stations in natural village	Positive	0.0076
	Living security	Average annual household income	Average annual household income of settlement	Positive	0.0257
		Percentage of insured persons in agricultural insurance	Population insured by agricultural insurance/total population of settlement	Positive	0.0313
		Diversity of income sources of villagers	Sources of income of households in settlement	Positive	0.0101
Ecological function	Scale of ecological land	Area of woodland	Area of woodland in natural village	Positive	0.1141
		Area of water	Area of water in natural village	Positive	0.1399
		Ecological facilities completeness	Whether to centralize domestic garbage and wastewater treatment	Positive	0.0412
	Ecological interference	Rubbish and wastewater outflow	Amount of domestic waste and wastewater discharged in settlement	Negative	0.0395
		Fertilizer application intensity	Intensity of fertilizer application	Negative	0.0388
		Slope	Slope of settlement	Negative	0.0544

The production function is the ability of villagers to engage in productive labor to obtain economic benefits and is provided by land for agricultural and livestock production, industrial production, and so on. Ke Town is located in an economically underdeveloped agricultural and pastoral area where traditional agriculture and animal husbandry are still the primary sources of income for farmers and herders, and only a few individuals work in the mining industry. As a result, this study chose two primary guideline layers of the scale of production land and production potential to evaluate the production function of the village area. The scale of productive land reflects the maximum limit of citizens' access to economic benefits, and the degree of grain production is determined by the production potential. Three indicators are included in the productive land scale: the area index of grassland, the area index of arable land, and the area index of industrial and mining land. They reflect the size of the territory available to citizens for agriculture, animal husbandry, and industry, respectively. Three variables are used to determine production potential: the quality grade of arable land, the quality grade of grassland, and the distance from industrial and mining locations. The town is sparsely populated, and agricultural land and pasture are mostly found on the outskirts of the villages. The distance is so close that it is difficult to reflect differences in the production conditions of settlements in terms of distance. However, the quality of farmland and grassland has a direct impact on crop growth and determines the level of product returns. Environmental pollution is present at industrial and mining sites with mining operations. The closer to the settlement, the more polluted it is. The distance can represent the citizens' convenience in engaging in mining operations while also reflecting the pollution level of industrial and mining sites.

Living function is the ability of villagers to live and drink daily and to engage in interpersonal activities. The major living land for villagers is rural roads and house-building amenities. This study chose three guideline layers to evaluate the living function of the village area: the scale of living land, the convenience of living, and the living security. The scale of living land represents the extent of the area in which villagers engage in everyday interpersonal interactions. The higher the scale, the broader the range of activities available to citizens. The degree of convenience for inhabitants to engage in live activities is reflected in their level of living convenience. Living security refers to the ability of villagers to maintain a regular life in the case of a natural disaster. The scale of living land includes four indicators: housing area per capita, percentage of traffic area, new housing construction rate in the past five years, and housing utilization rate in the past five years. The most significant place for the daily life of villagers is residential land. The rate of newly built dwellings in the last five years, as well as the rate of housing utilization in the last five years, show the vitality of settlement. The newer houses created and the greater the rate of house usage, the more dynamic the settlement and the stronger the agglomeration. Accessibility to the central town, distance to important roads, amount of information and communication facilities, and number of public service facilities are all indicators of life convenience. The greater the accessibility of settlements and proximity to the main road, the greater the impact of the central town on settlements and the more convenient it is to carry out social and economic activities. Villagers are in the most contact with information, communication, and public service facilities in their daily lives. The greater the facilities, the more diverse the range of life activities available to inhabitants. The average annual household income, the percentage of insured persons in agricultural insurance, and the diversity of income sources of villagers are all indicators of living security. The more disposable income villagers have, the higher the average annual household income. The lower the proportion of the employed population of settlements, the more significant the problem of aging in the settlement and the worse the prospects for village economic development. Agricultural insurance compensates villagers for natural disasters that occur while they are engaged in agriculture. The more diverse the income sources of farmers, the more secure the economic income of villagers.

The ecological function is the ability to provide villagers with ecological services and maintain ecosystem stability. The principal ecological land is grassland, woodland, and other vegetation. Two primary guideline layers of the scale of ecological land and ecological disturbance were used in this study to evaluate the ecological function. The robustness of a natural village ecosystem's ability to tolerate external damage and govern self-recovery is determined by the ecological land size. The degree of harm to the ecosystems of natural settlements is reflected in ecological disturbance. The scale of ecological land incorporates three indicators: the area index of woodland, the area index of water, and the ecological facilities' completeness. The size of the village ecology is affected by the size of the woodland and water area, and the larger the area, the stronger the stability. The ecological facilities' completeness refers to whether inhabitants centralize residential rubbish and wastewater treatment. Indicators of ecological interference include rubbish and wastewater outflow, fertilizer application intensity, and slope. The rubbish and wastewater outflow are generated by villagers engaged in production and living activities. The more pollution there is in the village environment, the higher the emissions. Fertilizer application intensity is the amount of fertilizer used by inhabitants to produce goods. The greater the amount of fertilizer utilized, the more serious the soil pollution problem. The amount of the slope influences the convenience of villagers' productivity and lifestyle.

3.4.4. Evaluation of the Vitality of Rural Settlements

There are numerous types of travel due to the necessities of daily production and life, such as shopping, visiting relatives, amusement, and so on [63]. Economic, cultural, and social differences in rural settlements influence travel destinations. This constitutes the social network of rural settlements based on the travel behavior of villagers. The breadth and frequency of excursions taken by villagers reflect the spatial linkages that exist among rural settlements [64]. The range denotes the travel destination, and the frequency is the number of travels. The greater the variety and frequency of trips, the stronger the spatial relationship and the more active the rural settlements.

SNA is a means of depicting the morphology, features, and structure of a network as a whole [65]. The node symmetry index is one of them, and it is used to determine the relevance of nodes in a social network. Nodes refer to rural settlements in the social network of rural settlements, while edges connecting nodes correspond to the spatial travel behavior of villagers. According to travel demand, the spatial travel behavior of villagers is classified into six categories: study, work, medical care, socializing, shopping, and tourism. The expert scoring system is used to determine the weight of each type of travel. Using social network analysis, the node symmetry index is utilized to indicate the vitality of rural settlements using the one-week travel data of villagers. The following is the calculating formula:

$$L = \frac{L_{in} - L_{out}}{L_{in} + L_{out}} \quad (1)$$

$$L_{in} = \sum_{i=1}^{n} \frac{w_i \cdot P_a}{P_A} \quad (2)$$

$$L_{out} = \sum_{i=1}^{n} \frac{w_i \cdot P_b}{P_B} \quad (3)$$

where L is the vitality of rural settlements; L_{in} is the vitality of rural settlements visited; L_{out} is the vitality of rural settlement trips; P_a is the number of people visited in a week for the i trip type of rural settlements; P_A is the total number of people visited in a week for all trip types of rural settlements; P_b is the number of trips in a week for the i trip type of rural settlements; P_B is the total number of trips in a week for all trip types of rural settlements; w_i is the weight of i trip type, and i is the trip type.

3.4.5. Tapio Decoupling Model

Decoupling is a physics concept that is used to examine two or more connected states that have interrelationships [66]. The most common decoupling models are the OECD (organization for economic co-operation and development) model, the Tapio model, the IPAT (environmental impact = population × affluence × technology) equation, and so on [67]. The coefficient of variation is used in this study to calculate the correlation index of the PLEF and the vitality of rural settlements. The Tapio model is designed to assess the decoupling relationship between PLEF and vitality. The relative elasticity value is used as the basis for classifying the optimization type of rural settlements, and the model is defined as follows (Table 2):

$$\overline{F} = \frac{\sum_{j=1}^{n} F_j}{n} \quad (4)$$

$$\overline{L} = \frac{\sum_{j=1}^{n} L_j}{n} \tag{5}$$

$$\sigma_F = \sqrt{\frac{\sum_{j=1}^{n} \left(F_j - \overline{F}\right)^2}{n-1}} \tag{6}$$

$$\sigma_L = \sqrt{\frac{\sum_{j=1}^{n} \left(L_j - \overline{L}\right)^2}{n-1}} \tag{7}$$

$$R = \frac{F'_j}{L'_j} = \left(\frac{F_j - \overline{F}}{\sigma_F}\right) / \left(\frac{L_j - \overline{L}}{\sigma_L}\right) \tag{8}$$

where $\overline{F}$ and $\overline{L}$ are the mean value of PLEF and the mean value of vitality of rural settlements, respectively; σ_F and σ_L are the standard deviation of PLEF and vitality of rural settlements, respectively; R represents the relative elasticity value of PLEF and vitality of rural settlements; F'_j is the correction index of PLEF; L'_j is the correction index of vitality.

Table 2. Tapio decoupling model of PLEF and vitality (note: the table is drawn by authors).

Optimization Type	Relative Elasticity Value	Relationship	Attribute	Meaning
Agglomeration and upgrading ($F'_j > 0$ and $L'_j > 0$)	$0 < R \leq 0.8$	$F'_j < L'_j$	Positive hook (strong in L)	Both F and L are at high level, with stronger in L
	$0.8 < R \leq 1.2$	$F'_j \approx L'_j$	Positive hook (strong both $F - L$)	Both F and L are at high level, and both are highly coordinated
	$R > 1.2$	$F'_j > L'_j$	Positive hook (strong in F)	Both F and L are at a high level, with stronger in F
General survival ($F'_j > 0$ or $L'_j > 0$)	$R < 0$	$F'_j > 0 > L'_j$	Decoupling (weak in L)	F is at a high level, L is at a low level
		$L'_j > 0 > F'_j$	Decoupling (weak in F)	L is at a high level, F is at a low level
Relocation and merger ($F'_j < 0$ and $L'_j < 0$)	$0 < R \leq 0.8$	$F'_j > L'_j$	Negative hook (weak in L)	Both F and L are at low level, with weaker in L
	$0.8 < R \leq 1.2$	$F'_j \approx L'_j$	Negative hook (weak both $F - L$)	Both F and L are at the low level, and both are highly coordinated
	$R > 1.2$	$F'_j < L'_j$	Negative hook (weak in F)	Both F and L are at low level, with weaker in F

4. Results

4.1. Evaluation Results of PLEF

The scores of the three key indicators of production, living, and ecological functions are determined using the assessment index system of PLEF of rural settlements. Each dimension is classified into three levels using the natural breakpoint technique, which is as follows (Table 3; Figure 7):

Table 3. Evaluation results of PLEF of rural settlements (note: the table is drawn by authors).

Village	Production Function			Living Function			Ecological Function			PLEF		
	H	M	L	H	M	L	H	M	L	H	M	L
Dashuigedong	0	12	14	1	1	24	5	15	6	3	7	16
Daxingchang	27	4	4	13	21	1	3	9	23	15	20	0
Dingxiangying	0	6	8	4	7	3	5	5	4	4	6	4
Furudong	8	10	2	8	12	0	4	11	5	10	10	0
Juzihao	11	14	5	8	12	10	2	14	14	8	17	5
Sanshengtai	5	9	12	6	11	9	0	9	17	2	17	7
Tianlimutu	4	5	0	1	4	4	3	4	2	4	5	0
Wulanhudong	10	8	2	10	8	2	1	5	14	7	13	0
Total	65	68	47	51	76	53	23	72	85	53	95	32
Total area/hm^2	134.18	268.62	134.72	199.60	178.70	159.23	179.94	235.22	122.35	256.78	220.22	60.52
Average area/hm^2	2.06	3.95	2.87	3.91	2.35	3.00	7.82	3.27	1.44	4.84	2.32	1.89

Figure 7. Evaluation results of PLEF of rural settlements. (**a**) is the result of the evaluation of production function of rural settlements, (**b**) is the result of the evaluation of living function of rural settlements, (**c**) is the result of the evaluation of ecological function of rural settlements, (**d**) is the result of the evaluation of PLEF of rural settlements (note: the figure is drawn by authors).

In terms of production function, there are 65 rural settlements with high-level production functions, with a total patch area of 134.18 hm2 and an average patch area of 2.06 hm2, mainly distributed around the central town. There are 68 rural settlements with medium-level production functions, with a total patch area of 268.62 hm^2 and an average patch area of 3.95 hm^2, and their distribution is relatively decentralized, with distribution in every administrative village. There are 47 rural settlements with low-level production functions, with a total patch area of 134.72 hm^2 and an average patch area of 2.87 hm^2, mainly distributed in Dashuigedong, Sanshengtai, and Dingxiangying villages. It can be seen that the production function of rural settlements in Ke Town is high, and the proportion of low-level production function is low. The production function of settlements gradually decreases with the increase in distance from the central town. The economic development of the central town is relatively good, with perfect infrastructure and richer production systems. As a result, settlements around the center have stronger production functions due to its influence. The settlements that are farther away, such as Dashuigedong Village, have more settlements with low-level production functions.

In terms of living function, there are 51 rural settlements with high-level living functions, with a total patch area of 199.60 hm^2 and an average patch area of 3.91 hm^2, mainly distributed in the southern part of Ke Town and closer to the central town. There are 76 rural settlements with a total area of 178.70 hm^2 and an average patch area of 2.35 hm^2, which are scattered. There are 53 rural settlements with low-level living functions, with a total patch area of 159.23 hm^2 and an average patch area of 3.00 hm^2, mainly distributed in the villages of Dashuigedong, Sanshengtai, and Juzihao. It can be seen that the characteristics of the living function of rural settlements in Ke Town are similar to the production function. The living function is gradually weakened with the increase in distance from the central town. However, unlike the production function, rural settlements with a high level of living function are concentrated in the southern part of Ke Town. This is because the topography of Ke Town is high in the north and low in the south, and the northern part is hilly and mountainous, making it inconvenient for villagers to travel.

In terms of ecological function, there are 23 rural settlements with high-level ecological function, with a total patch area of 179.94 hm^2 and an average patch area of 7.82 hm^2, which are mainly distributed in the villages of Tianlimutu, Juzihao, and Daxingchang. There are 72 rural settlements with medium-level ecological function, with a total patch area of 235.22 hm^2 and an average patch area of 3.27 hm^2, which are more dispersed, with a higher distribution ratio in the villages of Juzihao and Dashuigedong. There are 85 rural settlements with low-level ecological function, with a total patch area of 122.35 hm^2 and an average patch area of 1.44 hm^2, which are mainly distributed in the settlements around the central town, such as Wulanhudong Village and Sanshengtai Village. It can be seen that the ecological environment of rural settlements in Ke Town is poor, with low-level ecological functions accounting for nearly half of the area. Most high-level ecological functions are located in the border zone far from the central town. This indicates that settlements in remote areas suffer less human damage, and the ecological environment is effectively protected. The strength of the ecological functions of settlements decreases with the size of settlements. Larger settlements have more land and can better maintain the stability of the ecological environment.

From the perspective of PLEF, there are 53 rural settlements with high levels of PLEF, with a total patch area of 256.78 hm^2 and an average patch area of 4.84 hm^2, which are mainly distributed in the southern part of Ke Town. At the same time, the proportion of Tianlimutu Village is higher, and the number of settlements in this administrative village is small, but the scale is large. There are 95 rural settlements with medium-level PLEF, with a total patch area of 220.22 hm^2 and an average patch area of 2.32 hm^2, which are widely distributed. There are 32 rural settlements with a low level of PLEF, with a total patch area of 60.52 hm^2 and an average patch area of 1.89 hm^2, mainly distributed in Sanshengtai and Dashuigedong villages. It can be seen that the overall level of PLEF of rural settlements in Ke Town is good. There are few settlements with low levels of PLEF, and nearly 82% of the settlements belong to the intermediate level or above. Most of the rural settlements with low levels of PLEF are located in the border area, which is far away from the central town. In the southern region, where the terrain is flat and close to the central town, the level of PLEF is stronger.

4.2. Vitality of Rural Settlements

We measured the vitality of settlements based on the data on the spatial travel behavior of villagers. Then, the natural breakpoint method was used to classify the vitality of settlements into three levels: I (Low), II (Medium), and III (High), as follows (Table 4; Figure 8).

Table 4. Evaluation results of the vitality of rural settlements (note: the table is drawn by authors).

Village	I		II		III	
	Area/hm^2	Rural Settlements	Area/hm^2	Rural Settlements	Area/hm^2	Rural Settlements
Dashuigedong	54.81	18	30.57	8	0	0
Daxingchang	4.81	5	60.28	22	3.50	8
Dingxiangying	4.88	4	19.94	9	6.93	1
Furudong	17.47	7	26.78	9	8.72	4
Juzihao	26.87	10	49.65	13	34.44	7
Sanshengtai	27.57	9	24.43	15	3.78	2
Tianlimutu	59.62	4	12.83	4	15.02	1
Wulanhudong	4.41	3	34.92	14	5.29	3
Total	200.43	60	259.40	94	77.69	26

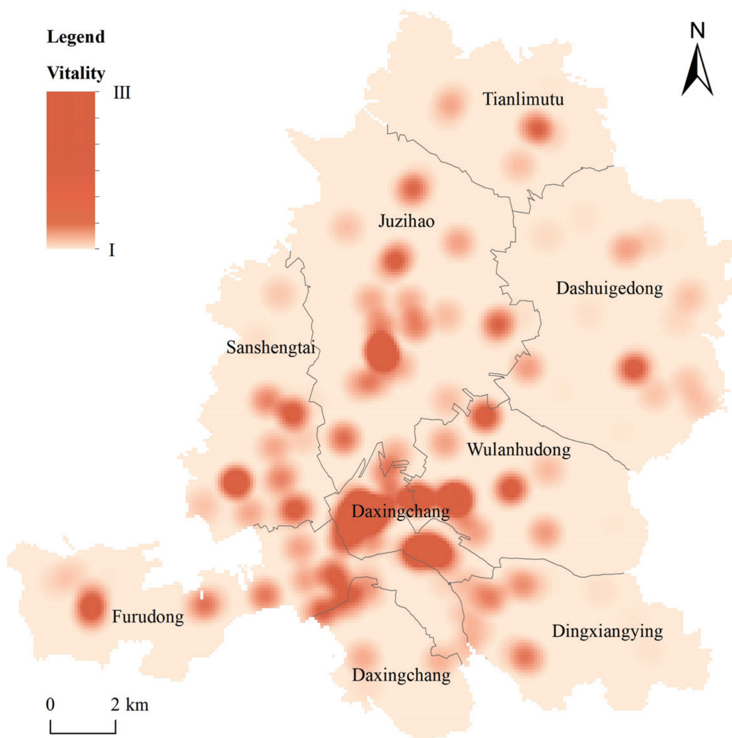

Figure 8. Evaluation results of the vitality of rural settlements (note: the figure is drawn by authors).

The calculation obtained the vitality of rural settlements in Ke Town between 0 and 85, which is categorized into three levels: I level (0~15), II level (16~43), and III level (44~85). There are 60 rural settlements belonging to Grade I vitality, with a total patch area of 200.43 hm^2 and an average patch area of 3.34 hm^2, which are mainly distributed in the villages of

Dashuigedong, Tianlimutu, Sanshengtai, and Dingxiangying. And most of them are far away from the central town in the border zone. There are 94 rural settlements with grade II vitality, with a large number and wide distribution, with a total patch area of 259.40 hm^2 and an average patch area of 2.76 hm^2. There are only 26 rural settlements with grade III vitality, with a total patch area of 77.69 hm^2 and an average patch area of 2.99 hm^2, mainly distributed around the central town. It can be seen that the closer to the central town, the higher the settlement vitality. This is due to the fact that the central town is in areas where social and economic activities are concentrated, with large flows of people and sufficient resources, which can provide villagers with more employment opportunities and is the main place for villagers to interact with each other.

4.3. Decoupling Characteristics of PLEF and Vitality in Rural Settlements

We calculated the modification index of PLEF and the vitality of rural settlements in Ke Town. Then, we explored the characteristics of the decoupling of PLEF and vitality by constructing a Tapio decoupling model, and the results are as follows (Table 5).

Table 5. The decoupling features between PLEF and vitality of rural settlements (note: the table is drawn by authors).

Village	Positive Hooking			Decoupling		Negative Hooking		
	Strong in F	Strong Both	Strong in L	Weak in F	Weak in L	Weak in F	Weak Both	Weak in L
Dashuigedong	0	0	0	5	3	12	2	4
Daxingchang	3	3	10	5	8	3	0	3
Dingxiangying	1	1	1	2	3	4	0	2
Furudong	5	1	3	3	6	0	0	2
Juzihao	4	1	2	7	5	4	6	1
Sanshengtai	1	0	1	6	3	10	1	4
Tianlimutu	0	0	1	0	6	1	0	1
Wulanhudong	5	3	4	3	4	0	0	1
Total	19	9	22	31	38	34	9	18

There are 50 rural settlements in Ke Town with a positive relationship between the PLEF and the vitality. The PLEF and vitality are at a high level, mainly distributed in the villages of Daxingchang, Wulanhudong, and so on. Among them, 19 rural settlements are strong in PLEF, 22 rural settlements are strong in vitality, and 9 rural settlements are as strong as both. The number of the decoupled relationship is 69, and the PLEF and the vitality show the decoupling status of "one high and one low". The distribution of rural settlements in this state is wide, of which the PLEF of rural settlements is weak (31) and vitality is weak (38). The number of negative relationships is 61, with PLEF and vitality levels at a low level, mainly in the villages of Dashuigedong, Sanshengtai, and Juzihao. Among them, 19 rural settlements are weak in PLEF, 22 rural settlements are weak in vitality, and 9 rural settlements are as weak as both. We find that PLEF is correlated with vitality in Ke Town. Daxingchang Village and Wulanhudong Village, which have sufficient resources, are close to the central town and have convenient transportation, are at a high level in terms of the PLEF and vitality. However, Dashuigedong Village, which is resource poor, far away from the central town, and with poor transportation, has a low level of PLEF and vitality.

4.4. Identification of Optimization Type of Rural Settlements

With reference to the document "The National Rural Revitalization Strategic Plan (2018–2022)", the optimization types of rural settlements in Ke Town are determined to be of five types: suburban integration, characteristic protection, agglomeration and upgrading, general survival and relocation, and merger. Firstly, regarding the urban construction land use boundary delineated in the document "The Overall Planning of Land Use in

Kekeyiligeng Town (2009–2020)", the rural settlements within the boundary are categorized as suburban integration type. Secondly, with reference to the "Chinese Traditional Villages List", "Wuchuan County Traditional Villages List", and other documents, the traditional villages with historical and cultural value in Ke Town are classified as characteristic protection types. Finally, we constructed a decoupling model between the PLEF of rural settlements and the vitality. Based on the combination of the two features, the optimization types of rural settlements in Ke Town are identified as agglomeration and upgrading, general survival and relocation, and merger. The details are as follows (Table 6; Figure 9):

(1) Rural settlements (20) are classified into suburban integration types. This type is located around the central town, most of which are distributed in the village of Daxingchang and a few in the villages of Dingxiangying, Furudong, and Wulanhudong. And it has the advantage of becoming the backyard of the central town. This type of rural settlement should be properly prepared for the development of arable land and grassland into industrial and commercial land because the town expands outward. Simultaneously, the integrated growth of urban and rural industries, infrastructure connectivity, and public service sharing must be accelerated. The original rural landscape should be kept in form as much as feasible, and governance should reflect the urban level. Prepare to receive the spillover of urban functions and meet the consumption needs of the town;

(2) Rural settlements (9) are classified into characteristic protection types. This type is distributed in the villages of Dashuigedong, Furudong, Sanshengtai, and Wulanhudong. This type of rural settlement is an important carrier for the manifestation and inheritance of excellent traditional Chinese culture. To construct a complete set of traditional cultural protection systems, it is important to perform a good job of traditional siting of settlements, patterns, natural landscapes and its exquisite scenery of the overall spatial form, and environmental protection. Completely safeguard historical sites, traditional structures, and cultural peculiarities. It also uses its cultural characteristics to strengthen and build infrastructure to facilitate the development of rural tourism and specific industries. Create a traditional rural settlement that integrates rural tourism development with rural protection;

(3) Rural settlements (42) are classified into agglomeration and upgrading types. Rural settlements with a positive relationship between the PLEF and the vitality are classified as this type. This type is distributed in the villages of Daxingchang, Furudong, Juzihao, and Wulanhudong. This type of rural settlement is large in scale, rich in natural resources, and has a good ecological environment and frequent population movement, making it a key area for rural revitalization. The government and citizens must develop village development plans in a scientific and rational manner, capitalize on their own resource advantages, and improve the backing of leading enterprises. They should continue to improve the village's production and living circumstances, optimize the ecological environment, boost population concentration and vitality, and construct a livable, workable, and beautiful village;

(4) Rural settlements (53) are classified into general survival types. Rural settlements with a decoupled relationship between the PLEF and the vitality are categorized as this type. This type is widely distributed in Ke town. This type of rural settlement should continue to maintain its original characteristics, improve the ecological environment, strengthen industrial development, and attract the return of the population. The path of rational function optimization is formulated by identifying the major functions of the settlements. To develop livable and functional villages with industrial benefits and healthy ecology and actively form tight relations with the agglomeration and enhancement type of rural settlements;

(5) Rural settlements (56) are classified into relocation and merger types. Rural settlements with a negative correlation between the PLEF and the vitality are categorized as this type. This type is distributed in the villages of Dashuigedong, Juzihao, Sanshengtai, etc. This type of rural settlement has a poor ecological environment and

backward infrastructure, and the relocation and annexation of the village should be completed as soon as possible. The total relocation and annexation of settlements is carried out under the premise of providing full respect to the citizens' own interests through poverty alleviation relocation, ecological and livable relocation, and rural agglomeration relocation. The original characteristics of relocated settlements should be preserved, and ecological space and ecosystems should be developed and improved in accordance with local conditions.

Table 6. Optimization type of rural settlements (note: the table is drawn by authors).

Village	Suburban Integration	Characteristics Protection	Agglomeration and Upgrading	General Survival	Relocation and Merger
Dashuigedong	0	3	0	7	16
Daxingchang	13	0	12	5	5
Dingxiangying	2	0	3	4	5
Furudong	2	2	8	6	2
Juzihao	0	0	7	12	11
Sanshengtai	0	3	2	7	14
Tianlimutu	0	0	1	6	2
Wulanhudong	3	1	9	6	1
Total	20	9	42	53	56

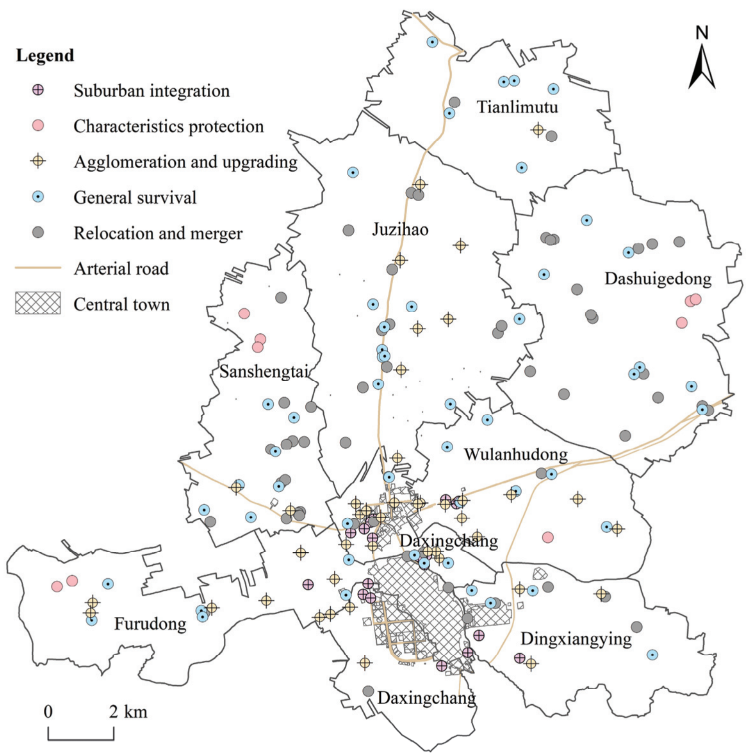

Figure 9. Optimization type of rural settlements (note: the figure is drawn by authors).

5. Discussion

5.1. Relationship between PLEF and Vitality of Rural Settlements

We found that the level of PLEF of rural settlements has significant regional differences in Ke Town. The settlements around the central towns have a higher level of PLEF than the remote mountainous areas [68]. This result is consistent with the results of previous research [69]. Central town emerges as a pivotal nexus that intricately links rural settlements, thereby exerting discernible influence characterized by radiation-driven dynamics and demonstrative leadership within the adjacent areas. These neighboring villages have access to public service facilities such as educational and medical services in the town. At the same time, the scale and proportion of productive land for industry, warehousing, and logistics within the countryside are increasing rapidly, which is influenced by the expansion of land for urban construction. In remote mountainous areas, however, the topography dramatically restricts the productive and living activities of villagers. In addition, the results of the evaluation of vitality showed the same characteristics as the PLEF. The vitality is stronger where rural settlements are located close to towns or transportation routes. This demonstrates that PLEF is associated with vitality in some way.

This study verifies the relationship between PLEF and vitality through the Tapio decoupling model. The improvement of PLEF is beneficial to enhancing the vitality of rural settlements. The settlements adjacent to the central town are distinguished by their intricate network of infrastructure, comprehensive industry, and sophisticated transportation systems, which can satisfy the economic, cultural, social, and ecological requirements of villagers. Most importantly, the whole industrial system provides villagers with substantial employment opportunities and stimulates the vitality of the settlement. The promotion of vitality driven by PLEF is more evident in specialized tourism villages [70]. These regions are rapidly deriving new non-agricultural functions of tourism services, cultural creativity, and commerce, such as regions rich with landscape resources, historical and cultural heritage, and special ecological agricultural resources. An array of specialized tourism villages has emerged featuring leisure agriculture and cultural tourism. The specialized tourism villages adjust the layout of settlements, improve public infrastructure, and complete the deficiency of public services. The rural areas are divided into clearer zones for production, living, and ecological functions. This type of village, driven by rural tourism, attracts masses of villagers for tourism, employment, and living, which stimulates the vitality of the countryside.

5.2. Implications for the Rural Spatial Reconstruction

Rural spatial reconstruction refers to the process of rural transformation and development under the background of urbanization, which is influenced by multiple factors, such as city-driven, self-renewal, and government regulation [71,72]. In this process, different optimization types of rural settlements play various roles [73]. Taking into account the five types of rural settlements classified in this study, we should accurately formulate the respective optimization paths to achieve the enhancement of rural structure and function. The suburban integration type should improve the industrial structure and service functions to promote the development of neighboring settlements. The characteristic protection type should deal with the relationship between the optimization and improvement of rural settlements and the preservation of characteristic culture. Policymakers need to sufficiently develop the existing characteristic industries in the village area and strengthen the level of industrial linkage so as to realize the virtuous circle of village protection, cultural inheritance, and economic development. The agglomeration and upgrading type should be expanded moderately to increase the degree of agglomeration of rural settlements and improve infrastructure construction. The general survival type should further strengthen control and planning of rural land to enhance the efficiency of land use in future development. More importantly, this type needs to ameliorate the problem of hollowing out by integrating rural landscapes and living environments for villagers. The relocation and merger type should formulate a rational relocation program to address the livelihoods of farmers and ecological protection in an integrated manner (Figure 10).

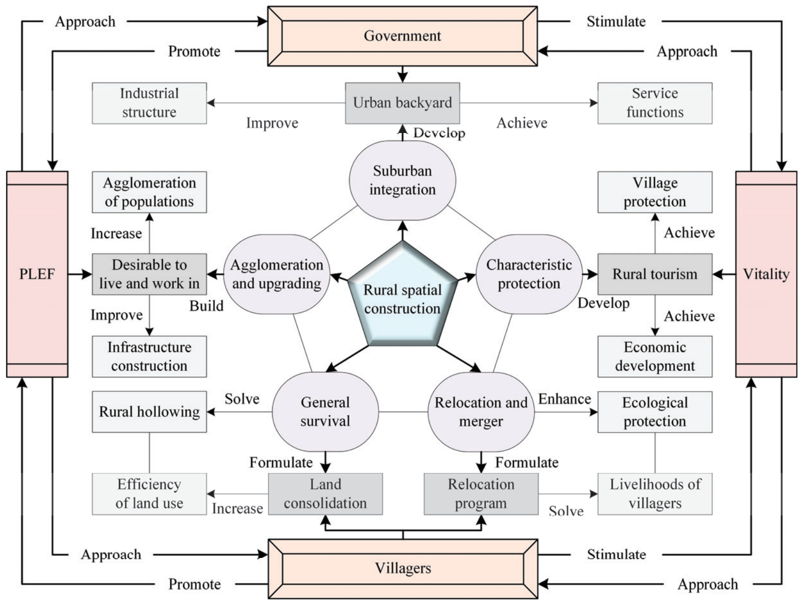

Figure 10. Pathways for rural spatial reconstruction (note: the figure is drawn by authors).

Presently, the majority of rural areas globally contend with inadequate infrastructure and backward industrial development, which leads to population outflows and diminishing vitality [74]. In the practice of rural spatial reconstruction, the government predominantly designs the establishment of new villages configured as singular-function residential districts [75]. However, these strategies often neglect the incorporation of comprehensive planning for rural production land, which has significantly diverged from the functional attributes of settlement production and living. In this context, the government should be directed towards the establishment of villages that embody attributes of livability, functionality, and aesthetic appeal, and utilize village planning as the means to guide the rational layout of land for rural settlements. Also, the government guides the strategic concentration of population, industry, and capital within settlements that stimulate endogenous rural development dynamics. This approach promotes industrial upgrading, facilitates the diversification and interaction of rural resource elements, and realizes the comprehensive enhancement and coordination of production, living, and ecological functions. Consequently, the government takes responsibility for fostering sustainable rural socioeconomic development by bolstering the vitality and attractiveness of rural settlements.

5.3. Limitation and Future Work

The vitality exhibited by rural settlements emanates from apprehensions regarding the potential diminishment of socioeconomic development within rural areas, including demographic attractiveness, land development attractiveness, and industrial development attractiveness [76,77]. This heightened concern has been prompted by the experience of developed nations, where the significance of the agricultural production sector has undergone a decline [78]. In addition, the functional requirements of villagers are also expressed as vitality. The functional requirements of villagers, on the other hand, lead to human-centered socioeconomic activity, namely the spatial travel behavior of villagers. It refers to the social activities carried out by villagers who go to other settlements to satisfy their requirements. These social activities evolve in response to changes in the physical environment, economic development, and technological advancement. Advances in science and technology have engendered transformative shifts in socioeconomic activities, such as shopping, socializing, traveling, and so on. Considering the data obtainability, this research exposes the vitality of rural settlements by investigating the characteristics of villagers' travel behavior inside the rural settlement social network system.

The quantification of the vitality of rural settlements finds its efficacy through the scrutiny of villagers' travel data. However, the extent of influence exerted by towns and other urban centers on rural settlements within their vicinity is not comprehensively addressed. According to Woods' research, the global countryside is a rural realm that consists of rural-to-rural and rural-to-urban connections. The Taobao logistics village, for example, has established close co-operation with other cities and villages around the globe [79]. However, this study only explores inter-rural relationships within regions. Cities and villages form the urban–rural system in the regional environment. The geographic configuration of this urban–rural system is grounded in the interplay of transportation and information networks, thereby engendering the generation of information, population movements, and material flows between urban and rural areas [80]. Cities and villages are intrinsically interconnected, giving rise to the hierarchical urban–rural system encompassing cities, towns, and villages. Within this framework, the central town emerges as a densely populated locale characterized by robust economic advancement and a vibrant cultural milieu. The towns exert a discernible siphoning effect upon rural settlements, and the geographical interaction exists between the two. However, owing to limitations in data collection, this study mainly investigates the spatial interactions among rural settlements. Future research endeavors should delve into the interrelationship between towns and rural settlements to improve the optimization strategy of rural settlements.

6. Conclusions

Identifying the optimization type of rural settlements has evolved into an important approach aimed at augmenting land use efficiency, optimizing spatial layout, and enhancing rural habitat environment, which serve as essential conduits for the sustenance of production and livelihood of villagers. It is part of the preliminary work in the rural reconstruction system. Rural settlements, as intricate amalgamations engendered through the interplay of manifold interactions, have gradually evolved from single functions to composite functions. This transformation is driven by the diversification of land use and the multifaceted requirements of villagers. Therefore, identifying the optimized types of rural settlements requires an accurate judgment of their development trends and current status. This study comprehensively accounted for the development vitality of rural settlements within the rural social network system in conjunction with the functional requirements of villagers. We proposed a theoretical framework from the perspective of PLEF and vitality, which is then employed to identify the optimization type of rural settlements in the northern farming–pastoral ecotone in China. The findings indicated a definite correlation between the PLEF and the vitality exhibited by rural settlements. Central towns emerge as the most densely inhabited zones, fostering heightened mobility, interpersonal engagements, and trade activities. Proximity to these central towns is associated with elevated PLEF levels and amplified vitality within rural settlements. This research augments the comprehension of the spatial relationships among rural settlements and serves as an exploratory tool for policymakers and rural planners to build reasonable and optimal solutions.

The purpose of identifying settlement types is to optimize the allocation of rural people, land, industry, and other aspects. Within the constraints of policies, rural planners must design realistic settlement optimization strategies in terms of function optimization, industry enhancement, and population clustering. This process must, however, duly recognize the inherent requirements of villagers. Policy regulators conduct the reconstruction of rural settlements while addressing the social requirements of villagers and respecting their genuine intentions.

Author Contributions: Conceptualization, methodology, formal analysis, writing—review and editing, Y.Z., P.W. and C.Y.; validation, Y.Z.; funding acquisition, P.W.; investigation, C.Y., Y.R. and F.L.; resources, Y.R.; data curation, F.L.; software, writing—original draft preparation, C.Y.; visualization, supervision, project administration, C.Y. and C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Youth Fund for the General Project of Humanities and Social Sciences of the Ministry of Education of China, grant number 21YJC840028, funded by P.W.; the Fuzhou University Talent Introduction Project, grant number XRC-22026, funded by Y.Z.; the Innovation and Entrepreneurship Training Program for Undergraduates in Fujian Province, grant number S202310386088, funded by F.L.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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Driving Mechanism of Comprehensive Land Consolidation on Urban–Rural Development Elements Integration

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Abstract: Identifying the driving mechanism of comprehensive land consolidation (CLC) on urban–rural development elements integration (URDEI) is of great significance for promoting the coordinated development of urban and rural areas. Based on the composition of urban and rural element systems, this study establishes the theoretical framework of the influence of CLC on URDEI and verifies the framework through empirical cases in Chongqing, China. The results show that (1) CLC promotes URDEI and realizes the rational allocation of urban and rural resources by improving the quality of urban and rural elements and opening up two-way flow channels. (2) The case analysis demonstrates that CLC can improve the quality of rural elements and increase the added value of the flow to the city, which in turn drives urban elements such as talents, technology, and capital to pour into the countryside, therefore forming a realistic path for the URDEI. This study helps understand the role of CLC in the transformation of URDEI and provides a reference for the scientific implementation of land consolidation.

Keywords: comprehensive land consolidation; urban–rural element integration; element flow; driving mechanism

Citation: Zuo, Y.; Yang, C.; Xin, G.; Wu, Y.; Chen, R. Driving Mechanism of Comprehensive Land Consolidation on Urban–Rural Development Elements Integration. *Land* **2023**, *12*, 2037. https://doi.org/10.3390/land12112037

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 1 October 2023
Revised: 27 October 2023
Accepted: 6 November 2023
Published: 9 November 2023

1. Introduction

The imbalance between urban and rural development is a global issue, prevalent in multiple countries and regions, including China, India, Brazil, and Latin America [1,2]. This imbalanced development leads to the widening wealth gap, exacerbates rural poverty, and poses challenges to the sustainable development of societies [3]. Promoting integrated urban–rural development has become a pressing concern in global development that urgently needs to be addressed [4]. China's urbanization has experienced sustained take-off, with its urbanization rate increasing from 17.9% in 1978 to 65.2% in 2022. Although this rapid urbanization has promoted economic and social development, it also brings several problems of uncoordinated urban and rural development [5–7]. On the one hand, rural labor and land resources are flowing into cities in large quantities, which results in a lack of endogenous power for rural development [8]. On the other hand, urban capital and technology cannot flow smoothly to rural areas, leading to a widening gap between urban and rural areas. For example, the proportion of migrant workers in the rural population has increased from 36.09% in 2010 to 56.02% in 2020, resulting in a large amount of abandoned cultivated land and hollow villages. To coordinate urban and rural development, the Chinese government has put forward a series of policies. For example, both the "Opinions of the Central Committee of the Communist Party of China and the State Council on Establishing and Improving the Institutional Mechanism and Policy System for Urban–Rural Integration Development" and the "14th Five-Year Plan for Promoting Agricultural and Rural Modernization" have stressed the importance of promoting the free flow and equal exchange of urban–rural elements and establishing the policy system of equal exchange and the two-way flow of urban–rural elements such as people, land, and money. Therefore, it is urgent to break through the barriers of traditional urban–rural element flow and establish a new development pattern of urban–rural integration [9].

To promote rural development and narrow the gap between urban and rural areas, land consolidation has been recognized as one of the most effective tools [10,11]. Internationally, researchers are also widely concerned with how land consolidation can improve urban planning, affect agricultural production, and promote harmonious community development. For example, modern land consolidation in Western Europe has been shown to improve the agricultural structure by reducing land fragmentation and increasing the scale of agricultural production. In East Asia, land consolidation has been widely used to supplement cultivated land, reduce land fragmentation, and ensure food security [12,13]. However, the effectiveness of land consolidation is also limited by practical conditions such as unclear land tenure, negative environmental impacts on land, and a lack of a land market, which leads to the fact that the effect of solving land use problems and improving agricultural development is not obvious in South Asian countries such as Nepal and Pakistan [14,15]. In this regard, China has adopted a new model of land consolidation, namely CLC. Different from traditional land consolidation, CLC is not a simple superposition of agricultural land consolidation, construction land consolidation, and ecological protection and restoration projects but further optimizes resource allocation between urban and rural areas through the 'Urban–Rural Link' policy. CLC takes rural elements, such as the consolidation object, and optimizes the land space through measures such as agricultural land consolidation, construction land consolidation, ecological protection and restoration, and historical and cultural protection, which is regarded as a platform and tool for the flow and exchange of urban–rural elements [16,17]. Therefore, it is of great theoretical and practical significance to clarify the driving mechanism of CLC on URDEI.

The impact of urban–rural elements integration on urban–rural development can be comprehensively analyzed in terms of promoting rural development and coordinating urban–rural development. Previous studies have paid great attention to coordinated urban–rural development from the perspective of URDEI, and most researchers believe that the connotation of urban–rural integration and development includes the free flow and rational allocation of urban and rural elements. How to break the bottleneck of urban–rural element mismatch is an inevitable choice to reshape the relationship between urban and rural areas in the new era. In this regard, element mismatch under the urban–rural dual structure [18], the current situation and optimization strategy of element flow regions [19], and the mechanism of factor flow on rural revitalization have attracted extensive attention from scholars [20]. Most studies on urban–rural factor integration focus only on the core elements of development, such as "people, land, and industry", and seldom take into account elements such as culture, ecology, and public services. For example, some scholars have explored the impact of the flow of specific elements such as people, goods, and funds on the development of urban–rural integration by establishing the evaluation system of urban–rural integration levels [21,22]. Others have proposed that it is necessary to give full play to the government's macro-control role for the two-way flow of urban and rural elements [23,24] to promote the integration of urban and rural economies, societies, and the environment. Li Qian et al. explored the differences in factor flows of labor, technology, and capital on the convergence of urban–rural integration development, which not only provides a reference for further urban–rural integration projects but also provides theoretical support for guiding the free and orderly flow of elements [21].

Some scholars have pointed out that land consolidation can effectively promote URDEI. Do, M.H and He, Q.S. suggested that farmland consolidation has attracted investment of urban capital, technology, talents, and other elements in agricultural production, and effectively promotes the development of modern agricultural production, using the man-using land fragmentation, the construction of farmland infrastructure, and the improvement in farmland ecological environment governance [25,26]. Liu, Y.S and Long, H.L also revealed that land consolidation measures, such as the 'increase and decrease linkage' of urban and rural construction land, rural land reclamation, and urban renewal, can effectively pull the rational flow and optimal allocation of urban–rural elements [27,28]. In addition, the implementation of 'increase and decrease linkage' of urban and rural construction land can also realize the conversion of rural construction land space into urban construction land space, to alleviate the extensive use of rural construction land space and the tension of urban construction land space.

Although the existing relevant research has laid the theoretical foundation for promoting URDEI, how and to what extent CLC drives URDEI to promote the coordinated development of urban and rural areas remains to be addressed [29]. There are two main challenges in the current state of research. First, the examination of the relationship between these two aspects remains at the qualitative analysis stage of theoretical exploration [30], while in-depth study through the quantitative method remains limited to the enabling role of land consolidation in the integration of urban and rural elements. Second, relevant case studies are scant, and empirical research on the mechanisms at the village and town scale. This may lead to an ineffective resolution of the imbalance between land use and urban–rural development. In addition, the lack of research and planning may increase environmental risks, such as land pollution and ecological degradation. To fill in the research gap, this research focuses on the key elements of urban–rural development, such as land, capital, and labor, and establishes an analytical driving mechanism framework for CLC on the flow and integration of urban–rural elements. This paper employs case studies and comparative analysis methods to investigate the approach to integrating urban–rural factors during the CLC process across the entire region. This will establish a model demonstration for the application of urban–rural integration in similarly mountainous and hilly areas.

2. Composition and Flow Law of Urban and Rural Elements

2.1. Composition of Urban and Rural Elements

Elements are the fundamental units constituting an objective system, and their type and structure significantly influence the system's function. The definition of elements varies across different fields. In economics, elements refer to the essential productive resources for social production and operational activities, encompassing land, capital, labor, information, and technology. Urban–rural elements typically pertain to the primary factors influencing the economic development of urban and rural regions. These factors can be categorized as tangible elements like land, capital, and population, as well as intangible elements such as technology, ecology, and culture [31–33]. With the advancement of the social economy, elements have progressively evolved to include services, information, technology, and other novel value-generating components [33,34]. This study aims to investigate the dynamics of urban–rural elements, considering aspects such as land, population, industry, ecological culture, technology, and public services. Considering that there are differences in the expression and connotation of the same element between the urban areas and rural areas under the urban–rural dual structure, precisely defining the boundaries of urban–rural elements is pivotal for understanding the driving mechanism of URDEI.

Land. Land is the most basic production element and the most potential natural resource in the rural and urban element system. Urban and rural lands play significantly distinct roles in development. Urban land is mainly allocated for infrastructure development, economic growth, and housing. In contrast, rural land is primarily designated for agriculture, residential use, and the preservation of rural traditional cultural landscapes [35]. Rapid urbanization has resulted in a trend of declining rural populations and expanding rural construction land, causing rural housing vacancies and inefficient land utilization. Effective land resource management and planning are essential for fostering the integration of urban and rural development and achieving sustainability. Thus, the Chinese government has implemented land consolidation policies to tackle challenges related to urban spatial limitations and inefficient rural land utilization [33].

Population. Population is a fundamental element in the development of urban–rural integration. The population factor has significantly impacted social, economic, and cultural progress throughout the process of urban and rural evolution. This impact has included promoting economic growth and innovation, preserving and disseminating culture, and maintaining ecological balance, among other effects. Influenced by their respective environments and lifestyles, urban and rural populations exhibit distinct characteristics. As a necessary input element for industrial development, labor mobility between urban and rural areas helps to promote knowledge spillover, information diffusion, and industrial growth. However, the migration of a significant population from rural areas to urban areas has led to great changes in the demographic structure of rural areas, and the problem of "aging" and "hollowing out" in rural areas has intensified, which threatens agricultural and rural development.

Industry. Industry serves as the essential driver of social and economic activity, both in urban and rural areas. Its development relies on conventional production elements like labor and capital, in addition to innovative knowledge production elements such as technology and talent. Therefore, an industry's factors generally affect the mobility of labor, capital, technology, and other elements and the transformation of regional economies, societies, and population structures in the context of urban–rural development. For instance, the growth of secondary and tertiary industries has facilitated the shift of labor from primary industries to non-agricultural sectors, leading to a significant improvement in public services and the standard of living. As a result, this has spurred further labor migration from urban areas to rural areas [36]. Currently, there is intense competition among the elements of urban industrial development, which has hindered the spread of industrialization to rural areas. Furthermore, the development of rural industries encounters issues such as the exclusive promotion of agricultural sectors. These elements exacerbate the challenges of urban–rural integration and coordination.

Capital. Government investments, industrial and commercial capital, social capital, and other capital elements all play a crucial role. Capital is essential to urban–rural economic and social development. However, due to the unbalanced development of urban–rural systems, urban areas possess greater attraction and aggregation capabilities for capital elements than rural areas. To achieve the efficient accumulation of rural capital elements and the sustainable development of rural areas, social capital and industrial and commercial capital are commonly introduced through policy leverage or increased direct investment from the government [37]. Taking into account the attributes of production elements and the scarcity of capital, various types of capital investments are critical for the flow of production elements such as land, technology, and labor. An imbalanced flow of funds impedes the development of rural areas and widens the resource allocation gap between urban and rural areas.

Technology. Technical elements refer to the knowledge, innovation, and skills used in production and economic activities. Existing research indicates that technology can enhance production efficiency, improve product quality, and enhance quality of life, making it a key determinant of urban–rural income disparities. With the support of talents, capital, policies, and other elements, the development level of urban technology far exceeds that of rural areas. The urban area is the highland of technology and equipment research and the center of outward diffusion. For example, urban technology can contribute to the development of rural agricultural industries through various forms, such as biotechnology and equipment technology.

Ecological culture. The distinct geographical patterns and humanistic environments of urban and rural areas create differences between urban and rural ecological elements and cultural elements, affecting the flow of population, capital, and other elements. For example, as the birthplace of farming culture, rural areas possess more abundant ecological resources than urban areas, providing potential drivers for attracting urban development elements to drive rural development. With the improvement of living standards and the growth of consumer demand, urban areas have become important markets for the consumption of rural agricultural products, and ecological and cultural products, as well as comfortable environmental resources.

Public service. Public services encompass 'hard' services such as infrastructure and cultural and environmental facilities, in addition to 'soft' services like healthcare, education, and social security [38]. Over the past few years, urban areas have witnessed a gradual improvement in the provision of public services and infrastructure, largely funded by government expenditures [39]. However, public services in rural areas have many shortcomings, and their development is relatively slow. Improving rural public services is conducive to narrowing the urban–rural income gap and promoting regional income and consumption equalization [40]. China has emphasized accelerating the completion of rural public service shortcomings and promoting the equalization of basic public services in urban and rural areas. It is crucial to boost infrastructure investment in rural areas and enhance the construction of public services to enhance the quality of rural development.

2.2. The Law of Urban–Rural Elements Flow

Under a market economy, the allocation of land, labor, capital, and other resources follows the market mechanism to optimize efficiency [4]. To address the issue of unbalanced distribution between urban and rural areas, China has implemented macro-control measures, including household registration reform, rural revitalization, and encouraging talent to move to the countryside. There exist asymmetric and uncoordinated characteristics of urban and rural elements in both one-way and two-way movement between the urban and rural areas, as depicted in Figure 1.

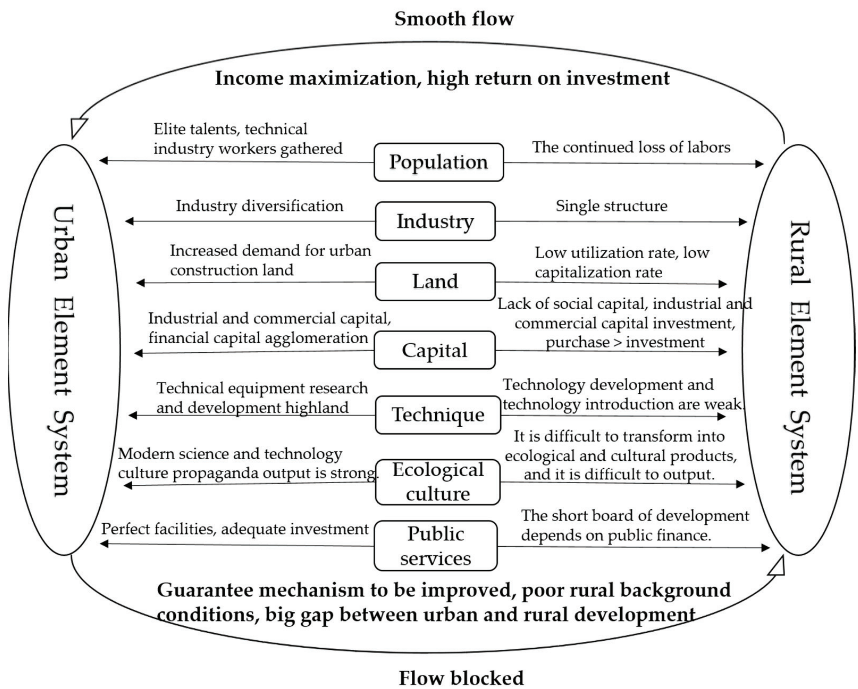

Figure 1. Basic characteristics and flow characteristics of urban and rural elements.

Based on the principle of maximizing income, the population primarily flows from rural to urban areas. This population flow is based on the satisfaction of material and spiritual needs, which can drive the diffusion and transfer of other urban–rural elements [41]. On the one hand, this migration pattern supplements the urban labor force, accelerates urbanization, and raises rural income levels. Technical term abbreviations are consistently explained throughout the text. However, increased population flow can result in social instability, wider wealth disparities, and development challenges, including rural labor shortages. The reform of China's household registration system has steadily reduced institutional barriers to population movement between urban and rural regions. As a result, both the scale and speed of population flow have accelerated [42,43]. To promote two-way population flow, the Chinese government has implemented institutional reforms and policy incentives that encourage government officials to work at the local level and urge migrant workers to return to their hometowns and start businesses.

Due to the combined influence of factors such as costs, markets, policies, and labor, the direction of business migration between urban and rural areas is complex. With the urban expansion, the contradictions of the urban population, resources, and environment are becoming increasingly acute, which leads to the migration of some enterprises that produce large quantities of standardized products to rural or township areas around the city. Furthermore, some megacities have also begun to relieve urban non-core functions to promote the upgrading of industrial structures and the optimization of spatial structures. In this regard, low-end industries such as agriculture, forestry, animal husbandry and fishery functions, general manufacturing functions, general wholesale, and retail functions have gradually moved to the suburbs and rural hinterland. In addition to one-way industrial migration, urban and rural areas can establish connections within the city's rural regions through supply chain collaborations. Urban businesses can partner with agricultural cooperatives or small-scale manufacturing enterprises in rural areas, achieving mutually beneficial outcomes.

Driven by industrialization and urbanization, land elements present a one-way flow, which is characterized by urban land expansion and rural land occupation. Land elements are transferred between urban and rural areas through means such as expropriation and transfer. With the increase and decrease in urban–rural construction land and the exploration and implementation of the land ticket system, the flow of land elements is more flexible. It is worth noting that the land transfer system will significantly affect the willingness of rural migrants to stay, and the explicit function of rural land property can effectively reduce the willingness of rural migrants to migrate [44].

The movement of capital elements occurs based on the yield differentials between urban and rural areas. Capital is the most profit-driven and scarce element. Capital flows between urban and rural areas based on the rate of return on income. The huge gap in the rate of return on capital between agriculture and non-agriculture has led to the long-term flow of capital to cities and towns. Most of the capital flowing from cities to rural areas is applied to the purchase of agricultural products and other related service activities, while rural development investment is relatively small. The mobility of labor can also lead to the flow of capital. When people move from rural to urban areas, they may bring their savings with them, which can be used for investment or entrepreneurship in urban areas.

Technical elements are usually combined with capital and gathered in cities; once there is not enough agricultural technology innovation, the dual economic urban–rural structure will inevitably emerge. However, if a city can provide certain technology for rural development, that is, urban and rural technology transfer, the investment in advanced urban technology in rural areas is often restricted by the limited infrastructure and services. At present, the Chinese government supports rural revitalization by innovating investment and financing mechanisms and leveraging and guiding more financial resources.

Culture and ecology flow between urban and rural areas in the form of cultural products, ecological products, and tourism services. Among them, urban culture spreads to rural areas with its inherent superiority and strength. However, the transformation path of rural ecological elements to ecological products and ecological services is relatively weak and is affected by labor, land, capital, and other human activities.

Public service flow refers to the promotion of relatively developed public services in cities to radiate to rural areas, the migration of public service resources to rural areas, and the extension of urban infrastructure to rural areas. Amomg, which promotes the interconnection of urban and rural public service facilities and infrastructure, is the most direct measure to improve the integration of urban and rural development. At present, the flow of public service elements is mainly in transportation, education, health, medical insurance, water, and other infrastructure and public services, which has promoted urban–rural interconnection and created necessary conditions for the coordinated development of urban and rural areas.

3. Theoretical Framework of the Influence of CLC on URDEI

To promote the integration of urban and rural development, the key is the integration of urban and rural elements, and the difficulty is in establishing a sound mechanism for the flow of URDEI [42]. Whether urban–rural elements can achieve effective flow and organic integration not only affects the allocation efficiency between related elements but also determines the promotion effect of input elements on urban and rural development to some extent. As a systematic project to promote the process of urban–rural integration, the CLC plays an important role in improving the quality of elements, optimizing the structure of elements, promoting the efficient integration and utilization of resources, and promoting the integration of urban and rural development. Based on the rural element system, the CLC in the whole region promotes the inflow of financial funds, social capital, advanced technology, and high-level talents into the countryside. The diving mechanism of CLC for promoting the two-way smooth flow and organic integration of urban and rural elements is shown in Figure 2.

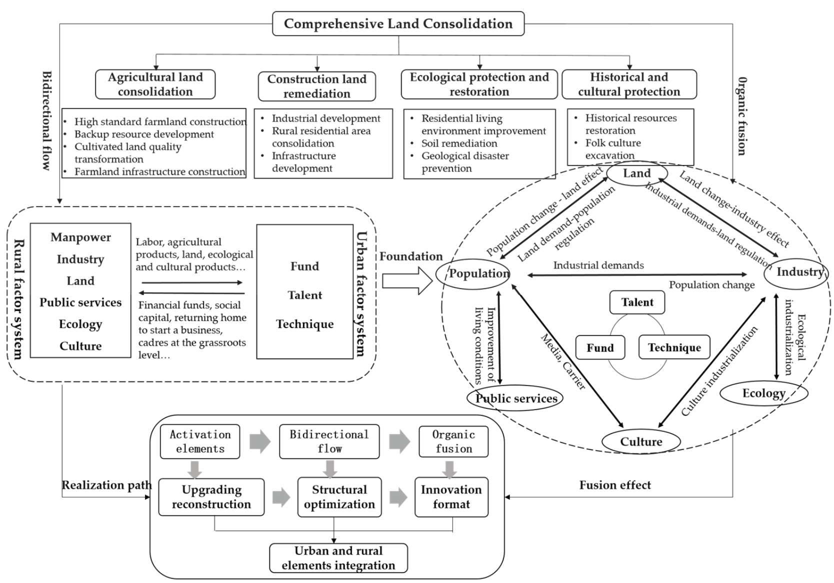

Figure 2. The driving mechanism of CLC on URDEI.

3.1. CLC Promotes the Smooth Flow of Urban and Rural Elements

The CLC helps integrate rural elements into urban areas. CLC promotes the outflow of land resources by facilitating land transfer and linking changes in urban and rural construction land. The implementation of centralized contiguous agricultural land consolidation can increase the effective cultivated land area, improve agricultural production conditions, promote land transfer, and facilitate the large-scale cultivation of cultivated land [45]. This will further save and liberate the rural labor force and smooth its transfer to non-agricultural industries. On the other hand, with the promotion of planting technology and agricultural equipment adapted to large-scale operation, the yield and quality of agricultural products have been effectively guaranteed, thus laying a foundation for improving the added value and commercialization rate of agricultural products and accelerating the integration of agricultural industry and non-agricultural industry. Regarding construction land consolidation, it can revitalize the use of rural collective construction land [46], which not only helps meet the demand for rural industrial development land but also makes use of surplus construction land indexes, increases the income of rural land indicators, and supports the demand for non-agricultural construction land to promote land saving and intensive use [26]. Through ecological protection and restoration and historical and cultural protection measures, the quality of rural ecological and cultural elements can be improved, so that more high-quality rural ecological and cultural products can meet the leisure tourism needs of urban residents.

The CLC drives urban elements into rural areas. The CLC project itself will bring a lot of government investment to rural areas. Secondly, with the improvement of the rural internal environment caused by CLC, rural areas have a greater chance to attract social capital, urban industrial and commercial capital, and financial capital. Land consolidation in agricultural areas can enhance farmland productivity and sustainability, attracting urban agricultural professionals, modern agricultural technologies, and other resources into rural areas, thereby elevating the level of rural industries. Simultaneously, promoting land transfer can draw urban investors and businesses into rural regions, leading to improved economic efficiency in rural areas. Additionally, land consolidation for construction purposes can enhance the quality of rural life, attracting urban residents and businesses to rural areas. For example, the improvement of production conditions and the development environment not only provides an opportunity for the introduction of urban e-commerce platforms and 'Internet +' technologies into rural primary, secondary, and tertiary industries, but also creates new models, new formats, and new scenarios for local industries. Simultaneously, organized construction land indicators can provide developmental space for incoming industries. The improvement of public service elements not only makes up for the shortcomings of rural development but also further enhances the radiation of cities to rural development, which can further promote the equalization of urban and rural public services and infrastructure interconnection [47,48]. Enhancing the rural ecological environment through ecological protection and restoration efforts can attract urban residents and tourists. Rural ecological tourism and environmental protection industries can become investment and employment opportunities for urban residents. Additionally, in conjunction with land consolidation, ecological compensation policies can draw urban environmental professionals and businesses into rural areas to participate in ecological restoration projects. The preservation of historical and cultural heritage can transform rural areas into cultural tourism destinations, which in turn attracts urban residents and businesses, including cultural and creative industries and professionals in cultural heritage preservation. Through cultural exchange and educational programs, talent elements such as cultural education institutions and artists can flow into rural areas, driving cultural heritage preservation and innovation in rural regions.

3.2. CLC Promotes the Organic Integration of Urban and Rural Elements

To address the widening urban–rural development gap, the government should facilitate the organic integration of urban and rural elements by removing obstacles to the flow of urban–rural elements. This will enhance the effectiveness of factor mobility. The CLC project is an effective way to promote URDEI. CLC directly acts on the land elements by engineering means and can promote the integration of land, industry, labor, talent, capital, technology, and other elements by adjusting the land use structure, optimizing the land use layout, and improving the land quality. In other words, CLC can effectively realize the efficient allocation and optimal combination of relevant elements and promote the new development pattern of urban–rural integration [13,28,49,50].

The effects of CLC driving the organic integration of urban and rural development elements typically manifest as population mobility and settlement, industrial innovation and upgrading, and the enhancement and expansion of infrastructure. Specifically, population, land, and industry are at the core of the rural element subsystem, which influence each other internally and constantly interact with the external environment, forming a whole with dissipative structure characteristics. The inflow of capital, talent, and technology from urban areas into rural regions facilitates the upgrading of rural industries and assists in the development of competitive sectors, such as modern agriculture, rural tourism, and cultural and creative industries. Modern enterprise management and its various types of processed products and service products have a great impact on traditional rural business forms, which still lack a relatively mature development environment. To adapt to rural transformation development, the implementation of CLC can promote rural land transfer and scale management to change the traditional small-scale farming mode and create conditions for agricultural mechanization and medium-scale management. This, in turn, will improve the comprehensive agricultural production capacity, improve the rural ecological environment, and absorb advanced urban management concepts, industrial and commercial capital, technology, and talents into rural areas, and thereby promote the integration of urban–rural elements [2]. Furthermore, CLC increases the investment in rural public services and infrastructure, which cannot only reduce the imbalance in the distribution of fiscal expenditure between urban and rural areas [51], but also connect the transportation network, logistics network, and information network between rural areas and urban areas, and improve the URDEI [52,53]. The CLC program combines ecological protection and restoration with historical and cultural preservation. It promotes the industrialization of ecological and cultural elements through the restoration of historical resources and the exploration of folk culture. The pilot experience of CLC across the country also shows that CLC promotes the input of financial funds and social capital, advanced technology, high-level talents, and other elements into rural areas, and has become a platform and an effective method for the organic integration of urban and rural elements [54].

4. Empirical Analysis

4.1. Study Area

Chongqing, situated in southwest China, is a mountainous city. On the one hand, significant geographical barriers exist between urban and rural areas, requiring innovative approaches to promote urban–rural interaction and cooperation. On the other hand, Chongqing faces a significant urban–rural development gap, with a wide disparity in per capita disposable income (the per capita disposable income of urban residents is 45,509 yuan, while the per capita disposable income of rural residents is 19,313 yuan). There is an urgent need for urban–rural integration and development. Therefore, Chongqing has been designated as a "pilot area" for comprehensive reform and development of urban–rural coordination and a pioneering demonstration zone for urban–rural integration in the country. To elucidate the impact of CLC on URDEI, this study examines six completed CLC initiatives in the western region of Chongqing as a case study (Figure 3). Before consolidation, the case area faced numerous practical challenges, including a shortage of labor, a monolithic industrial structure, and low land use efficiency. To alleviate these issues, it is imperative to reallocate land use and development elements comprehensively. By consolidating agricultural and construction land, implementing ecological protection and restoration initiatives, and preserving sites of historical and cultural significance, the government and social capital integrate funds to draw skilled professionals and advanced technological advancements back to rural areas. The case area has improved the rural living environment, revived the collective construction land, optimized the industrial layout, and achieved integrated development. This has accelerated the process of urban–rural integration in the community.

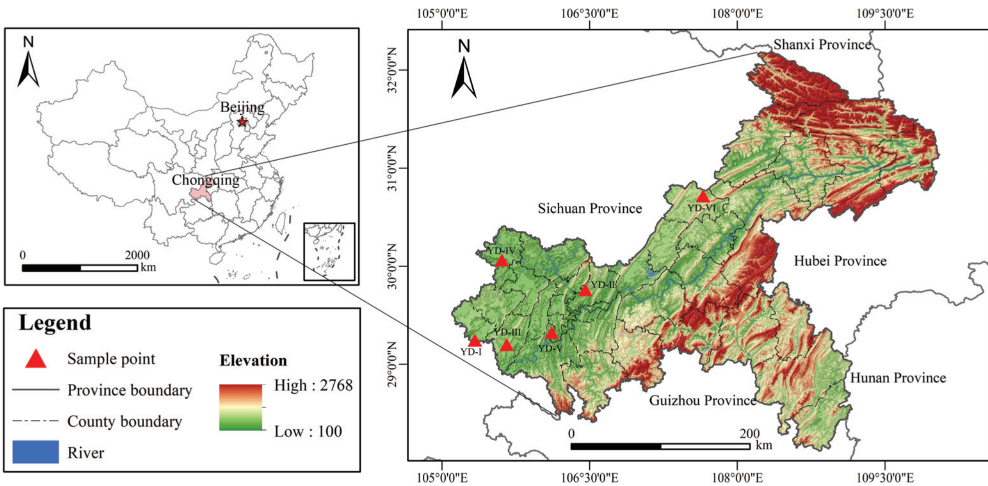

Figure 3. Location map of research case.

4.2. Data Sources and Processing

The data primarily originated from the township governments in the six sampled counties as well as field surveys. The data in this article can be categorized into two types: CLC project data collected from departments related to natural resources, agriculture, and rural affairs, and on-site visits and surveys conducted in selected project areas. Semi-structured interviews were used to engage in conversations with residents to gather micro-level data on factors such as the inflow and outflow of high-end talents, the number of investment enterprises, investment amounts, etc. Missing data were supplemented using county statistical yearbooks.

4.3. Analysis of the Process of CLC on URDEI

Based on the theoretical mechanism of promoting the integration of urban and rural elements through integrated land consolidation, the process of driving the integration of urban and rural elements through integrated land consolidation is divided into three stages: activating rural elements, the bidirectional flow of urban and rural elements, and the organic integration of urban and rural elements. These three stages are manifested in the process of implementing integrated land consolidation through element quality improvement, structural optimization of elements, and innovation in rural business formats. Therefore, the impact of integrated land consolidation on the integration of urban and rural elements in the research area can be demonstrated by examining the consolidation measures in the integrated land consolidation area and comparing the development before and after implementation. The process of URDEI driven by CLC can be divided into three stages, namely, the element quality improvement stage, the element structure optimization stage, and the element integration innovation stage.

In the first stage, the rural elements are upgraded. Given the practical challenges associated with land use and environmental conditions, CLC primarily focused on enhancing the quality of development elements such as land, ecology, culture, and public services through the implementation of engineering measures (Table 1). The optimization of land elements was primarily achieved through farmland reorganization, construction land development, and rural residential land consolidation. Farmland reorganization measures included the terracing of arable land, irrigation facilities, parcel integration, and the upgrading of the farmland road network. For instance, some arable land with slopes greater than 6° but good road conditions were transformed into terraces to meet the needs of medium-sized mechanical farming. After the completion of slope land consolidation projects, soil fertilization was carried out to ensure the quality of cultivation. On average, the land quality grade increased by 0.33, and the suitability for mechanization improved by an average of 2.38% compared with pre-consolidation conditions. Additionally, protective ponds and farmland drainage channels were newly constructed in all sample areas to meet the irrigation needs of the surrounding farmland. To reduce the fragmentation of the farmland landscape, paddy fields were merged with scattered land parcels, and idle land within parcels was consolidated. Construction land consolidation primarily involved integrating and optimizing scattered land parcels to have a full range of functions, including residential, industrial, infrastructure, and public services. This consolidation also facilitated the adjustment of urban and rural land elements. For example, new village settlements with supporting infrastructure and public service facilities were built to guide the scattered rural land to withdraw from the project. After the implementation of the consolidation project, the area of construction land and the number of scattered construction land plots showed a downward trend.

Table 1. The way to improve the quality of land elements in the study area.

Regulation Content		Realization Path	Main Associated Elements
Optimize land utilization	Settlement space optimization	❖ Construction of new village settlements, supporting infrastructure, and public service facilities to enable farmers to live in concentration; ❖ Construction land (especially scattered rural homesteads) gradually withdrew, forming a concentrated distribution area of cultivated land with good water conservancy and soil and water conservation measures.	Rural homestead
	Revitalization of idle inefficient space	❖ Rural construction land reclamation.	Collective construction land
	Building modern agricultural production space	❖ Comprehensive improvement of the existing cultivated land, terrace transformation, improvement of the field road network, the construction of automatic irrigation system, and improvement of the ecological environment of farmland to achieve suitable cultivation, water and fertilizer integration, and intelligent management of modern mechanized agriculture.	Cultivated land, Technology
	Industrial development space cultivation	❖ Implement modern agricultural technology training in the field of modern agricultural production and agricultural employment research; ❖ To carry out tourism-related skills training for the tourism employment population in the study area, improve the quality of the labor force, and contribute to the revitalization of rural talents [51].	Population, Industry, Capital, Technology

Table 1. *Cont.*

Regulation Content		Realization Path	Main Associated Elements
Improve environmental quality	Ecological environment governance	❖ Install sewage treatment equipment for large and super-large courtyards with a scale of more than 10 households throughout the community; ❖ Support garbage collection, sewage treatment, rest facilities, improving fitness activities area, parking lot, etc.	Ecology
	Improvement of living environment	❖ Extract the characteristics of the roof, wall pillars, roof foundations, verandas, doors and windows, and architectural colors of traditional buildings in Bayu, reflect the local conditions of Bayu; ❖ The residential environment improvement of relatively concentrated residential areas mainly involves large residential areas.	Public services
	To improve the road system	❖ To meet the new village residents' travel and agricultural industry development, the new road connected to the traffic system of the study area, forming a convenient and efficient internal traffic system.	Public services
	Characteristic courtyard building	❖ Establish a colorful courtyard featuring seasonal crops; ❖ Establish a characteristic residential village for tourism visits.	Culture
	Rural Cultural Heritage	❖ Repair and protect the existing cultural attractions, dig deep into the rural farming culture and create a farming culture experience area.	Culture

The improvement of environmental quality in the study area was mainly carried out from hard conditions represented by the ecological environment and life quality and soft conditions represented by the cultural atmosphere. Among them, ecological protection and restoration were used to explore the characteristic resources and guide agricultural green production to upgrade the industry. The study area mainly adopted field ridge restoration, slope water system management, and ecological slope protection to implement ecological protection and restoration. For example, YD-I controlled agricultural non-point source pollution by stripping and reusing coastal topsoil and the construction of slope protection and ridge protection for important water systems such as Jinlong Lake and Qingsheng River. After the renovation, the project area formed large mountain plateau ponds, which created conditions for the development of aquaculture. The protection of historical culture mainly focuses on the display and experience of the farming culture and the improvement of the surrounding environment of the courtyard. After the completion of the rural tourism scenic spot, the project area has increased employment opportunities in catering, accommodation, retail, agricultural trade, and scenic spot management, attracting local migrant workers to return home to start their businesses. The improvement in the quality of urban–rural development elements is shown in Table 2.

Table 2. Changes in the quality of urban–rural development elements before and after CLC.

Element Type	Measurement Index	YD-I	YD-II	YD-III	YD-IV	YD-V	YD-VI
Land	Increasing infield rate (%)	5.01	0.09	0.09	0.08	0.09	9.34
	Cultivated land quality class	1.10	0.20	0.60	1.00	−1.40	0.50
	Appropriate rate of mechanization (%)	0.48	0.65	0.27	0.20	0.11	12.54
Ecology	Green vegetation coverage rate (%)	3.56	2.75	12.71	6.81	13.19	5.83
	Biological abundance index (%)	0.01	0.00	−0.07	0.04	0.01	0.01
Culture	Protection and cultivation of historical attractions (Department)	12	5	17	5	7	7
	Characteristic courtyards (pcs)	200	400	286	45	121	18
Public services	Road network density (m/hm^2)	5.88	14.65	11.00	16.22	4.48	7.80
	New activity room (pcs)	23	13	48	21	6	14

In the second stage, there was an optimization of the factor structure. Building upon the activation of rural development elements, there was a further optimization of land use structure, labor force composition, capital formation, and industrial structure (Table 3). After the land consolidation, the structure of land utilization was improved. Through the consolidation of agricultural land, the area available for land transfer increased, leading to a more concentrated spatial distribution and a more regular shape of arable land. This significantly met the requirements for land transfer and large-scale farming, providing favorable conditions for mechanized production and the introduction of social investments. Through the consolidation of rural construction land, the issues of scattered, disorderly, and vacant villages were significantly improved. Inefficient land use in rural areas was further rejuvenated, and the trend of urban–rural integration became more apparent. CLC promoted the transfer, leasing, and mortgage of land use rights, turning land into capital. Infrastructure improvements increased productivity and living standards in rural areas, attracting more capital into the countryside, including social capital and government investments. This provided more financial support for rural areas and helped improve their capital structure. Through interviews and surveys, it was found that after the consolidation, there was an increase in the number of people returning to their hometowns for entrepreneurship as well as an influx of skilled workers from outside the region. This led to changes in the age structure and education levels of the regional workforce. As agricultural production conditions improved in the sample area, there was a shift in agricultural structure, with large-scale farming households actively adjusting and optimizing their cropping patterns. This was one of the most significant changes in rural industries. After the project's implementation, non-agricultural industries, such as processing manufacturing, and tourism, were able to develop in rural areas. The structure of the primary, secondary, and tertiary industries in rural areas was optimized, and modern agricultural technology services experienced accelerated development.

Table 3. Changes in the structure of urban–rural development elements before and after CLC.

Element Type	Measurement Index	YD-I	YD-II	YD-III	YD-IV	YD-V	YD-VI
Labor force	Migrant workers	1440	725	189	93	83	113
	Returning entrepreneurs (unit)	16	13	15	2	9	27
Funds	GDP per capita (yuan)	0.07	2.10	0.20	0.12	0.01	0.42
	Government investment (ten thousand yuan)	1000	6700	2930	4841.75	1193.36	1792
	Social investment (ten thousand yuan)	680	960	75,500	11,028	1183.07	7269.9
	Net income of cultivated land (ten thousand yuan)	82.00	258.00	52.17	207.12	81.4	90.12
Land	Construction land balance (hm^2)	1.58	5.12	2.12	0.00	0.50	0.24
	Transfer land area (hm^2)	26.67	0.00	34.06	−6.33	25.80	1.67
Industry	New business entities	6	30	17	7	1	2
	New jobs (pcs)	800	705	20	40	70	190

In the third stage, there was an innovative transformation of the industrial landscape through the integration of elements. The enhancement in the quality of rural elements and their structural optimization led to the emergence of new business models, technologies, and management methods in the field of rural development, capable of meeting the ever-changing market demands. In the sampled areas, the consolidation of agricultural land improved irrigation facilities and implemented strip field consolidation to create conditions for the development of new agricultural industries. This included the introduction of large-scale rice-fish farmers, which promoted the advancement of modern agriculture. Through the application of modern agricultural technologies, land use efficiency was enhanced, leading to increased agricultural product yields and improved quality. Farmers were guided to develop high-value-added agricultural practices, such as organic farming, green agriculture, and specialty agriculture, to increase their income. Furthermore, the consolidation of construction land resulted in comprehensive planning for idle farmhouses, encouraging the utilization of these vacant structures for rural tourism, homestays, and cultural creative industries. This also provided an opportunity for industrial and commercial capital to enter rural areas. The introduction of professional managers, agricultural technology experts, and other human resources further stimulated the endogenous growth of rural development. The establishment of eco-tourism cooperatives encouraged business participation and facilitated the organized flow of land and capital between urban and rural areas. The exploration of distinctive cultures brought about new economic growth opportunities. Already constructed rural resorts were designed to fulfill functions such as dining, accommodation, leisure, healthcare, and picking activities, which drove the development of industries in the research area and increased the income of rural residents. Tailoring strategies to the specific local context, the sampled areas applied advanced technologies and experiences in non-point source pollution control and eco-friendly agricultural practices, as well as flood and drought resilience technologies. This not only improved but also beautified the living environment.

Overall, the project area has realized the mechanization of grain and oilseed harvesting and the unification of economic fruit planting management. First of all, with the assistance of agricultural horticultural facilities and ecological breeding technology, a 'green, ecological, circular and coordinated' agricultural industrial chain with local characteristics is created; then, through the processing and sales of local fruit, rice, and other characteristic agricultural products, the agricultural production chain is further extended. Based on farming culture, we should give full play to the versatility of land consolidation supporting facilities, meet the needs of tourists for leisure and entertainment, promote the coordinated development of agricultural culture and tourism, and create a new sustainable development format of the three-industry integration.

5. Discussion

With the full implementation of the rural revitalization strategy and the further evolution of urban–rural relations, land consolidation has entered a new stage of CLC [13]. The goal of CLC has been transformed into cultivated land protection, ecological civilization construction, and urban–rural integration [55]. Its essential function is to activate rural idle resources effectively, optimize land layout, improve land use efficiency, and promote rural transformation development to connect cities. CLC can effectively solve the problem of resource shortages in rural development, guide the rational flow of urban and rural resources, and be an important platform for the integration of urban and rural elements.

While many scholars believe that CLC contributes to the integration of urban and rural elements and the development of urban–rural integration [30,56,57], current research on how CLC promotes the integration of urban and rural elements remains unclear. The theoretical framework constructed in this paper indicates that CLC has a positive effect on promoting the integration of urban and rural elements and addressing the issue of urban–rural imbalance. This further underscores how CLC can facilitate the integration of urban and rural elements. The key to its role lies in CLC serving as an interactive platform for elements, effectively promoting the integration of rural elements into urban areas, the introduction of urban elements into rural areas, and enhancing the interaction between elements in rural and urban areas. Through field surveys and empirical analysis, it has been demonstrated that CLC improves element quality, optimizes element structure, and further develops rural industries. Our findings align with those from some case studies in other regions of China (e.g., Zhejiang Province, Beijing Province) that show the positive role of CLC in exploring rural culture and achieving overall resource allocation between urban and rural areas through the innovative "CLC + urban–rural integration development" model [58].

It is of great international reference value for China to promote the integration of urban and rural elements through CLC to support urban–rural integration development, but its potential shortcomings and negative effects are also worthy of attention in the future. On the one hand, it has brought serious labor losses, and some farmers still maintain self-sufficient living conditions due to the lack of labor. This may be due to the entrepreneurial opportunities provided by the implementation of CLC and the fact that jobs cannot meet the employment needs of rural labor. On the other hand, the lack of scientific engineering design of CLC limits its effectiveness. This is mainly due to the lack of agricultural production theory and technical guidance in the CLC process. The survey at the household level shows that farmers have greater expectations for the construction of irrigation ditches and the consolidation of soil blocks, and some farmers who are not involved in the transfer of village collective land are particularly strong. In addition, the implementation of CLC may have potential ecological risks [59]. Studies have shown that the human disturbance of land consolidation in the natural environment may lead to the degradation of ecosystem services and the decline of landscape diversity. Therefore, it is imperative to strengthen the scientific planning and design of CLC, establish effective monitoring and evaluation mechanisms, and implement continuous supervision for a certain period after project implementation. Deviations should be promptly corrected during project execution to mitigate adverse impacts. It is also important to recognize that CLC is not a universal formula for addressing urban–rural development issues and improving the current urban–rural imbalance. The specific implementation process of CLC needs further refinement to ultimately achieve a referenceable and replicable model for integrated urban–rural development. Its specific implementation process needs to be further improved to finally realize the urban–rural integrated development path model that can be used for reference and promotion. With the progression of globalization, both developed and developing countries are actively exploring various effective measures to promote rural revitalization and balance between urban and rural development, such as the latest European common agricultural policy in the 21st century (2014–2020), Japan's agricultural support policy, research on rural economic development in Italy, etc. [60–62].

The limitation of this paper is that it only analyzes the integration of local urban–rural elements and the driving mechanism of URDEI through a CLC project. In fact, due to the differences in regional background conditions and development plans for the implementation of CLC, the demand for the integration of urban–rural elements in different regions is also different. It is also important to study other types and practices of CLC. Essentially, this study presents an approach to promoting the integration of urban–rural elements and the development of urban–rural integration through CLC measures. While this approach may not be completely applicable to elsewhere, it serves as a valuable reference for other countries and regions facing similar urban–rural development challenges.

6. Conclusions

To achieve the integration of urban and rural development, the promotion of URDEI is crucial. To this end, CLC improves the quality of rural elements, promotes the flow of urban–rural elements, and facilitates their organic integration. The theoretical framework for the impact of CLC on URDEI is established based on the identification of the urban and rural element systems. The core objective of CLC in promoting URDEI is to affect the reciprocal feedback relationship between rural and urban elements by enhancing the quality grade and spatial arrangement of land elements. CLC optimizes land use through approaches such as agricultural and construction land consolidation, ecological protection and restoration, and historical–cultural preservation. It promotes the integration of land with industries, labor, talents, capital, technology, and other elements and plays an important role in advancing the new model of the agricultural industry. It also facilitates the equalization of basic public services in urban and rural areas.

This case study shows that the path of CLC to promote the UREI can be realized in three steps. Firstly, the improvement of rural elements creates the basic conditions for the two-way flow of urban–rural elements. Through agricultural land consolidation, construction land consolidation, ecological protection and restoration, and historical–cultural protection, the quality of land elements and the living environment in rural areas can be improved, and the development of cultural and tourism industries will be promoted. The second stage is to promote the optimal allocation of urban–rural elements. The scale and mechanization of land elements have gradually increased, the proportion of the output value of the secondary and tertiary industries has improved, and the number of various buildings that can reflect the local ecological and cultural characteristics has increased. Thirdly, CLC will guide the organic integration of urban–rural elements and build a new format of rural development. The renovation project brings new economic growth points, improves the participation of technology, talents, capital, and other elements in rural development, and enhances the ability of rural areas to develop local industries and attract exogenous investment, which will promote the continuous inflow of urban elements through industrial development.

CLC and URDEI should be mutually reinforcing and complementary, and our findings provide valuable policy recommendations for the implementation of CLC. Firstly, it is important to establish and improve relevant laws and regulations on CLC and integrated urban–rural development, clarify the objectives, tasks, responsibilities, and obligations of CLC, and ensure coordination and integration between urban–rural planning, land use planning, and CLC planning. Secondly, it is important to strengthen the financial investment in land improvement projects and promote technological innovation and application in land improvement. Financial support is an important condition for the scientific implementation of CLC. It is necessary to give full play to the guiding role of government funds to drive the flow of social resources into the countryside and accelerate the pace of rural revitalization construction. Finally, a perfect monitoring and evaluation system for CLC and URDEI should be established to provide timely evaluation and feedback on the remediation work and continuously optimize the remediation strategy. We should establish a long-term CLC mechanism to promote the integrated development of urban and rural elements. Not only should we pay attention to the two-way flow of urban and rural factors, but also promote the improvement and optimization of the quality of local factors in the countryside so that urban factors can flow into and stay in the countryside, and continue to have an impact on the development of the countryside, and so that CLC can become an important starting point for the construction of an integrated urban–rural development pattern.

Author Contributions: Conceptualization: Y.Z. and C.Y.; Methodology: Y.Z., C.Y. and G.X.; Writing—original draft preparation: Y.Z.; Writing—Review and Editing: Y.W. and R.C.; Funding acquisition: C.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 42171257) and the Natural Science Foundation of Chongqing (cstc2020jcyj-msxmX0843).

Data Availability Statement: The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Measurements and Influencing Factors of New Rural Collective Economies' Resilience toward Mountain Disasters in Indigent Areas: A Case Study of Liangshan Yi Autonomous Prefecture, China

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Abstract: Economic activities in disaster-prone areas are significantly susceptible to mountain disasters, and enhancing the resilience of new rural collective economies (RRCEs) is a pressing challenge that needs to be overcome in the areas of disaster risk management and sustainable development. The target research area comprises 48 representative villages in Liangshan Yi Autonomous Prefecture (LP). An assessment framework based on the Resilience Index Measurement Analysis (RIMA) model is established to evaluate the RRCEs in the face of mountain disasters, and the influencing factors regarding the RRCEs are examined. The results show that (1) typical villages in the new rural collective economies (NRCE) have a low level of resilience. (2) Transformational capacity is the key to improving RRCEs. (3) Off-farm villages exhibit the highest level of collective economic resilience, followed by diversified villages, while the lowest resilience level is observed in purely agricultural villages. (4) Talent security and institutional security are important for achieving a high level of resilience. Both of these factors significantly influence RRCEs. (5) The combined influence of talent, financial, institutional, technological, and business security contributes to the diverse factors that shape RRCEs. In other words, the path to achieving resilience in the new rural collective economies is characterized by multiple routes that lead to a common goal. Building on this, we propose recommendations in five key areas, namely, encouraging scientific research and innovation, improving disaster insurance coverage, strengthening the emergency protection system, facilitating collective economic development, and selecting suitable strategies to enhance resilience based on local conditions. The aim is to offer valuable insights for disaster-prone areas to enhance RRCEs and realize sustainable development and rural revitalization.

Keywords: new rural collective economies (NRCE); rural revitalization; mountain disasters; resilience; Resilience Index Measurement Analysis (RIMA)

Citation: Yuan, Y.; Li, M.; Tian, C.; Xu, Y. Measurements and Influencing Factors of New Rural Collective Economies' Resilience toward Mountain Disasters in Indigent Areas: A Case Study of Liangshan Yi Autonomous Prefecture, China. *Land* **2023**, *12*, 2042. https://doi.org/10.3390/land12112042

Academic Editor: Charlie Shackleton

Received: 20 October 2023
Revised: 4 November 2023
Accepted: 6 November 2023
Published: 9 November 2023

1. Introduction

Due to climate change, there has been a rise in mountain disasters for mountainous areas, including flash floods, mudslides, landslides, and avalanches [1]. Mountainous areas comprise approximately 20% of the total global land area, with China alone accounting for approximately two-thirds of this area, leading to a significant exposure to mountain disasters [2]. Mountain disasters pose a multifaceted threat, as they are capable of washing away towns and rural settlements, which can result in casualties and economic losses. Such disasters can also block critical infrastructure such as highways, bridges, and power systems [3]. Additionally, these disasters cause sedimentation in natural resources, such as arable lands and forests, reroute rivers, and cause ecological damage, thereby hindering the high-speed and sustainable development of rural economies in mountainous areas [4]. This phenomenon besets resource-rich mountainous regions with topographic challenges and economic setbacks, exacerbating the issue of rural residents falling into poverty or returning to poverty as a result of these disasters [5].

Resilience, as a nonengineered approach in disaster management, has gained prominence in recent years [6,7]. Originating from the field of ecology, resilience refers to the capacity of a system to restore equilibrium after a disturbance [8]. With rural areas worldwide facing economic uncertainty and ecological crises that pose significant threats to the livelihoods and sustainable development of rural residents, there has been a growing emphasis on rural revitalization and increased attention toward rural resilience [9,10], which has been employed to analyze the coping capacities and strategies of rural households following the financial crisis [11], the sustainability of farmers' livelihoods [12], the stability of family farm operations [13], and the capacity for sustainable rural development [14]. Several studies have identified the factors influencing rural resilience, including the sense of responsibility and belonging among villagers [9,15], land ownership [16], and the level of digital network infrastructure [17]. Natural disasters such as floods, earthquakes, and mudslides that surpass rural resilience thresholds within a short period can also severely damage rural infrastructure, economies, and human security [18,19].

Maintaining the dynamism of rural economic development is essential to increasing rural resilience and promoting sustainable rural development [20]. The focus of rural economic development varies according to the global stage of social and economic development [21]. In developed countries, the rural economy is dominated by commodity-based agricultural production [22]. The promotion of integrated rural development is one of the primary objectives of the EU Common Agricultural Policy (CAP) [23]. In developing countries, rural economies are predominantly characterized by smallholder economies. Nevertheless, the structure of the rural economy in these countries is undergoing significant transformations due to industrialization, urbanization, globalization, a gradual shift away from agriculture by farmers [24], and the progressive mechanization of agricultural production. Based on the experience of developed countries, bottom-up initiatives, such as rural revitalization, can assist rural economies in maintaining dynamism, adapting to change, and achieving sustainable development [25].

The rural collective economy is a unique economic form under the socialist system of public ownership [26] and has transitioned from primary cooperatives to advanced cooperatives, from people's communes to a two-tier management system, and from adapting to market-oriented reforms to exploring diverse approaches for economic realization. This evolution is further emphasized in the No. 1 central document for 2023, which calls for the exploration of various avenues for developing the new rural collective economies (NRCE) that includes resource contracting, property renting, intermediary services, and participations in asset shareholding. New rural collective economies are forms of rural public economic systems that are based on rural collective economic organizations. They encompass collective assets allocated to collective members, a robust internal governance structure, economic strength, and governance efficiency. Their scope includes the collective economies inherited from the people's commune system, along with new forms of the collective economy, such as farmers' professional cooperative economies, joint-stock cooperative economies, and the economic associations that have emerged in the new era [27]. As NRCEs develop under the leadership of township party committees and grassroots party organizations, human factors are being incorporated into the management of the collective economies. This emphasizes the comprehensive development of spatial and ecological resources, the equitable sharing of benefits generated through systematic development among village members, and the promotion of increased wealth and income for the general rural population. Consequently, NRCEs play a significant role in consolidating and expanding the achievements obtained in regard to poverty alleviation and ensuring the common prosperity of all people at the present stage [28].

Numerous studies have been conducted to explore the factors, paths, and models of the new rural collective economic development. Li et al. created an integrated framework that linked urban-rural development and rural economic resilience and highlighted the fact that continuous investments in infrastructure, public services, and industries can enhance the resilience of rural economies [29]. Cui et al. examined 338 impoverished villages and discovered that China's precise poverty alleviation policy succeeded in stimulating endogenous development in rural areas. This policy improved production factors, optimized economic structures, enriched functional roles, and significantly enhanced the level of rural economic resilience [30]. Natural disasters can damage crops, farmland water conservancy projects, and infrastructure in disaster-prone areas. This damage adversely affects the transportation of agricultural materials and the sale of agricultural products, thus posing a significant threat to the development of the rural collective economies. Furthermore, the development of the rural collective economy is constrained by various factors. These include natural factors such as unfavorable geographic locations, inadequate transportation conditions [31], and limited natural resources [32]. Additionally, social factors, such as the long-standing two-tier management system that emphasizes division over unification [33], low human quality for management and innovation [28], and a weak awareness of collective action among members, and economic factors, such as excessive collective debt [34] and the lack of a political and economic separation between rural collective economic organizations and village committees [35], have limited the development of the rural collective economies. Different scholars have proposed various models based on different classifications. For instance, Gao et al. categorized models into operating, joint venture, leasing, service, and party-building models based on their respective modes of operation [26]. A systematic review of the existing studies both at home and abroad reveals that few scholars have considered the resilience of new rural collective economies (RRCEs), particularly in the context of mountainous areas that are prone to natural disasters. Given the significant impact of the stable development of NRCEs on both the national economy and on people's livelihoods, there is a need to address the quantitative evaluation and spatial differentiation research that regards its resilience.

Liangshan Yi Autonomous Prefecture (LP), which is located in China, is known for its high levels of poverty. While significant progress has been made in poverty eradication, consolidating these achievements and preventing the resurgence of widespread poverty remains critical. Recognizing its significance in facilitating the stable transition of impoverished villages, the local government places great emphasis on the development of village-level collective economies as a key measure for uplifting communities and assisting individuals in escaping poverty. LP is susceptible to frequent mountain disasters and has a limited community disaster defense capacity. Mountain disasters pose significant environmental constraints on poverty-reduction efforts, increase the risk of people falling back into poverty, and hinder the development of the rural collective economies. Building upon these circumstances, LP is used as a case study, and the region's specific conditions are incorporated in the analysis. This serves to enhance the existing Resilience Index Measurement Analysis (RIMA) model that was developed by the Food and Agriculture Organization of the United Nations (FAO) [36–38], which we use to analyze RRCEs in coping with mountain disasters. In this study, the characteristics of its subdimensions are further examined as well as the factors influencing RRCEs. Furthermore, this study can serve as a valuable case study for informing the economic development strategies of other rural communities worldwide that are prone to natural disasters. This paper is aimed at making the following potential contributions: (1) An analytical framework is established to evaluate RRCEs in poverty-eradication areas under the coercive impact of mountain disasters. (2) Recommendations are provided to enhance RRCEs by addressing the existing challenges they face in coping with mountain disasters. These insights can serve as a valuable reference for promoting sustainable economic development in rural communities, both within China and globally.

2. Methodology and Data Sources

2.1. Overview of the Study Area

LP is located in the southwestern part of Sichuan Province, and it serves as a transition zone between the Sichuan Basin and the Yunnan–Guizhou Plateau as well as the Qinghai–Tibetan Plateau. It spans from 26°02′–29°18′ N, 100°03′–103°52′ E. The topography steadily descends from northeast to southwest, featuring a maximum elevation of 5904 m and a minimum elevation of 310 m, resulting in a substantial height difference of 5594 m (Figure 1). The region is situated in the Western Rift Valley of Panxi, which is characterized by complex geological formations and an exceptional climate that renders its natural environment highly fragile [39]. The area undergoes frequent occurrences of mountain disasters, including flash floods, mudslides, and landslides [40]. LP encompasses 17 counties and cities in its jurisdiction, covering an area of 60,423 square kilometers. The region is rich in labour resources, providing sufficient human capital for the development of NRCEs, and is home to a resident population of 4,858,400 individuals. It is characterized by the presence of 14 hereditary ethnic groups, including Han, Yi, Tibetan, Mongolian, and Naxi. LP is renowned as China's largest Yi settlement, with a Yi household population of 2,936,500 as of the end of 2021, constituting of 54.56% of the total household population.

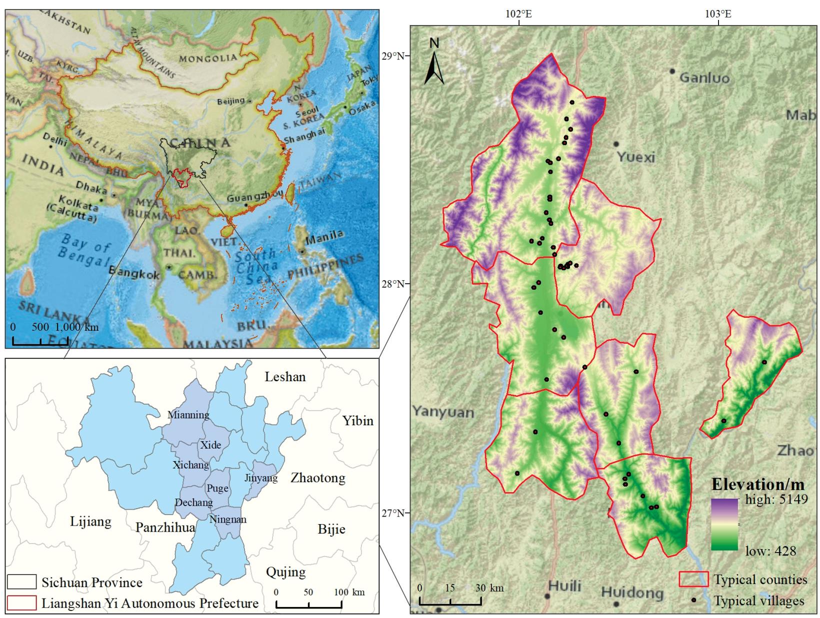

Figure 1. Geographic location of the study area.

2.2. Data Sources

Combined with the recommendation of local government departments, after several on-site surveys and a comprehensive consideration of the disaster characteristics, topography and geomorphology, the population density, socioeconomic development and farmers' income levels of each area, and seven counties and cities, namely, Mianning, Xichang, Xide, Dechang, Jinyang, Puge, and Ningnan, were selected for inclusion in this study as typical counties and cities of the region, and the basic information of each county and city is shown in Table 1. Typical counties and cities were selected on the basis of (1) strong mountain disaster interferences. Most of the mountain disasters in LP occur on the banks of river valleys and are distributed along the water system network. (2) The level of socio-economic development has a gradient. Jinyang County, Xide County, and Puge County are the key counties for national rural revitalization, with strong policy inclinations, while Mianning

County, Xichang City, Dechang County, and Ningnan County belong to the Anning River Basin, which is an important growth pole for economic development in LP. The basic principles followed in the selection of typical villages are the following: (1) there have been mountain disasters or there are hidden spots of mountain disasters and (2) NRCEs have different stages of development.

The survey process used the participatory rural appraisal (PRA) method to conduct one-on-one interviews with 51 local village leaders, and each questionnaire took approximately two hours. The content of the interviews included the basic situation of the administrative village, the development of the rural collective economies, and the level of the disaster's threat or loss. Finally, 48 valid questionnaires were obtained. The geographic information data came from the National Science and Technology Infrastructure Platform, the National Earth System Science Data Center (http://www.geodata.cn, accessed on 10 April 2023), and the Geospatial Data Cloud (http://www.gscloud.cn, accessed on 10 April 2023). The socio-economic data are from the statistical yearbook in 2019 for LP.

Table 1. Basic information on the selected counties and cities in 2019.

Name	Area (km^2)	Average Altitude (m)	Landform	Population Density (Person/km^2)	GDP per Capita/CNY	Per Capita Disposable Income of Rural Residents/CNY
Mianning	4422	2744.14	semi-high mountainous areas	91.6	31,842	16,136
Xichang	2657	2170.91	river valley	257.7	61,120	19,656
Xide	2202	2613.55	semi-high mountainous areas	102.6	18,700	9736
Dechang	2300	2258.35	river valley	94.6	34,701	19,052
Jinyang	1587	2146.06	semi-high mountainous areas	134.2	22,773	9745
Puge	1905	2493.45	semi-high mountainous areas	114.7	18,128	11,417
Ningnan	1672	1881.45	semi-high mountainous areas	119.6	34,349	17,186

2.3. Methodology

2.3.1. Evaluation of the Indicator System

Building upon the theory of complex adaptive systems, Martin defined economic resilience as the regional economic system's ability to adapt and restructure its industrial, technological, and institutional frameworks in response to market, competitive, and environmental shocks [41]. This adaptive capacity is aimed at mitigating the impacts of such shocks, sustaining the system's ongoing development, or even leveraging such shocks to facilitate the system's renewal. Martin categorizes economic resilience into four interconnected dimensions: preventive capacity (PVC), coping capacity (CPC), adaptive capacity (ADC), and transformational capacity (TFC). On this basis the RRCEs is defined in this study as the internal conditions of the rural collective economic system in the absence of a mountain disaster or in the stable state of the rural collective economic system that transitions into a new and higher level through the reorganization of elements and structural adjustments after the impact of a mountain disaster. The resilience of rural collective economic system is measured from four dimensions, namely, the PVC, CPC, ADC, and TFC (see Table 2).

PVC refers to the proactive measures taken prior to a disaster to mitigate the losses inflicted upon the rural collective economies. Disaster insurance coverage serves as an objective reflection of farmers' awareness of disaster prevention and mitigation and acts as an effective mechanism for mitigating losses. It leads young people to exhibit a heightened understanding of disaster prevention and mitigation activities, including emergency drills and village-wide awareness campaigns. Through their influential role, young laborers can effectively disseminate their understanding of disasters to their older and younger relatives and friends within their social circles. CPC is defined as the ability of the rural collective economic system to withstand shocks and maintain its normal functioning in the event of a disaster. Maintaining well-defined monitoring systems and assigned responsibilities for disaster sites are crucial for villages to effectively gather disaster information and promptly respond by issuing early warnings. The number of emergency shelters indicates the accessibility and convenience of emergency shelters for rural residents. At the same time, capacity characterizes the inventory of the available equipment that can withstand the impacts of disasters [19]. ADC is defined as the remedial measure that the rural collective economy can provide after a disaster occurs and the series of changes in the economy, society, and farmers' lives that occur in the face of the disaster process. Per capita income characterizes the average economic level of farming households, and higher economic conditions empower such households with greater adaptability, thereby reducing the pressure on the village. Those individuals receiving the minimum subsistence allowance represent a vulnerable group, and village collectives prioritize their development by providing them with assistance. The higher the proportion of low-income individuals is, the more challenging it becomes to advance the collective economies [42]. An adequately developed health care system can strengthen the rural social security capacity and mitigate the impact of uncertainties [43]. TFC is evident in the efforts undertaken by the government, village collectives, or farm households to maintain, repair, or support the development of the rural collective economies. The per capita cultivated land area reflects the level of resource endowment in rural areas. A higher per capita cultivated land area signifies a more abundant foundation for the development of the primary industry [29]. The number of agricultural technicians signifies the extent of the local government's support for agricultural science and technological development. Higher levels of technological progress can foster new dynamics for economic development [44]. The per capita village collective economic organization book capital reflects the level of financial capital within the village collective. Areas with a strong economic base can promptly adapt to mountain disaster shocks, thereby enhancing the stability of economic development [45]. The distance of an area from the county core reflects its level of infrastructure development. Smaller distances indicate a stronger spillover effect of urban development, resulting in increased employment and educational opportunities for the residents of those areas and their children [30].

Table 2. Variable system for assessing RRCEs.

Dimension	Indicator	Variable	Definition	Unit
PVC	Disaster prevention awareness	Disaster insurance coverage (X_1)	Ratio of the number of farmers who purchased disaster insurance to the total number	%
	Human capital	Percentage of labor force (X_2)	Ratio of the population in the 15–64 age group to the total population	%
CPC	Emergency response	Number of persons with clear responsibilities (X_3)	Number of specialized disaster site monitors and responsible persons	person
		Number of emergency shelters (X_4)	Number of emergency shelters in the village	number
		Emergency shelter capacity (X_5)	Ratio of the number of people who can be accommodated in emergency shelters to the total household population	/

Table 2. *Cont.*

Dimension	Indicator	Variable	Definition	Unit
ADC	Economic foundation	Per capita income (X_6)	Income level of the rural population	CNY
	Social security	Proportion of underinsured persons (X_7)	Ratio of the number of underinsured persons to the total household population	%
		Number of doctors and sanitarians (X_8)	Number of doctors and sanitarians in village health care facilities	person
TFC	Production conditions	Cultivated land area per capita (X_9)	Ratio of the cultivated land area to the total household population in the village	hm^2
	Technological advancement	Number of agricultural technicians (X_{10})	Number of agricultural technicians in the village	person
	Industrial development	Per capita funds from village collective economic organizations (X_{11})	Ratio of the book capital of the village collective economic organizations to the total population	CNY
	Transportation accessibility	Distance from the county core (X_{12})	Village distance from the nearest county core area	km

2.3.2. Assessment Methodology

Since resilience is the result of multiple factors that are difficult to directly measure [46], a latent variable model is constructed to measure RRCEs based on the RIMA model. The RIMA model was first proposed in 2008 [36] to measure the resilience of farm households to food security risks. It has been updated over many iterations and developed into the latest RIMA-II model [38]. The RIMA series model considers each dimension as a latent variable and comprehensively measures the resilience index based on factor analysis and the multiple indicators–multiple causes (MIMICs) model, which is an approach that better avoids the limitations of subjectivity that exist in conventional resilience assessment methods, and it is widely used in the field of resilience assessment [37] (Figure 2).

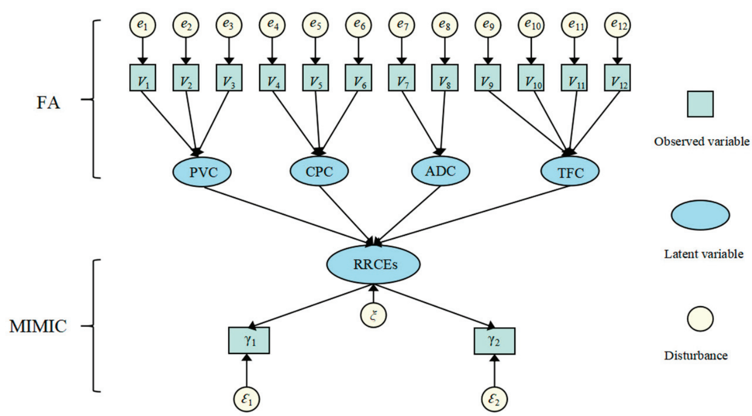

Figure 2. RIMA model framework.

(1) Constructing a matrix of raw indicators

With n villages and h evaluation indicators, the original indicator matrix is established as $X = \{X_{ij}\}n{*}h$ $(1 \leq i \leq n, 1 \leq j \leq h)$, where X_{ij} is the value of the j indicator for the i village.

(2) Dimensionless treatment

The original indicators in the indicator system were converted to dimensionless indicators using the following formula from the polarity standardization method:

$$P_{ij} = (X_{ij} - X_{min})/(X_{max} - X_{min}) \quad (1)$$

where P_{ij} is the value of the j dimensionless indicator for the i village, X_{ij} is the value of the j raw indicator for the i village, X_{min} is the minimum value of the j raw indicator, and X_{max} is the maximum value of the j raw indicator.

(3) Factor analysis

Due to the correlation between variables in the evaluation index system, factor analysis can be used to replace the original indicators by selecting four independent public factors that contain most of the information of the original indicators in accordance with the idea of dimensionality reduction to simplify the relationship between complex variables without losing the original information. The results of KMO and Bartlett's test of sphericity show that the KMO test coefficient (0.640) was greater than 0.5 and the Bartlett's test coefficient (Sig.) was 0, which, being less than 0.05, indicated that the original data were suitable for factor analysis. According to the correlation size between the public factors and the evaluation indices, the first public factor mainly describes the TFC of the rural collective economic system, the second public factor mainly expresses the ADC, the third public factor mainly expresses the CPC, and the fourth public factor mainly expresses the PVC. The cumulative variance contribution rate of these 4 public factors reaches 68.30%, which constitutes a reasonable degree of explanation.

(4) Constructing the MIMICs model

The MIMICs model is a form of structural equation used to estimate unobservable variables. In order to solve the model, it is necessary to estimate a set of joint equations, introducing cause and indicator variables, establishing a relationship between unobservable and observable variables, and making it suitable to estimate unobservable resilience [47–49]. In the MIMICs model, the RRCEs is considered a latent variable that is related to a set of causal variables that are used to determine economic resilience on the one hand and that affect a set of observable indicator variables on the other. Thus, the MIMICs model consists of two parts, the measurement model and the structural model, which portray the impact of the PVC, CPC, ADC, and TFC on the RRCEs and the extent to which the RRCEs responds to the indicator variables, respectively.

Thus, the MIMICs model consists of two parts, the measurement model and the structural model, which reflect the relationship between the new rural collective economic resilience and the indicator and cause variables, respectively. The measurement model is expressed as follows:

$$\gamma_1 = \lambda_1 \text{ RRCEs} + \varepsilon_1 \quad (2)$$

$$\gamma_2 = \lambda_2 \text{ RRCEs} + \varepsilon_1 \quad (3)$$

$$\gamma_3 = \lambda_3 \text{ RRCEs} + \varepsilon_3 \quad (4)$$

$$\gamma_4 = \lambda_4 \text{ RRCEs} + \varepsilon_4 \quad (5)$$

where RRCEs denotes the resilience level of the rural collective economies, γ_1 and γ_2 denote indicator variables related to RRCEs, λ_1 and λ_2 denote the parameters of the measurement model, and ε denotes the measurement error vector.

The structural model is expressed as follows:

$$\text{RRCEs} = \beta_{\text{PVC}} \text{ PVC} + \beta_{\text{CPC}} \text{ CPC} + \beta_{\text{ADC}} \text{ ADC} + \beta_{\text{TFC}} \text{ TFC} + \xi \quad (6)$$

where PVC, CPC, ADC, and TFC denote the cause variables' levels of preventive capacity, coping capacity, adaptive capacity, and transformational capacity, respectively; β_{PVC}, β_{CPC}, β_{ADC}, and β_{TFC} denote the parameters of the structural model; and ξ denotes the random perturbation term. RRCEs is a relative concept rather than an absolute unit of measurement, and the larger its value is, the stronger the ability to combat risk and the more stable the development of the NRCE.

The four dimensions of rural collective economic resilience proposed in this study, i.e., PVC, CPC, ADC, and TFC, serve as the MIMICs model's four causal variables. In addition, four indicator variables, namely, per capita collective economic income, the number of cooperatives, the number of agribusinesses, and the number of family farms and large-scale farmers, were selected in this study for use in the MIMICs model analysis, and the indicators were selected on the following basis. The resilience of the rural collective economy directly determines the income and distribution of the collective economies such that the more robust the resilience is, the stronger the sustainability of the collective economic development and the higher the income; thus, the per capita collective economic income indicator was selected. A stable natural and social environment is conducive to the growth and expansion of new agricultural business entities, so the number of cooperatives, the number of agricultural enterprises, and the number of family farms and large farming households were selected to characterize the stable development of the NRCE (Table 3).

Table 3. MIMICs model construction for the evaluation of the RRCEs.

Variable Type	Variable Name	Definition	Unit
Causal variables	PVC	Based on the four common factors extracted from the factor analysis (latent variables)	/
	CPC		/
	ADC		/
	TFC		/
Indicator variables	Per capita collective economic income	Ratio of the village collective economic income to the total household population in 2022	CNY
	Number of cooperatives	The number of shareholding economic cooperatives and specialized cooperatives	number
	Number of agricultural enterprises	The number of leading agricultural industrialized enterprises	number
	Number of family farms and large-scale farmers	The number of family farms and large-scale farmers	number

2.3.3. Analysis Methodology for the Factors Influencing RRCEs Based on Qualitative Comparisons

Due to the village-scale nature of this study, obtaining a large sample size is challenging, making traditional statistical or econometric analysis methods unsuitable for attribution analysis. Qualitative comparative analysis (QCA) is a comparative analytical method that is focused on cases, where each case is seen as a combination of conditions. By comparing the differences among cases, QCA is used to identify the causal relationships between condition groups and outcomes, thus addressing the following research question: 'Which groups of conditions lead to the occurrence or nonoccurrence of the desired outcome?' This approach is particularly suitable for attribution studies with small sample sizes [50]. In this paper, the intention is to use QCA, which is based on set theory, to analyze the multiple and complex mechanisms that contribute to the RRCEs from a group state perspective. This is because, unlike the traditional statistical analysis of binary relationships, QCA recognizes the fact that the interdependence and diverse combinations of causal conditions form multiple and concurrent relationships. This approach facilitates a more comprehensive understanding of the distinct driving mechanisms underlying the resilience of village domains. Hence, QCA is better suited for investigating the interplay of multiple factors that influence the RRCEs from a holistic perspective. Furthermore, the paths for enhancing the RRCEs in each village domain are diverse. Multiple causal pathways can lead to the same equivalent outcome, and the QCA method can effectively identify the complete the equivalence of different antecedent condition groups that are not mutually contradictory but do contribute to the interpreted outcome.

The QCA analysis comprises two main stages. The first stage involves testing whether a single condition (including its nonsets) is a necessary condition for the RRCEs. If a condition is consistently present when the focal outcome occurs, then it is considered necessary for the outcome. Consistency is used as the criterion to evaluate necessary conditions, and a consistency value that exceeds 0.9 indicates that the condition is necessary for the outcome. The second stage involves conducting a conditional grouping analysis to assess the sufficiency of different groups, based on multiple conditions, to cause the outcome [51]. Consistency is also employed to assess the adequacy of the configuration, with a minimum acceptable standard of 0.75 [51].

The new endogenous development theory integrates endogenous and exogenous theories, emphasizing the combined influence of internal and external resources and promoting sustainable development. It aligns with the current mainstream rural development theory used in developed European countries [52]. This study incorporates both existing research findings and current realities [53–55]. The stable development of the rural collective economy requires a combination of internal and external resources, including (1) human resources, (2) financial resources, (3) institutional supply, (4) technical conditions, and (5) natural resources. Accordingly, the factors that influence the RRCEs are analyzed using QCA, and the selected conditional variables are outlined in Table 4. (1) Talent security: This study reveals a strong correlation between elite talent and the stable development of the rural collective economies. Villages led by individuals with overall capabilities such as returnees, university students, and businessmen are assigned a value of 1 while others receive a value of 0. (2) Financial security: the development of the rural collective economy cannot be separated from government support, especially in disaster-prone areas where economic development is threatened by the multiple threats of mountain disasters, which require the government to invest large amounts of money to help. (3) Institutional security: The reform of the rural property rights system is essential for the development of the rural collective economies. The analysis is used to assess the impact of institutional safeguards based on the extent and effectiveness of the reform. (4) Technological security: the adoption of advanced agricultural technologies, such as drip irrigation, are denoted by a value of 1 if the technological conditions adequately support the long-term development of the rural collective economy and of 0 otherwise. (5) Business security: Business assets represent the resource endowment of the village. A more favorable business environment correlates with greater income, reflecting the resource base of the collective economy.

Table 4. Variable definitions.

Variable Name	Definition and Assignment
RRCEs	Based on the results of the previous analysis of the natural breakpoint method, villages with a low resilience level in the 3-class hierarchy were assigned a value of 0, and villages with a medium-high resilience level were assigned a value of 1.
Talent security	Villages with returning entrepreneurs, college students, businessmen, and other entrepreneurial leaders are assigned a value of 1, and 0 is assigned otherwise.
Financial security	Set to 1 if there is a financial allocation and to 0 otherwise.
Institutional security	Set to 1 for a thorough reform of the rural property rights system and to 0 otherwise.
Technological security	Set to 1 for the adoption of advanced agricultural technologies and to 0 otherwise.
Business security	Set to 1 for having a business income and to 0 otherwise.

3. Results

3.1. The Evaluation of the RRCE toward Mountain Disasters

The MIMICs model constructed above was empirically analyzed through the use of the AMOS software 24, and the fitting results are shown in Table 5. For the test index of goodness of fit, it is generally believed that a model fits well when $1 < \chi^2/df < 3$, RMSEA < 0.08, and CFI > 0.95, indicating that the model fits well. The model $\chi^2/df = 1.097$, RMSEA = 0.045, and CFI = 0.952 indicates a good model fit [56]. All four causal variables significantly and positively affect the RRCEs. The resilience level increases by 0.029, 0.029, 0.037, and 0.075 units for each unit increase in the PVC, CPC, ADC, and TFC, respectively. The unstandardized coefficient of the TFC is the largest, indicating that by enhancing the value of the capacity by 1 unit, the TFC obtains a utility of 2–3 times higher than that of the PVC, CPC, and ADC; thus, the TFC is the key to enhancing the resilience level of the rural collective economic system in the study area. For every 1 unit increase in the level of resilience of new rural collective economies, the number of cooperatives increases by 0.944 units, the number of agribusinesses increases by 1.178 units, and the number of family farms and large-scale farmers increases by 0.894 units. Accordingly, an assessment model for the RRCEs can be obtained:

$$\text{RRCEs} = 0.029\ \text{PVC} + 0.029\ \text{CPC} + 0.037\ \text{ADC} + 0.075\ \text{TFC} \tag{7}$$

Table 5. Results of the MIMICs model for the evaluation of RRCEs.

Variable Type	Variable Name	Non Standardized Coefficients	Standard Errors	T Value	p-Value
Causal variables	PVC	0.029 *	0.017	1.691	0.091
	CPC	0.029 *	0.017	1.648	0.099
	ADC	0.037 *	0.020	1.832	0.067
	TFC	0.075 ***	0.024	3.080	0.002
Indicator variables	Per capita collective economic income	1.000			
	Number of cooperatives	0.944 **	0.409	2.311	0.021
	Number of agricultural enterprises	1.178 ***	0.401	2.935	0.003
	Number of family farms and large-scale farmers	0.894 **	0.374	2.392	0.017

Notes: *, **, and *** denote 10%, 5%, and 1% significance levels, respectively. Collective economic income per capita is a predetermined scale indicator for the model, and it has a parameter of one.

3.2. Spatial Distribution Pattern of the RRCEs in Regard to Mountain Disasters

The distribution of the RRCEs in the sample villages ranges from −0.166 to 0.410. The level of rural collective economic resilience is divided into three categories according to the natural discontinuity point method, which shows that the resilience of typical villages is dominated by medium and low levels, accounting for 45.84% and 39.58% of the total, respectively, and that these villages are mainly located in the northern region. Only seven villages have a high level of resilience, and they are concentrated in Ningnan County, Mianning County, and Xide County. The level of resilience of the rural collective economy in the study area is not high, and it generally shows a spatial pattern that is slightly higher in the south than in the north (Figure 3).

The range of the PVC values in typical villages is −1.331–2.866, and the PVC of villages in the northern region exhibits a significantly higher value than those in the southern region (Figure 4). Villages were categorized into low, medium, and high levels of PVC, accounting for 43.75%, 33.33%, and 22.92% of the total, respectively. This expands the range of villages with a high PVC, which differs from villages with high rural collective economic resilience levels. The range of the CPC varies from −1.300 to 3.997, showing spatial characteristics similar to those of the rural collective economic resilience, with higher values observed in the south and lower values in the north. The ADC ranges from −1.412 to 4.240. The majority of villages (52.08%) exhibit a medium level of ADC, followed by those exhibiting a low level (43.75%), with only two villages at the high level. This pattern forms an olive-shaped structure, with lower values observed in the north and higher values in the south. The TFC spans from −1.491 to 3.741, and villages with low, medium, and high levels account for 45.83%, 37.50%, and 16.67% of the total, respectively. A concave central section with prominent north and south ends characterizes the spatial distribution of the target area.

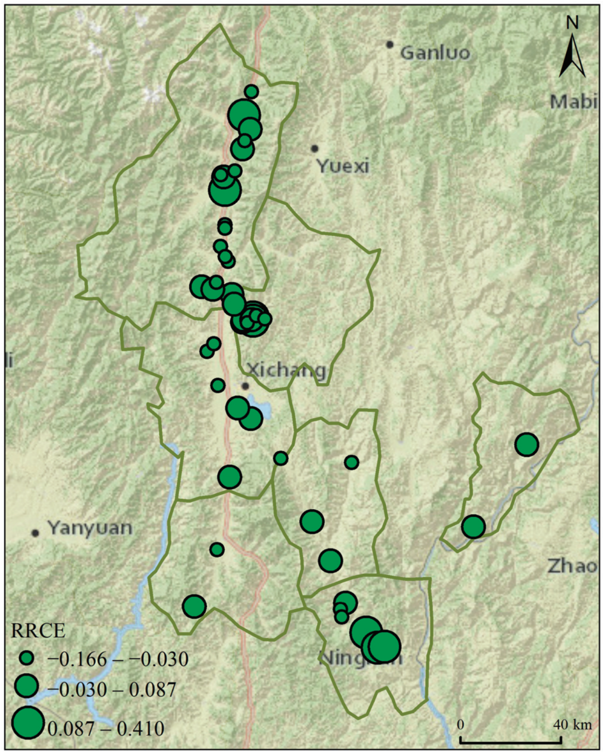

Figure 3. Spatial distribution pattern of RRCEs.

3.3. Comparison of Different Types of RRCEs

Based on the variations in nonfarming and income diversification seen within the new rural collective economies and considering the findings of previous research [57], rural collective economic development is classified into three categories: purely agricultural, diversified, and off-farm. Villages without a non-farm income from the NRCE are classified as purely agricultural, while those with a nonagricultural income share in excess of 95% are categorized as off-farm. Those villages falling between these extremes are considered diversified. Out of the total sample of 48 villages, 12 were classified as purely agricultural, 24 as diversified, and 12 as off-farm, accounting for 25.00%, 50.00%, and 25.00% of the sample, respectively.

Regarding the RRCEs, off-farm villages exhibit the highest level of resilience (mean value of 0.013), followed by diversified villages (mean value of 0.002) and purely agricultural villages with the lowest level (mean value of −0.011). These findings suggest that the variations in these three industrial structures in the new rural collective economies contribute to the differences in resilience levels. In terms of the PVC, the ranking of the development types is as follows: diversified (mean value of 0.274) > purely agricultural (mean value of −0.240) > off-farm (mean value of −0.336). Additionally, the standard deviation of off-farm villages is the highest (1.079), indicating significant variations in this category. These results suggest that off-farm villages need to address their limitations and work toward reducing internal disparities. In terms of the CPC, the ranking of the development types proceeds as follows: off-farm (mean 0.315) > diversified (mean −0.011) > purely agricultural (mean −0.335). This indicator reveals the most substantial difference in capacity among the different development types, with a deviation of 0.650, a fact that highlights that the disparity in resilience among villages primarily manifests in their CPC. Regarding the ADC, the ranking of the development types is as follows: diversified (mean 0.097) > purely agricultural (mean −0.059) > off-farm (mean −0.230). This capacity indicator shows the least variation among the different types of villages. In terms of the TFC, the ranking of the development types is as follows: off-farm (mean 0.299) > purely agricultural (mean 0.042) > diversified (mean −0.127) (Figure 5).

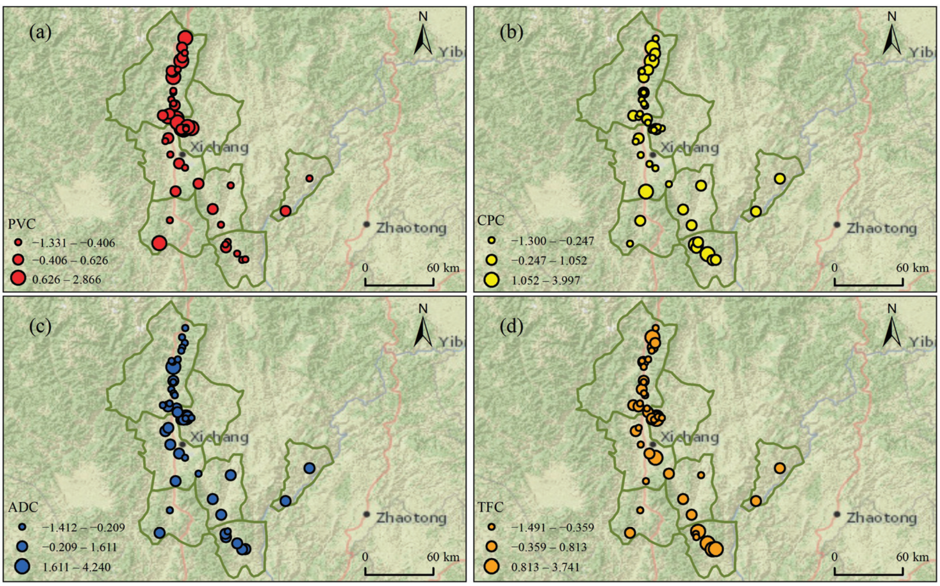

Figure 4. Spatial distribution pattern: (**a**) PVC, (**b**) CPC, (**c**) ADC, and (**d**) TFC.

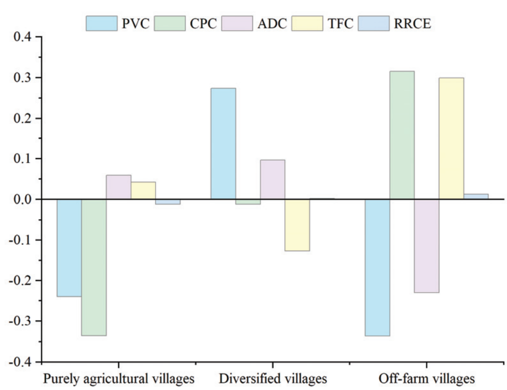

Figure 5. Comparison of PVC, CPC, ADC, TFC, and RRCEs in purely agricultural, diversified, and off-farm villages.

3.4. Factors Influencing the RRCEs in Regard to Mountain Disasters

3.4.1. Necessity Analysis of Individual Conditions

According to the analysis results of the natural breakpoint method conducted in the previous section, villages with low resilience levels were assigned a value of 0, and villages with medium-high resilience were assigned a value of 1. First, whether a single condition (including its nonset) constitutes a necessary condition for the RRCEs was tested. According to the test results, the consistency of talent security is 0.962; thus, it can be regarded as a necessary condition for the focal outcome, and further, through the coverage rate, we know that it can be used to explain more than 59.5% of the cases; that is, 59.5% of the total rural collective economic development is dominated by elite capacity. Therefore, talent security can be seen as an important influence on the RRCEs (Table 6).

Table 6. Analysis of necessary conditions.

Conditional Variables	High Resilience Level of RRCEs		Low Resilience Level of RRCEs	
	Consistency	Coverage	Consistency	Coverage
Talent security	0.962	0.595	0.773	0.405
~Talent security	0.038	0.167	0.227	0.833
Financial security	0.692	0.692	0.364	0.308
~Financial security	0.308	0.364	0.636	0.636
Institutional security	0.577	0.625	0.409	0.375
~Institutional security	0.423	0.458	0.591	0.542
Technological security	0.731	0.559	0.682	0.441
~Technological security	0.269	0.500	0.318	0.500
Business security	0.654	0.515	0.727	0.485
~Business security	0.346	0.600	0.273	0.400

3.4.2. Sufficiency Analysis of Conditional Groups

The above factors affecting the RRCEs yielded a total of 32 ($2^5 = 32$) groups. Consistency is also used as a measure of group adequacy, but the minimum acceptable standard is 0.75, and the frequency threshold is 1. The final group results are shown in Table 7. The six optimal forms of conditional combinations constituted by the five conditional variables, with a coverage of 0.808, show strong explanatory power, whereas S2a and S2b share the same core conditions; thus, they are second-order equivalent groups.

Table 7. Group analysis of high levels of RRCEs.

Conditional Combination	Number of Shared Cases	Talent Security	Financial Security	Institutional Security	Technological Security	Business Security	Raw Coverage	Unique Coverage	Consistency
S1	3	●	⊗		⊗	⊗	0.115	0.038	1
S2a	3		☐	●	☐	⊗	0.115	0.038	1
S2b	3	■		●	■	⊗	0.115	0.038	1
S3	3	●	⊗	●	⊗		0.115	0.038	1
S4	10	■	●	⊗		●	0.308	0.308	0.8
S5	8	■	●	●	●		0.269	0.192	0.875
Solution coverage								0.808	
Solution consistency								0.875	

Notes: ■ or ● indicate that the condition exists, ☐ or ⊗ indicate that the condition does not exist, ● or ⊗ indicate a core condition, and ■ or ☐ indicate an edge condition. A blank space indicates that the condition may or may not exist.

(1) Talent security type (S1): For Group S1, when talent security is present, other conditions become irrelevant in realizing high levels of rural collective economic resilience. Therefore, talent security is considered both a necessary and sufficient condition for achieving high levels of resilience.

(2) Institutional security type (S2a): The presence and centrality of institutional security within Group S2a indicates that institutional security, compared to other conditions, plays a significant role in achieving high levels of resilience. Therefore, institutional security itself can be considered a sufficient condition for explaining the results and represents another critical factor that influences the RRCEs.

(3) Talent-technological-driven with institutional security type (S2b): For Group S2b, institutional security serves as the fundamental condition, complemented by human

resources and technical security, needed to generate a high level of rural collective economic resilience. This indicates that even villages without significant business assets can achieve a high level of rural collective economic resilience when operating within a robust institutional security framework supported by adequate human resources and technical assistance.

(4) Institutional and talent dual-security type (S3): In Group S3, talent security, nonfinancial security, institutional security, and nontechnological security emerge as the core conditions, indicating that the presence of abundant human resources and comprehensive institutional reforms can effectively address financial and technical challenges and lead to a high level of rural collective economic resilience. For instance, on the basis of the prevention and treatment of potential disasters, the Echigeze village, leveraging its advantageous geographic location, has achieved a high level of rural collective economic resilience through strategic measures. These measures include implementing collective membership identifications, conducting asset verifications, holding elections for a supervisory board or council, generating rental income from vacant factory buildings, and appointing a dedicated individual to oversee the management of the collective economies. Notably, the Ochi Geze Village has accomplished this feat despite facing a severe shortage of agricultural technicians to support their arable land resources.

(5) Talent-driven under the duality of financial and business security type (S4): In Group S4, financial security, noninstitutional security, and business security constitute the core conditions, with talent security playing a secondary role. This suggests that villages with imperfect institutions can still attain high levels of resilience in their rural collective economies, given that the local government provides financial support for industrial development and brings in talented individuals for effective management. The original coverage of this group is 0.308, and its unique coverage is also 0.308, signifying that this is the path with the highest explanatory power.

(6) Talent-driven under the triad of financial, institutional, and technological security type (S5): For Group S5, financial, institutional, and technological security occupy central roles, while human security plays a complementary role. The role of business assets in fostering rural collective economies with high levels of resilience is discretionary within this environment.

4. Discussion

4.1. Characterization of the RRCEs in Regard to Mountain Disasters

In the context of global warming, southwest China has experienced an increase in the frequency and intensity of extremely heavy rainfall [58], which has led to frequent mountain disasters [59] that have significantly impacted human economic and social systems [60]. These challenges are particularly pronounced in rural areas with limited infrastructure and public services [61]. Exogenous rural development policies have proven effective in enhancing the capacity of villages to withstand and recover from external shocks [62], leading to an increased economic resilience that relies on greater support being provided to villages [30]. However, it is essential for these policies to account for the unique characteristics of diverse rural areas, as their outcomes have been mixed [21]. Endogenous rural collective economies achieve sustainable development by strengthening the supportive role of grassroots rural organizations and harnessing the internal dynamics of rural development, thereby delivering sustained benefits to farmers. The frequent incidence of mountain disasters in the southwestern region has impeded the progress of the rural collective economies. Current engineering-based measures are limited in adequately addressing the requirements of rural-community disaster management, including legal and regulatory frameworks, disaster-prevention awareness and education, disaster insurance, and emergency response plans. Assessing the rural collective economic system in disaster-prone areas from a resilience standpoint underscores that the countryside functions as a spatial–territorial system [63]. This perspective acknowledges the significance of physical space, geographic characteristics, population density, cultural values, and other factors within the rural context [64]. Moreover, it recognizes the importance of natural environmental elements in the southwestern mountainous areas in shaping the overall rural system.

In this study, the crucial role of the rural collective economies' ability to adapt to mountain disasters in building resilience is highlighted. Enhancing the TFC is key to improving resilience levels. Mountain disasters and meteorological events pose a significant risk to crops, farmland water conservancy projects, roads, communication equipment, and other infrastructures in the impoverished mountainous areas of southwest China. Restoring damaged infrastructures necessitates substantial inputs of skilled personnel, materials, and financial resources. This inevitably impacts industrial inputs in the short or even long term, imposing heightened demands on the development of the already-fragile rural collective economies. In light of this, the central government and local authorities have allocated significant financial resources to promote the growth of the rural collective economies, beginning with its nascent stages and progressively strengthening it. These "shell villages" and weak villages can choose appropriate development methods under the guidance of local governments. However, there is a lack of awareness among villagers regarding collective action [65], and the prevalence of 'free-riding' behavior in the operation of cooperatives represents a common challenge [66]. Moreover, the limited penetration of local governments at the grassroots level has led to the convergence of rural industry types and the lack of product competitiveness [67], thus impeding the progress of the rural collective economy in its early stages. To achieve significant developmental progress, fostering innovation and devising tailored approaches that align with local conditions is crucial. For instance, the success of Japan's 'one village, one product' movement, which has been adopted in various Asian and developing countries [68–70], can be attributed to administrative support for self-governance which allows for the expression of rural social autonomy, thereby harnessing local potential [71].

Considering the varying resilience of different industry types in addressing mountain disasters, rural collective economic development in LP is classified into three categories in this study: purely agricultural, diversified, and off-farm. The findings indicate that off-farm villages exhibit the highest level of resilience, followed by diversified villages, while purely agricultural villages demonstrate the lowest level of resilience. These results suggest that the agricultural industry is particularly susceptible to natural disasters, making it the most fragile industry type. As early as the 1940s, Japan implemented the Agricultural Disaster Compensation Law, which has played a significant role in supporting the development of the agricultural industry in impoverished areas [72]. Additionally, there is a consensus on the use of agricultural insurance as a preventive measure [73]. To achieve the healthy and sustainable development of rural specialty industries in poverty-stricken areas, establishing a comprehensive industrial chain is crucial. In addition to agriculture, the agricultural-product-processing industry can significantly increase farmers' incomes by enhancing the added value of agricultural products. To safeguard the interests of village collectives and farmers, establishing a rights protection system based on farmers' professional cooperatives and shareholding economic cooperatives is essential. This ensures that more of the added value of agriculture remains within rural areas and prevents the encroachment of external capital on rural collective resources, which can be detrimental [74,75]. Tourism built upon local cultural and natural resources can also yield economic benefits for village collectives and farm households, albeit only after substantial upfront investments in infrastructure development. For instance, in the anti-poverty initiative undertaken in the Appalachian region of the United States, significant government investments in road construction played a pivotal role in enhancing transportation in mountainous areas and reducing isolation from the outside world. This, in turn, created the necessary conditions for poverty eradication [76].

4.2. Factors Influencing the RRCEs

The study results show that talent security significantly influences the RRCEs. Higher cultural quality, greater professional competence, and broader horizons among business managers enable the exploration of new approaches in the collective economic system to address the challenges posed by mountain disasters. These findings align with previous studies [29]. While the presence or absence of financial security does not consistently impact the level of the RRCEs, Cui et al. argued that government support plays a critical role in driving collective economic developments in developing countries [30]. Moreover, they highlight the fact that government support has a more pronounced effect in areas with deeper poverty levels. The observed disparity can be attributed to the presence of distinct coercive variables in each study area. For instance, Cui et al. examined Lankao County in Henan Province, a key county for national poverty alleviation efforts, to explore the resilience of rural economic system in addressing external economic fluctuations, macro-controls, industry competitions, and other disruptions. In contrast, the primary threat to LP is mountainous disasters, for which basic disaster-resilience measures, such as disaster prevention and mitigation awareness, and disaster-escape skills among rural residents are required [30]. These measures cannot be solely achieved through financial support but rather also require publicity and education by village cadres or schools, as well as emergency drill training. Institutional security is a prerequisite for the development of the rural collective economies. At the same time, technology serves as a safeguard, while business assets form its foundation. Incomplete institutional reform [35], the insufficient promotion of agricultural and animal husbandry technology [77], and a lack of business assets [33] hinder the stable development of the rural collective economies. This, in turn, impacts the collective income of villages and the individual incomes of rural residents. Consequently, rural collective economies become unable to bear the burden of disaster reconstruction funds and subsidies for residents affected by disasters, which leads to a reduction in the level of resilience.

4.3. Remaining Issues, Prospects, and Policy Implications

This paper utilizes the RIMA model to assess an RRCEs. The advantage of this model lies in its ability to overcome the subjective biases often associated with conventional resilience-assessment methods. Moreover, the incorporation of structural equation modeling allows for greater flexibility in capturing the four capacity dimensions. However, one limitation of this method is the inability to observe the specific contribution of each evaluation index to the resilience level. To address this, establishing a matrix of component score coefficients in factor analysis and cause variable coefficients in the MIMICs model is recommended. This approach can help to uncover the importance ranking of the evaluation indicators. Furthermore, considering the existence of various types of mountain disasters, recognizing that the RRCEs may differ under different types of mountain-disaster coercions is crucial. Therefore, conducting future in-depth analyses to explore the resilience differences and commonalities among different disaster types is recommended. LP is an area inhabited by ethnic minorities, where residents have developed a unique disaster culture through their interactions with nature [78]. This includes practices such as nature worship and ancestor worship, which reflect the Yi people's understanding of disasters, their perception of the relationship between human beings and nature, and their ethical view of nature in harmony with the sky and human beings. In the future, further exploration of the impact of this local knowledge on the RRCEs regarding mountainous disasters is recommended.

Combined with the results of the current study, the following policy recommendations are presented to enhance the RRCEs in the face of mountain disasters: (1) Improve the coverage rate of disaster insurance and enhance the PVC. Given the high vulnerability of the agricultural industry, it is essential to increase the coverage rate of agricultural insurance. This can be achieved by leveraging the public service capacity of the rural collective economies. The village's collective economic organization should further engage in negotiations with insurance companies to determine the types of insurance and compensation standards. (2) Improve the emergency protection system and enhance the CPC. Comprehensive disaster-relief programs that encompass assistance for vulnerable groups and affected industries need to be developed. Additionally, clear working guidelines or standard systems for various phases of disaster management, including prevention and preparedness, monitoring and early warning, emergency response, and recovery and reconstruction, need to be established. (3) Rural collective economies should be grown, and the ADC should be enhanced. The rural governance system of "government and society" is prone to the loss of collective assets and revenues. Attempts should be made to divest the functions of basic self-governing organizations and to appoint full-time accountants for the dynamic management of the resources, assets, and funds of the collective economies and the distribution of revenues in the village to unleash the vitality of the collective economies and keep the revenues in the village to the greatest extent possible rather than being encroached upon by external capital. To further bridge the income gap between farmers in the village, a special help fund for low-income groups can be set up to provide additional subsidy funds for poverty-stricken, marginalized, and low-income households. (4) Scientific research and innovation should be promoted to enhance the TFC. The establishment of a human resource development mechanism that combines academic education, skills training, and practical exercises should be actively explored to provide specialized talent for rural development and disaster prevention and mitigation. Several agricultural high-tech industrial demonstration zones and agricultural science and technology parks should be built in villages with a good foundation for industrial development; ecological agriculture, leisure and tourism agriculture, creative agriculture, etc., should be vigorously developed; the deep integration of agriculture with secondary and tertiary industries such as cultural tourism, leisure and recreation, and e-commerce and logistics should be promoted; and an industry–academia-research cooperation mechanism oriented toward the market should be promoted along with the synergistic innovation of enterprises, colleges and universities, and scientific research institutes to revitalize the countryside to form a diversified and stable industrial structure. (5) Context-specific approaches should be adopted. Villages should select appropriate paths and targeted measures based on their economic development level and the characteristics of their natural environments. These paths can include talent security, institutional security, talent-technological-driven with institutional security, institutional and talent dual-security, talent-driven under the duality of financial and business security, and talent-driven under the triad of financial, institutional, and technological security. The development of disaster prevention and mitigation and that of the collective economies should be considered while promoting a stable increase in farmers' incomes. The government should also prioritize efforts to promote sustainable rural development.

5. Conclusions

Considering the vulnerability to mountain disasters of the rural collective economic development in the mountainous areas of southwest China, the RIMA model is enhanced in this study to establish an assessment index system for measuring an RRCEs. The index system encompasses four dimensions, PVC, CPC, ADC, and TFC, and takes 48 typical villages in LP as the research object to analyze the spatial differentiation characteristics of rural collective economic resilience and explains the factors that influence the resilience of rural areas. In this study, the spatial differentiation characteristics of rural collective economic resilience are examined and the factors that influence its level are identified. This study finds that the RRCEs is generally low, and the TFC is the key to improving the resilience level. Considering the variations in nonfarming activities and income diversification within the rural collective economies, the villages were classified into purely agricultural, diversified, and off-farm types. It was found that the agricultural industry is highly vulnerable in the face of mountain disasters and that the RRCEs in off-farm villages is significantly higher than that of the other two. Drawing upon the new endogenous development theory and employing QCA, this study reveals that talent security functions as a significant factor in cultivating a high level of resilience in the rural collective economies. Additionally, institutional security emerges as another crucial factor contributing to a high level of resilience in the rural collective economies. These two factors constitute an important influence on the high resilience level of rural collective economies. Six pathways toward achieving a highly resilient rural collective economy are identified in this study. These pathways include the talent security type, institutional security, talent-technological-driven with institutional security, institutional and talent dual security, talent-driven under the duality of financial and business security, and talent-driven under the triad of financial, institutional, and technological security. Behind the RRCEs lies the result of the synergistic effect of multiple factors. The level of resilience can be enhanced through an effective combination of factors, even when different paths lead to the same destination. Villages should consider their economic development level and resource background conditions and choose the appropriate path based on their local conditions. By implementing targeted measures that coordinate disaster mitigation and development, the RRCEs can be enhanced.

Author Contributions: Conceptualization, Y.Y. and M.L.; methodology, Y.Y.; software (Amos24, ArcGIS10.8), Y.Y.; validation, Y.Y., M.L. and Y.X.; formal analysis, Y.Y.; investigation, Y.Y. and M.L.; resources, Y.X.; data curation, Y.Y.; writing—original draft preparation, Y.Y. and M.L.; writing—review and editing, C.T. and Y.X.; visualization, Y.Y. and C.T.; supervision, M.L.; project administration, M.L; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was jointly funded by the Strategic Priority Research Program of the Chinese Academy of Sciences (grant number: XDA23090501), the National Natural Science Foundation of China (grant number: 41671152, 42001244), and the Sichuan Science and Technology Program (grant number: 2022JDR0209).

Data Availability Statement: The DEM data and administrative boundary data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/ accessed on 10 April 2023) and the National Earth System Science Data Center. Statistical yearbook (https://tjj.lsz.gov.cn/sjfb/lsndsj/tjjnj2020/ accessed on 10 April 2023).

Acknowledgments: The authors would like to thank Yukuan Wang, Pei Xu, and the Haozhe Zhang for their help in theoretical guidance and picture drawing.

Conflicts of Interest: The authors declare no conflict of interest.

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Spatial–Temporal Coupling Analysis of Land Use Function and Urban–Rural Integration in Heilongjiang, China

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Abstract: Urban–rural integration relies on the rational flow of factors between urban–rural areas. Land represents a closely related factor between urban–rural areas, so the effective utilization of land resources can promote the flow of urban–rural factors. Therefore, there is a certain correlation between land use function and urban–rural integration. The purpose of this study is to explore the coupling and coordination relationship between the two systems and to find out the spatial–temporal differentiation characteristics in the process of land use function and urban–rural integration. The main conclusions are as follows: (1) The comprehensive level of land use function and urban–rural integration in Heilongjiang Province shows an overall upward trend, but there is a large differentiation on a municipal scale. (2) The coupling coordination degree of the two systems in Heilongjiang Province shows a spatial distribution pattern of "high in the north and low in the south, high in the middle and low in the east and west". From 2013 to 2022, except for Harbin and Yichun, the overall trend in other regions is gradually upward. (3) The obstacle degree analysis of land use function and urban–rural integration in Heilongjiang Province shows that there is a close correlation of obstacle factors between the two systems.

Keywords: land use function; urban–rural integration; coupling; spatial–temporal analysis

Citation: Zhang, N.; Yao, Y.; Wang, L.; Li, Q. Spatial–Temporal Coupling Analysis of Land Use Function and Urban–Rural Integration in Heilongjiang, China. *Land* **2023**, *12*, 2152. https://doi.org/10.3390/land12122152

Academic Editors: Xueru Zhang, Yaqun Liu, Xingyuan Xiao and Maria Rosa Trovato

Received: 15 October 2023
Revised: 23 November 2023
Accepted: 7 December 2023
Published: 11 December 2023

1. Introduction

An enormous gap exists between rural and urban areas [1]. On average, people in urban areas have more job opportunities and better access to education, safe drinking water, health services, and high-quality infrastructure than rural populations. As a result, at least 80 percent of people living in poverty are found in rural areas, even though rural areas account for only 45 percent of the world's population [2]. Inequalities related to location—also known as "spatial inequalities"—can be extreme between rural and urban areas, especially in developing countries. According to the United Nations, the scope of adequate sanitation in the rural areas of developing countries has increased from 26% in the 1990s to 52% in the 2010s and from 47% to 82% in urban areas during the same period. Therefore, significant progress has been made in this particular aspect in rural areas, but they still lag far behind urban areas. Furthermore, the same holds true for other issues such as secondary school attendance and electricity [3]. A large rural–urban gap may lead to social division, rural dissatisfaction, and even unrest in some countries [4]. In summary, an urban–rural integration (URI) development strategy is designed to solve the urban–rural gap during the process of rapid urbanization and industrialization [5].

URI promotes the free flow of labor, land, capital, and other factors between urban–rural areas [6], such that URI helps to achieve the balance of urban–rural economic development and social equality [7]. URI development emphasizes multi-scale, multi-field, and all-round infiltration and integration. Land is the spatial carrier of an urban–rural regional system [8,9]. Land is also the most basic and important medium for the circulation and allocation of various elements between urban–rural areas while promoting the development of URI. The land use function (LUF) refers to the products and services that can be provided for human beings through land use [10]. LUF is a mirror reflecting the stage of urban–rural socio-economic development [11,12]. Meanwhile, a reasonable LUF is an important method for solving various problems in the process of URI development. LUFs have changed significantly during the development of URI [13]. The change affects the multi-dimensional integration of the urban–rural economy, society, and ecology [14–16]. In this vein, assessing the interaction between LUF and URI is of vital importance to the development of urban–rural integration.

China is experiencing the same unbalanced urban–rural development as developed countries have experienced [17,18]. The urban–rural dual land management system in China has led to contradictions such as urban–rural segmentation and lagging rural development [19,20]. Since the reform and opening up policy, the average urban–rural income ratio was 2.57 in 1978, reached a peak of 3.11 in 2010, and narrowed to 2.56 in 2020 [4]. In order to coordinate urban–rural development, China has successively put forward strategic plans for URI development, for instance, "Rural Revitalization" and the establishment of national pilot areas for integrated urban–rural development. The implementation of the above measures depends on the adequate fulfillment of LUFs. For the sake of URI development, the interaction between URI and LUF needs to be coordinated, and the dynamic trade-offs in both spatial and temporal dimensions need to be explored, thereby enhancing the overall benefits [21]. The speed of URI in the northeast of China is significantly slower than in other regions [22]. Heilongjiang Province in the northeast of China is the sixth largest province in China. It is the ballast stone for China's food security and an important old industrial base. Thus, this study has taken Heilongjiang Province as an example to analyze the relationship between LUFs and URI.

Extant research has made progress in URI [23–26]. The evaluations of the URI level mainly adopt three types of indicators: comprehensive indicators, comparative indicators, and catch-up indicators [4]. The influencing factors cover the multi-dimensional coordinated development evaluation of urban–rural economy, society, and ecology [27]. The analysis of the spatial pattern of URI included spatial auto-correlation analysis [28], the Markov chain model [29], hot spot analysis [30], and other methods. In terms of LUF, the conception was originally defined as the function of cultivated land production [31]. The SENSOR project has expanded the LUF to the three most closely related economic, environmental, and social levels in the region. It has been widely recognized by the international academic community [32]. At present, China's land spatial planning divides LUFs into production, living, and ecological functions [33]. LUFs are affected by regional natural resource endowments, socio-economic conditions, and policy factors, resulting in spatial and temporal changes [34]. The evaluation process of LUFs has undergone a transformation from static analysis to dynamic simulation [35]. The evaluation index system with social, economic, and ecological dimensions is constructed [36,37] based on the support of investigation and statistical data so that LUFs are comprehensively and quantitatively evaluated [38]. After the quantitative evaluation of land use versatility, the results are expressed by spatial analysis technology or a mathematical model [39].

Notably, although extant research provides extensive theoretical research and empirical analysis on LUFs [9,40,41] or URI [42–44], few studies have focused on the relationship between LUFs and URI. The existing study between URI and LUFs mainly focuses on the relationship between similar topics such as industrial integration and URI or the transformation of land use and the optimal allocation of land use from the perspective of urban–rural integration. Moreover, LUF and URI are complicated systems that involve many factors. The compositive research method on the measurement of URI and LUF should be used. We contend that LUF, in addition to directly influencing the level of URI, may also have indirect effects on URI by influencing industrial structure, urbanization level, and infrastructure and public services' accessibility. In line with this reasoning, examining and comparing the spatio-temporal coupling characteristics of LUF and URI could provide new insights into the paths to achieve regional URI.

We focus on exploring the spatial–temporal coupling analysis between land use function and urban–rural integration, selecting Heilongjiang Province in China as the research area for empirical analysis, so as to answer two questions: "What spatial–temporal characteristics are LUF and URI?" and "How is coupling coordination degree between LUF and URI?" We provide a methodological contribution for quantitatively measuring the level of URI and LUF and the coupling coordination between LUF and URI, and we expose a theoretical model based on the element–structure–function perspectives in analyzing the relationship between LUF and URI. It is helpful to explore the roles of LUF in achieving URI.

In a nutshell, this research aims to assess the coupling level and the spatial–temporal difference between URI and LUF in Heilongjiang Province at the city level. Firstly, we construct a theoretical framework of the coupling analysis of URI and LUF, with the inclusion of indicators specifically reflecting urban–rural linkages and land use functions. Secondly, due to the limitations of the statistical data availability, we conduct an empirical analysis using city-level data from 2013, 2017, and 2022. Thirdly, the evaluations of LUF and URI are explored with the comprehensive index model and the spatial–temporal characteristics are analyzed. Then, the analysis of the coupling and coordination degree between LUF and URI is explored with the coupling coordination degree model, as well as the spatial–temporal characteristics. Fourthly, we analyze the obstacle degree of LUF and URI in Heilongjiang Province. Finally, the coupling regional difference between URI and LUF is identified to reveal the current development status and challenges faced by specific regions in URI. We hope that our findings will shed light on the relationship between URI and LUF and provide help to other countries in achieving the coordinated development of URI and LUF.

2. Theoretical Framework and Methods

2.1. Theoretical Framework

The land system is the interface between human society and the natural environment, so it is a typically complex system [45]. The land system consists of natural, humanistic, and social elements. All the elements form specific structures and functions. The land use and land management functions in the land system interact to promote the operation of the land system. Land is the core element and the spatial support for urban–rural development [46]. The social, economic, and ecological transitions of land use cause the land system to experience a drastic, unbalanced evolution [47]. There is a coupling trend and law between the changes in the land system and the evolution of urban–rural relations in China [48]. The land use function is closely related to the operation of the land system, and it affects the operation of the land system. Consequently, it affects the allocation of urban–rural factors, urban–rural regional structure, and urban–rural development functions [49]. The function of land use corresponds to the stage of urban–rural integrated development. Controlling the land use function and regulating the operation of the land system can effectively alleviate the problems in the process of urban–rural integrated development.

On the one hand, the land use function affects urban–rural integration. The inefficient utilization of land, such as the urban bias toward land appreciation income and the obstructed circulation of land factors, has increased the urban–rural division. Nowadays, the food and ecological security functions of rural land use have increased, while the social security and economic functions have shown a downward trend [50,51]. The intensive level of urban land use has been greatly improved, and the economic function has been significantly improved [52]. The improvement in land use function is conducive to realizing the optimal allocation of land resources in urban–rural areas. On the other hand, the evolution of the urban–rural relationship has driven the optimization of the land use function. With urbanization's high-quality development, the spillover effect from urban areas to rural areas gradually appears. Rural land value can be promoted by the development of marketization and industrialization. The restructuring of the global economy and the upgrading of industrial structures require China's development to keep up with the pace. Rural areas have become a new development space and growth point [53]. The reshaping of the new urban–rural economic, social, ecological, and spatial relations has become an important development direction that will improve the comprehensive function of land use to meet the new development needs.

URI and LUF involve various aspects of socio-economic development. The study of the relationship between URI and LUF entails an integrated framework. To that end, we draw from the previous literature to establish the main theoretical constructs. The influencing factors of URI are explored from four dimensions: urban–rural economic integration, urban–rural social integration, urban–rural spatial integration, and urban–rural ecological integration [4,27,54,55]. The influencing factors of LUF are explored via a complex coupling system formed by three dimensions: economic function, social function, and ecological function [36,37,56,57]. The interaction between the urban regional system and the rural regional system shows that the process of URI development is the process of the continuous release of LUF. URI development is hindered by the low efficiency of land resource utilization and the prominent contradiction between land and humans; in contrast, it is improved by new types of urbanization and rural revitalization. The mechanism between URI and LUF includes the following three aspects. Firstly, URI means urban–rural economic integration, which drives the improvement in the economic function of regional land use [58]. Hence, it is necessary to acknowledge the above close connection. The higher the level of economic factors in URI and LUF, the more prosperous the urban–rural regional system. Secondly, rural areas are typically at a disadvantage in terms of regional social development [3]. The public service level and people's living standards should be promoted in the process of URI, and rural areas should also share convenient and efficient social services. To promote the social level of URI, the social function of regional land use should be improved [19]. Finally, the urban-centric development strategy leads to a concentration of economic and social elements in the cities and, at the same time, the destruction of the ecological environment. Green development and ecological civilization ideas provide opportunities for the ecological function of urban–rural land use to fulfill its role. In addition, the improvements in the ecological function of regional land use can equalize urban–rural ecological environmental development and realize the sustainable prosperity and well-being of both urban and rural areas. Urban–rural economic, social, and ecological integration are interrelated to form urban–rural–spatial integration (Figure 1).

2.2. Measuring the Level of LUF and URI with the Comprehensive Index Model

The comprehensive index model method constructs the value function by integrating multiple individual indexes of different objects, forming a general index, and then achieving the purpose of evaluation through index comparison. Its fundamental idea is to transform the diversified index into an index that can reflect the comprehensive situation that requires evaluation. We used the comprehensive index model to evaluate the development level of LUF and URI in Heilongjiang Province in 2013, 2017, and 2022.

Firstly, a comprehensive exponential equation was determined. The calculation formula is as follows:

$$W = \sum_{j=1}^{p} Aij \cdot Qj(i = 1, 2, \cdots, R; j = 1, 2, \cdots, P) \tag{1}$$

where W is the comprehensive index of the land use function or urban–rural integration of the measurement object; i is the evaluation object; j is the evaluation index; R is the number of evaluation objects; P is the number of evaluation indicators; Aij is the standardized value of the evaluation index of the ith evaluation object; and Qij is the weight value of the evaluation index.

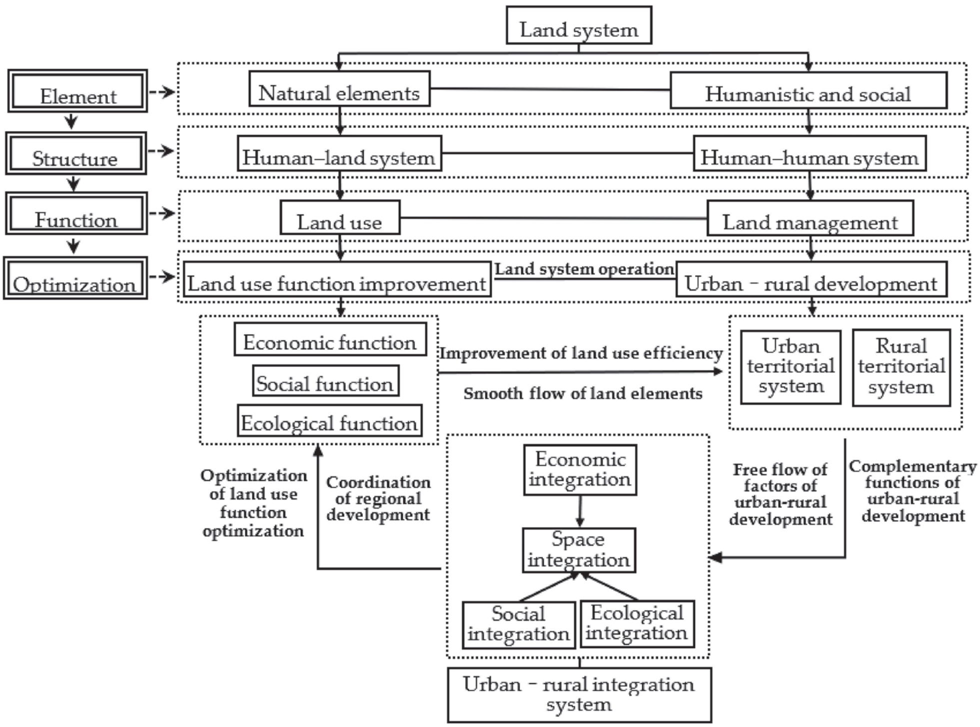

Figure 1. Theoretical framework of LUF and URI.

Secondly, the evaluation index system (LUF and URI) was constructed. Integrating the analytical framework, previous studies, and the land use situation in Heilongjiang Province, the level of LUF was evaluated by using the index system, including the three-dimensional land multi-functional spatial structure of "economy-society-ecology". For each land use function, the corresponding indicators were selected for quantitative measurement, and the evaluation index system of multiple utilization was constructed (Table 1). The selection of these indicators is mainly based on the following criteria: (1) the indicators are closely related to the functional connotation of land use; (2) the indicators have been applied in previous studies; (3) the indicators are quantitatively measured at a municipal scale; and (4) the indicators are holistic, dominant, and normative.

Based on the theoretical framework, the rural revitalization of the total goal, and "The urban and rural integration development system mechanism and policy system opinions", the evaluation index system of URI included the economic integration, social integration, spatial integration, and ecological integration of the urban–rural area. Then, the current study selected 14 indicators to construct the evaluation index system of urban and rural integrated development level (Table 1).

Thirdly, the index data were processed dimensionlessly. When calculating the evaluation index, the data of different indexes were different, so dimensionless treatment was needed. We used the maximum difference normalization method for data standardization and obtained the data normalization matrix.

Finally, the coefficient of variation method was used to determine the weight of the evaluation index. Compared with other methods such as the analytic hierarchy process, Delphi process, and fuzzy analysis method to determine the index weight, the coefficient of variation method has the advantages of strong references, wide applicability, ease of understanding and implementation, and provides robust objectivity, which is widely used in the process of the actual index weight determination.

The mean $\overline{Xij}$ and standard deviation Sij were calculated from the normalized values:

$$\overline{Xij} = \frac{1}{R}\sum\nolimits_{i=1}^{R} Xij \tag{2}$$

$$S_{ij} = \left[\frac{1}{R}\sum_{i=1}^{R}(X_{ij} - \overline{X_{ij}})^2\right]^{\frac{1}{2}} \tag{3}$$

The coefficient of variation CV was calculated for each index:

$$CV = {S_{ij}} \Big/ {\overline{X_{ij}}} \tag{4}$$

The specific weights are shown in Table 1.

Table 1. Evaluation index system of LUF and URI.

Target Layer	Criterion Layer	Element Layer	Indicator Layer	Unit	Indicator Attributes	Indicator Weight (%)
LUF evaluation [56,57]	Economic function	Agricultural production (L1)	The ratio of output value of agriculture, forestry, animal husbandry, and fishery to total output value (L11)	%	+	5.19
			Land reclamation rate (L12)	%	+	4.46
			Grain yield (L13)	t/hm^2	+	3.90
		Non-agricultural production (L2)	Proportion of secondary and tertiary industries (L21)	%	+	5.52
			Land economic density (L22)	CNY 10^8 /km^2	+	9.74
			Investment in fixed assets (L23)	CNY 10^8	+	14.7
	Social function	Residence support (L3)	Population density (L31)	10^4 person/km^2	–	4.53
		Social guarantee (L4)	Rural employees (L41)	10^4 person	+	9.38
			Per capita disposable income ratio of urban and rural residents (L42)	—	—	3.08
		Food supply (L5)	Per capita grain possession (L51)	t/ 10^4 person	+	6.71
	Ecological function	Resource conservation (L6)	Forest coverage rate (L61)	%	+	6.16
			Green coverage rate of built-up area (L62)	10^8 m^3/ 10^4 person	+	4.22
			Water resources per capita (L63)	%	+	19.67
		Pollutant discharge reduction (L7)	Wastewater discharge (L71)	10^4 t	—	2.74

Table 1. *Cont.*

Target Layer	Criterion Layer	Element Layer	Indicator Layer	Unit	Indicator Attributes	Indicator Weight (%)
URI evaluation [4,55]	Economic integration	Economic production integration (U1)	Urban–rural per capita GDP (U11)	CNY/person	+	16.36
			The tertiary industry structure as a proportion of GDP (U12)	%	+	3.32
		Investment Integration (U2)	Urban–rural fixed asset investment ratio (U21)	—	—	1.95
	Social integration	People's living standards integration (U3)	Per capita disposable income ratio of urban–rural residents (U31)	—	—	3.31
			Urban–rural minimum living security ratio (U32)	%	—	3.25
		Public services integration (U4)	Urban and rural ordinary middle school students teacher–student ratio (U41)	%	—	1.43
			Urban and rural beds in medical and health institutions ratio of ten thousand person (U42)	%	+	20.18
	Space integration	Urbanization (U5)	Urbanization level (U51)	%	+	6.90
			Ratio of built-up area (U52)	%	+	15.29
		Traffic integration (U6)	Road traffic network density (U61)	%	+	6.17
	Ecological integration	Resource conservation (U7)	Forest coverage rate (U71)	%	+	11.74
			Energy saving and emission reduction rate (U72)	%	+	4.32
		Pollutant discharge reduction (U8)	Wastewater discharge (U81)	10^4 t	—	3.26
			Smoke emissions (U82)	10^4 t	—	2.52

2.3. Analysis of the Coupling and Coordination Degree between LUF and URI

(1) Coupling coordination degree model

"Coupling" means that two or more systems achieve the effect of coordinated development through interaction and influence. Under the interaction of each subsystem, they show a relationship of mutual influence and mutual restriction. The closer the system is, the stronger the coupling is. The coupling degree is a measure that comprehensively considers the degree of the interaction of each subsystem [59].

Firstly, LUF and URI levels were regarded as two systems, and the coupling relationship between them was analyzed by the formula:

$$CP = 2\sqrt{\frac{W \cdot T}{(W+T)^2}} \tag{5}$$

In the formula, CP is the coupling degree of land use function and urban–rural integration level. The larger the CP value, the higher the coupling degree. W is the comprehensive index of land use function, and T is the comprehensive index of urban–rural integration level.

Secondly, the coordination degree was calculated. The calculation focused on the application of quantitative methods to evaluate the degree of closeness of the interaction between LUF and URI systems, which effectively reflected the degree of coordination of the development level of each coupling system. The formula is:

$$CD = \sqrt{CP \times N} \quad (6)$$

where $N = \alpha W + \beta T$.

In the formula, CD is the coupling coordination degree of the two systems of land use function and urban–rural integration level, and $0 \leq CD \leq 1$. The larger the CD value is, the higher the coordination degree of the interactive coupling between land use and urban–rural integration level will be. N is the comprehensive coordination index of the synergistic effect of the two systems. α and β are undetermined coefficients, and the sum is 1. This paper only studies the two subsystems of land use function and urban–rural integration level, so the two are equally important, therefore $\alpha = \beta = 0.5$.

(2) Coupling coordination stage and type division

The relative development degree model reflects the land use function and the level of urban–rural integration [60], as shown in the following formula:

$$R = W/T \quad (7)$$

In the formula, R is the relative development degree coefficient, W is the comprehensive index of land use function, and T is the comprehensive index of urban–rural integration level.

W divides the coupling and coordination status of the municipal land use function and urban–rural integration level system in Heilongjiang Province into 10 types (Table 2).

Table 2. Type division standard of coupling coordination relationship.

Coupling Coordination Degree D Value Interval	Rank of Harmony Degree	Coupling Coordination Degree
(0.0–0.1)	1	Extreme disorder
[0.1–0.2)	2	Serious disorder
[0.2–0.3)	3	Moderate disorder
[0.3–0.4)	4	Mild disorder
[0.4–0.5)	5	On the verge of disorder
[0.5–0.6)	6	Reluctant coordination
[0.6–0.7)	7	Mild coordination
[0.7–0.8)	8	Moderate coordination
[0.8–0.9)	9	Serious coordination
[0.9–1.0)	10	Extreme coordination

2.4. Obstacle Degree Model

In order to find out the obstacle factors that restrict the LUF and URI, we have constructed the obstacle factor model to analyze them. The obstacle degree model was analyzed and evaluated by using the indexes of the "index deviation degree (Q_{ij})" and "obstacle degree (M_{ij})" indicators. The model is as follows [61]:

$$Q_{ij} = 1 - X_{ij} \quad (8)$$

$$M_{ij} = \frac{W_j \times Q_{ij}}{\sum_{i=1}^{n} W_j \times Q_{ij}} \quad (9)$$

where X_{ij} is the single index standardized value; W_j is the weight of the j index; and M_{ij} is the obstacle degree for the URI and LUF of the i indicator. The larger the value of M_{ij}, the greater the obstacle degree of the indicator to the target.

2.5. Study Area and Data Sources

2.5.1. Study Area

In Heilongjiang Province, the cities comprise Harbin and 12 other cities and the Daxing'anling region. It is a major agricultural province and an important old industrial base. These factors lay the foundation for URI development. The total land area of the province is 473,000 km^2, ranking sixth in the country. The main mountainous areas with high forest coverage are in the northwest, north, and southeast of Heilongjiang Province. Heilong River, Wusuli River, Songhua River, and Suifen River form the four major water systems. There are 253 lakes with a perennial water surface area of more than 1 km^2. The Nenjiang River and Songhuajiang River run through the whole province from southwest to north to form the Sanjiang Plain in the northeast and the Songnen Plain in the southwest. The proportion of cultivated land, forest land, water wetland, and grassland in Heilongjiang Province is 35%, 45.9%, 7.4%, and 2.5%, respectively, in 2022 (Figure 2).

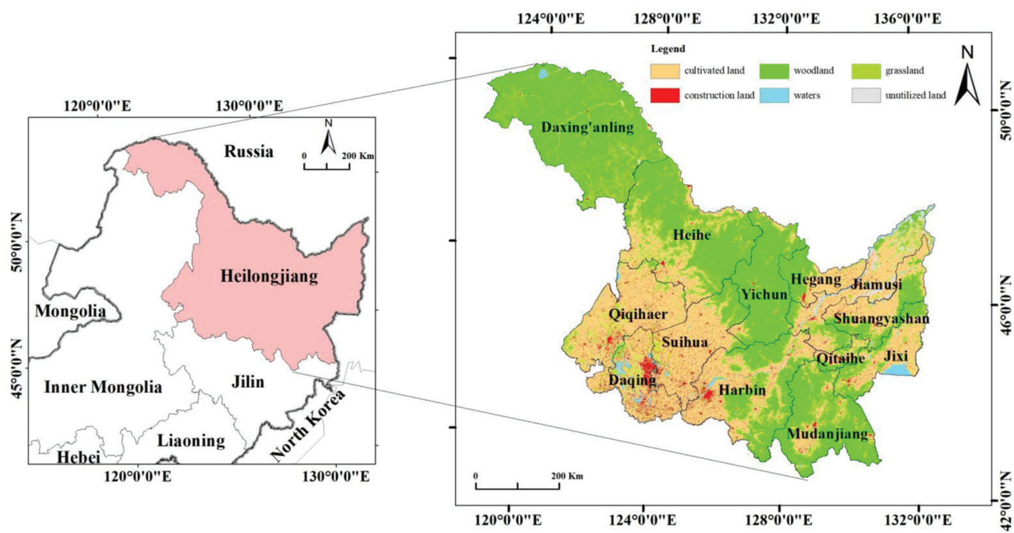

Figure 2. Location and land use status of Heilongjiang Province in 2022.

2.5.2. Data Sources

As the basic administrative unit in China's administrative divisions, the city is the most commonly used statistical data unit in current statistical departments. At the same time, we also considered data integrity and accessibility. Therefore, the study takes the municipal level in Heilongjiang Province as the research unit. Based on the development status of Heilongjiang Province and considering the availability of data, the years 2013, 2017, and 2022 were selected as the study points and 2013–2022 as the study period.

This paper studies the functional level of land use management and the level of urban–rural integration development with two types of social and economic survey data and land use data. The social and economic survey data mainly include the statistical Bulletin of National Economic and Social Development of Heilongjiang Province in 2013, 2017, and 2022 and the statistical Yearbook of Heilongjiang Province and other cities; the land use data are the survey data of land use change in Heilongjiang Province. In view of the missing data, this paper mainly uses the mean method, reference method, and other methods for supplementary processing.

3. Results Analysis

3.1. Evaluation of LUF

3.1.1. Temporal Variation Characteristics of LUFs

From 2013 to 2022, the comprehensive index of LUFs in Heilongjiang Province showed an overall upward trend, but there was a large gap between the regions (Figure 3). The fastest improvement in land use comprehensive function was in Daxing'anling, which increased from 0.048 in 2013 to 0.738 in 2022, an increase of 15 times; other areas basically show a uniform upward trend.

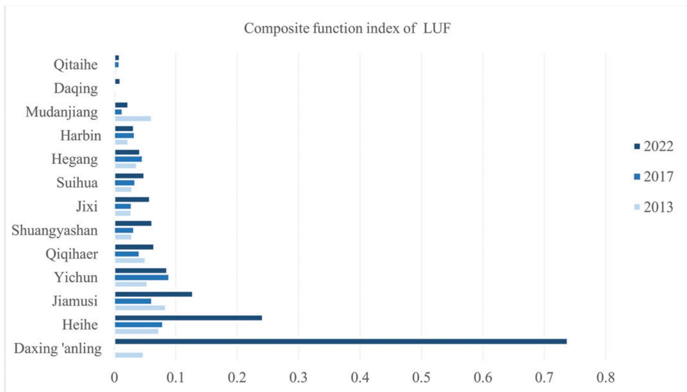

Figure 3. The composite function index of land use in Heilongjiang Province in 2013, 2017, and 2022.

From 2013 to 2022, the land use function of Heilongjiang Province generally showed a trend of "ecological function > social function > economic function", in which ecological function and social function were dominant (Figure 4). The economic function was generally low. The economic function in Harbin is the most prominent, having experienced a trend of first increasing and then decreasing. The social function continued to increase. The social functions of Jiamusi, Qiqihar, Heihe, Suihua, Jixi, Shuangyashan, and Mudanjiang showed the fastest growth. The ecological function showed an overall growth trend. Compared with the above two functions of land use, the ecological function had an absolute advantage and was dominant.

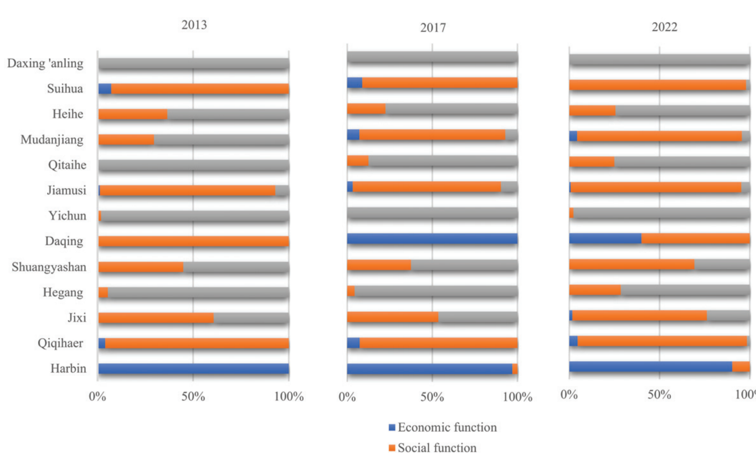

Figure 4. The proportion of single functions of land use in Heilongjiang Province in 2013, 2017, and 2022.

3.1.2. Spatial Pattern Distribution Characteristics of LUFs

By constructing the evaluation index system of LUFs, the single index of LUFs and the comprehensive index in 13 cities and regions in 2013 and 2022 were calculated. According to the standard deviation method, LUF indexes in Heilongjiang Province were divided into five levels. These reflected the spatial distribution characteristics and trends in LUF levels.

(1) The spatial distribution characteristics of LUF

From 2013 to 2022, the comprehensive LUF in Heilongjiang Province showed a spatial distribution pattern of "high in the west and low in the east, high in the north and low in the south", showing a gradually decreasing trend from the western and northern cities to the southeast and southwest (Figure 5a–c).

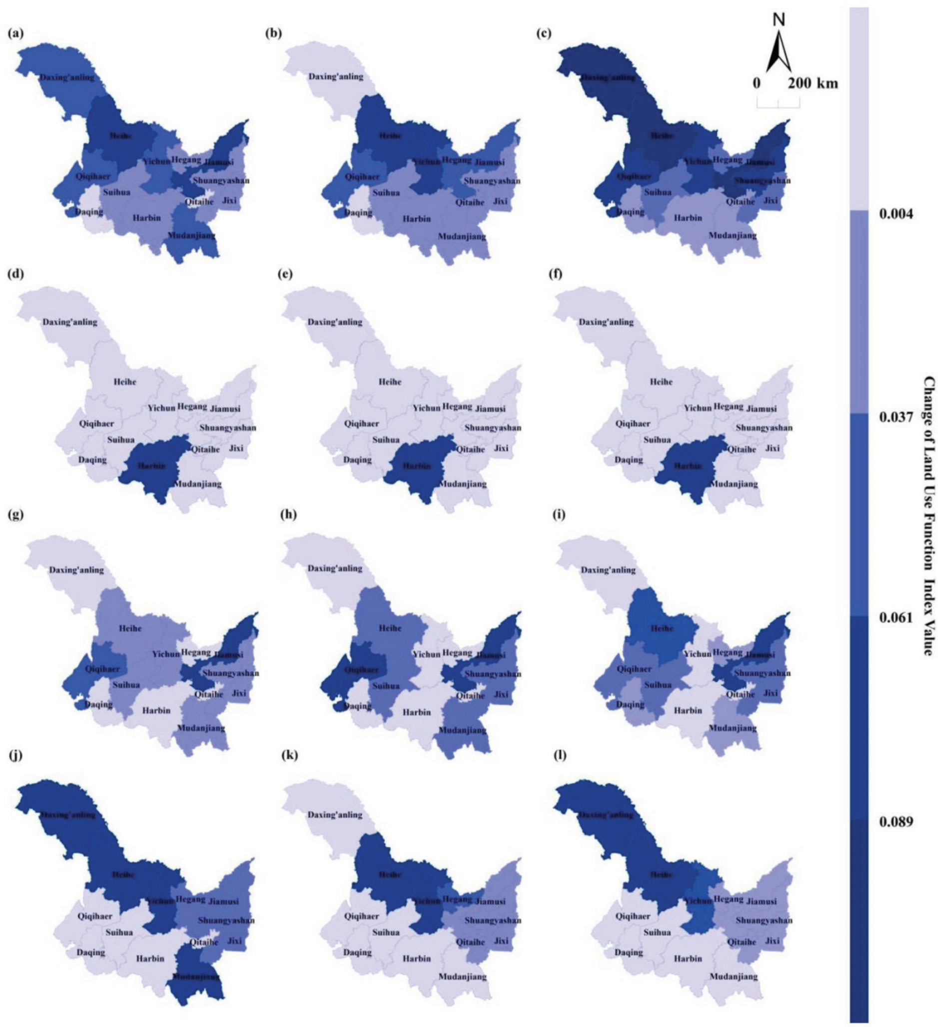

Figure 5. Spatial pattern distribution of LUFs in Heilongjiang Province in 2013, 2017, and 2022. (**a**–**c**) Spatial pattern distribution of comprehensive LUF in 2013, 2017, and 2022; (**d**–**f**) spatial pattern distribution of economic LUF in 2013, 2017, and 2022; (**g**–**i**) spatial pattern distribution of social LUF in 2013, 2017, and 2022; (**j**–**l**) spatial pattern distribution of ecological LUF in 2013, 2017, and 2022.

The economic LUF remained stable, and the economic LUF in Harbin was the most prominent across the study's time period (Figure 5d–f). The distribution of the social LUF showed the pattern of "high in the west and east". The distribution scale of high social LUF in the west decreased, but the level improved. The distribution of social LUF in Yichun city decreased significantly. The distribution in Hegang City increased slightly (Figure 5g–i). The ecological LUF showed a pattern of "high in the northwest and east", which was located in the distribution of the Greater Khingan Mountains, Lesser Khingan Mountains, and Sanjiang Plain. The ecological LUF in Mudanjiang significantly weakened. The ecological LUF in the Daxing'anling area decreased and then increased (Figure 5j–l).

3.2. Evaluation of URI

3.2.1. Temporal Variation Characteristics of URI Level

From 2013 to 2022, the composite level of URI in Heilongjiang Province generally showed an upward trend. The areas with rapid growth were Yichun, Shuangyashan, and Hegang City. The highest composite level of URI in Heilongjiang Province was Harbin City. The level of URI development was divided into two stages: in the first stage (2013–2017), the level of URI developed slowly. During this period, although the intensity of rural construction increased and the number of rural preferential policies increased (except for Harbin, which had a good foundation for URI) the growth rate of other cities was basically flat or slightly improved, and Heihe declined. The second stage (2017–2022) was a rapid growth period of urban–rural integration development. With the efficient promotion of the rural revitalization strategy and the rapid development of urbanization, the rural population continued to shift to the large cities, the population urbanization and the non-agricultural employment population continued to rise, the development of the second and third industries in urban and rural areas was good, and the level of urban–rural integration development was growing rapidly (Figure 6).

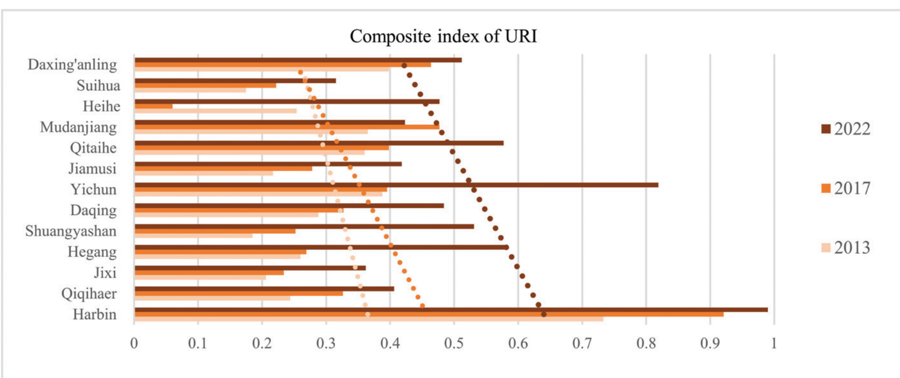

Figure 6. The composite index of URI in Heilongjiang Province in 2013, 2017, and 2022.

From 2013 to 2022, the economic development levels of URI in Heilongjiang Province were on an upward trend but were at the lowest compared with the other three indexes. The economic development in Harbin was the most prominent and experienced a process of increase. The social and spatial integration of URI in Heilongjiang Province showed a stable trend. The social integration was higher than the spatial integration of URI. The ecological level of URI in Heilongjiang Province showed an overall growth trend. Compared with the above three indexes, the ecological one increased most rapidly and has already become the dominant one in 2022 (Figure 7).

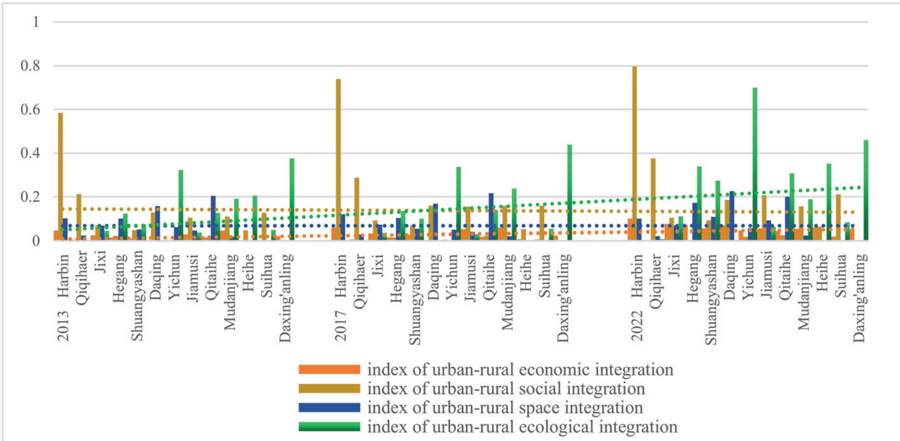

Figure 7. The economic development level, public service level, people's living standards, and ecological level of URI in Heilongjiang Province in 2013, 2017, and 2022.

3.2.2. Spatial Pattern Distribution Characteristics of Urban–Rural Integration Level

According to the standard deviation method, the URI indexes of cities in Heilongjiang Province were divided into seven levels. This reflected the spatial distribution characteristics and trends of URI. From 2013 to 2022, the level of urban–rural integration in Heilongjiang Province showed spatial distribution characteristics of "high in the middle and low in the east and west, high in the south and low in the north". The level of URI in Daqing and Harbin was generally higher than the average level of other cities (Figure 8a–c). The spatial distribution of urban–rural economic integration changed from a pattern of "high in the northwest and in the southeast" to that of most areas improving, except for Qiqihar and Suihua City (Figure 8d–f). The spatial distribution of urban–rural social integration showed no evident changes. The urban–rural social integration in Harbin kept its remarkable status from beginning to end. Qiqihaer, Jiamusi, and Suihua cities slightly increased. The other areas remained stable (Figure 8g–i). The spatial distribution of urban–rural space integration was mainly concentrated in areas except for the north of Heilongjiang Province (Daxing'anling, Heihe, and Suihua). Qiqihaer, Jiamusi, and Mudanjiang cities slightly increased. The other areas remained stable (Figure 8j–l). The spatial distribution of urban–rural ecological integration showed a pattern of "high in the northwest and east", which was similar to that of ecological LUF (Figure 8m–o).

3.3. Evaluation of Coupling Coordination Degree between Land Use Function and Urban–Rural Integration Level in Heilongjiang Province

3.3.1. Time Series Characteristics of Coupling Coordination between Land Use Function and Urban–Rural Integration Level

The coupling coordination degree and relative development degree of land use function and the urban–rural integration level system of Heilongjiang prefecture-level cities in 2013, 2017, and 2023 were calculated (Figure 9). From 2013 to 2022, the coupling and coordination levels of land use function and urban–rural integration level showed an increasing trend. From 2013 to 2017, the level of coupling and coordination between the two increased slowly; from 2017 to 2022, the level of coupling and coordination between the two entered a period of rapid development. From 2013 to 2022, the areas with an increase in the coupling coordination level above 0.1 were Daxing'anling, Heihe, Jiamusi, Suihua, Shuangyashan, and Qiqihar. The largest increase was Daxing'anling, reaching 0.37, followed by Heihe and Jiamusi, both of which were 0.19.

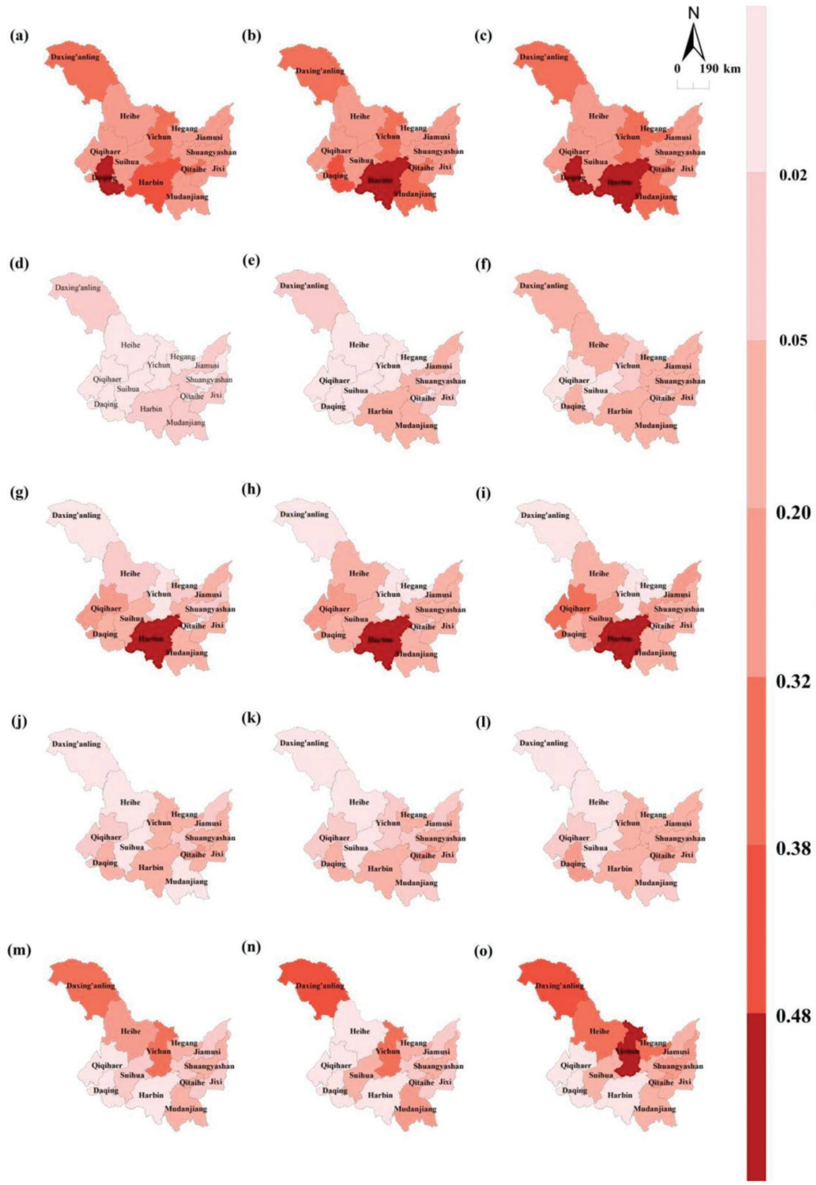

Figure 8. Spatial pattern distribution of URI in Heilongjiang Province in 2013, 2017, and 2022. (**a**–**c**) Spatial pattern distribution of comprehensive URI in 2013, 2017, and 2022; (**d**–**f**) spatial pattern distribution of urban–rural economic integration in 2013, 2017, and 2022; (**g**–**i**) spatial pattern distribution of urban–rural social integration in 2013, 2017, and 2022; (**j**–**l**) spatial pattern distribution of urban–rural space integration in 2013, 2017, and 2022; (**m**–**o**) spatial pattern distribution of urban–rural ecological integration in 2013, 2017, and 2022.

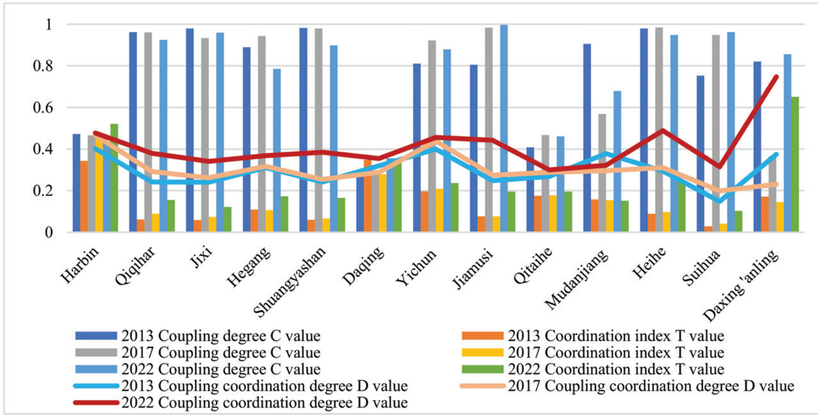

Figure 9. Coupling coordination degree between LUF and URI in Heilongjiang Province.

3.3.2. Spatial Pattern Distribution Characteristics of Coupling Coordination between Land Use Function and Urban–Rural Integration Level

According to Table 2, the evaluation results are divided into stages (Table 3), and the spatial evolution pattern of coupling and coordination of the two systems in each district and county in 2013–2023 was obtained (Figure 10).

Table 3. Coupling coordination evaluation results.

	2013		2017		2022	
	Coupling Coordination Degree	**Coupling Type**	**Coupling Coordination Degree**	**Coupling Type**	**Coupling Coordination Degree**	**Coupling Type**
Harbin	0.402	On the verge of disorder	0.466	On the verge of disorder	0.477	On the verge of disorder
Qiqihaer	0.242	Moderate disorder	0.292	Moderate disorder	0.379	Mild disorder
Jixi	0.241	Moderate disorder	0.262	Moderate disorder	0.341	Mild disorder
Hegang	0.311	Mild disorder	0.317	Mild disorder	0.368	Mild disorder
Shuangyashan	0.242	Moderate disorder	0.254	Moderate disorder	0.385	Mild disorder
Daqing	0.319	Mild disorder	0.288	Moderate disorder	0.355	Mild disorder
Yichun	0.400	Mild disorder	0.439	On the verge of disorder	0.456	On the verge of disorder
Jiamusi	0.248	Moderate disorder	0.275	Moderate disorder	0.442	On the verge of disorder
Qitaihe	0.268	Moderate disorder	0.288	Moderate disorder	0.300	Moderate disorder
Mudanjiang	0.378	Mild disorder	0.296	Moderate disorder	0.322	Mild disorder
Heihe	0.295	Moderate disorder	0.311	Mild disorder	0.488	On the verge of disorder
Suihua	0.148	Serious disorder	0.199	Serious disorder	0.315	Mild disorder
Daxing'anling	0.375	Mild disorder	0.230	Moderate disorder	0.747	Moderate disorder

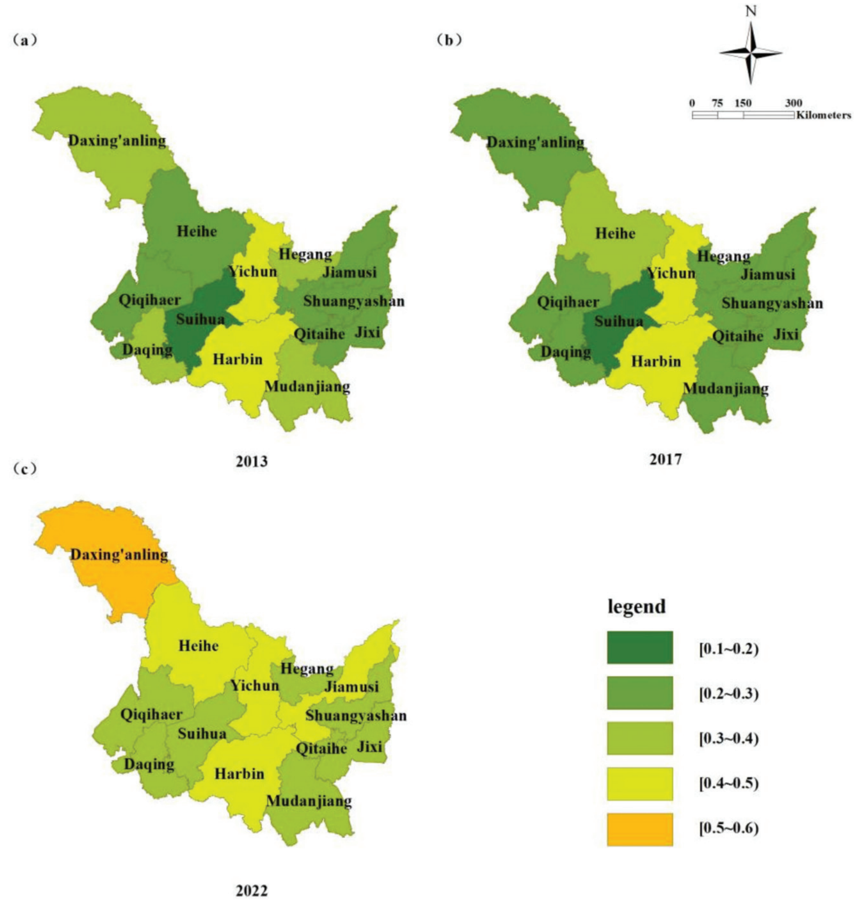

Figure 10. Spatial evolution pattern of coupling and coordination of two systems in cities of Heilongjiang Province (**a**) Coupling and coordination of two systems in cities of Heilongjiang Province in 2013; (**b**) Coupling and coordination of two systems in cities of Heilongjiang Province in 2017; (**c**) Coupling and coordination of two systems in cities of Heilongjiang Province in 2022.

From Table 3 and Figure 10, it can be seen that from 2013 to 2022, the coupling and coordination of land use function and urban–rural integration level in Heilongjiang Province presented distinct spatial and temporal distribution characteristics, mainly as follows:

From the perspective of the coupling coordination degree of the whole province, the coupling coordination degree of the two systems showed a spatial distribution pattern of "high in the north and low in the south, high in the middle and low in the east and west", and during 2013–2022, except for Yichun and Harbin, the overall trend was gradually upward. However, except for the first promotion to moderate coordination in the Daxing'anling area in 2022, other cities were in states of being in serious disorder, moderate disorder, mild disorder, and on the verge of disorder, and there was a large scope for improvement. Among them, the coupling degree of Yichun and Harbin was generally higher than the coupling coordination level of the two systems of other cities in Heilongjiang, and the change was relatively stable. However, the level was still on the verge of disorder, and there was a large scope for improvement. In Suihua City in Heilongjiang Province, the level was more speedily enhanced, such that from 2013, when it seriously lagged behind the other cities in Heilongjiang Province, it was logged at first in the serious disorder stage then progressed to the mild disorder stage. The overall coupling degree of the Daxing'anling region showed an increasing trend, and in 2022, its coupling degree rose to a moderate coordination stage. Hegang, Mudanjiang, and Daqing were in the stage of mild disorder from 2013 to 2022, and improvement was slow. The coupling coordination degree of Shuangyashan City, Qitaihe City, and Jixi City increased from the moderate disorder stage to the mild disorder stage. The coupling coordination degree of Jiamusi City increased from the moderate disorder stage to the stage of being on the verge of disorder. From 2013 to 2022, the improvement in Shuangyashan City, Qitaihe City, and Jixi City was basically in a state of synchronous optimization. In 2013, Heihe City and Qiqihar City were at the stage of moderate disorder, but the coupling coordination degree of Heihe City was better than that of Qiqihar City. By 2022, Heihe City was upgraded to the stage of being on the verge of disorder, while Qiqihar City was upgraded to the stage of mild disorder.

3.4. Obstacle Degree of LUF and URI

The main obstacle factors affecting the land use function in Heilongjiang Province came from L_7 (pollutant discharge reduction), L_2 (non-agricultural production), and L_4 (social guarantee) in the element layer. There were spatial differences in the obstacle factors, and the sequence of obstacle factors in the same district changed with time: the districts where L_7 was the first obstacle factor included the developed industrial cities (Qiqihar and Daqing). It also included the resource-based districts (Jixi, Shuangyashan, Qitaihe, and Hegang), farmland concentrated distribution districts (Jiamusi and Suihua), and the economic center (Harbin). The districts where L_2 was the first obstacle factor were located in the Greater Khingan Mountains and the Lesser Khingan Mountain regions (Yichun, Heihe, and Daxing'anling). The second obstacle factor was basically concentrated in L_2, and the third obstacle factor was mainly concentrated in L_4 (Figure 11).

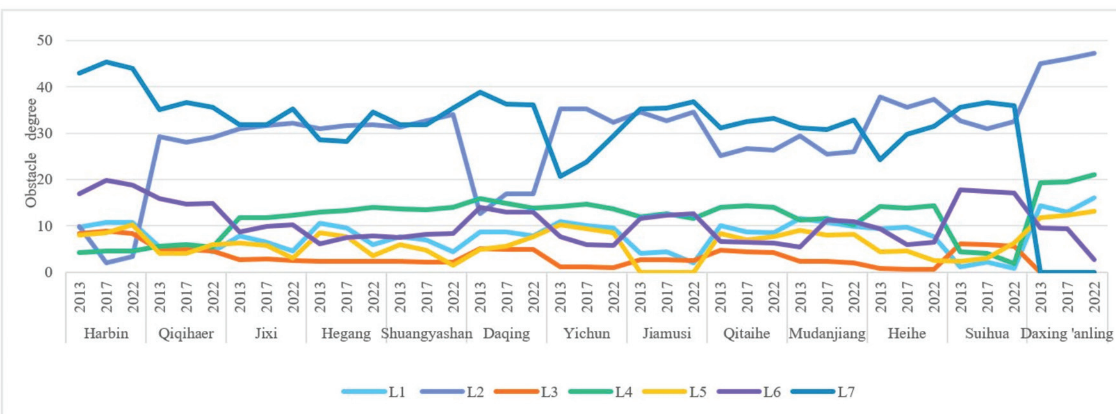

Figure 11. Obstacle degree of LUFs.

The main obstacle to urban–rural integration development came from U4 (public services integration), U8 (pollutant discharge reduction), U6 (traffic integration), and U2 (investment integration) in the element layer. Except for Harbin, the first obstacle factor in all regions was U4. The second obstacle factor in each region mainly focused on U8 and U6. The third obstacle factor in each region was mostly concentrated on U2 (Figure 12).

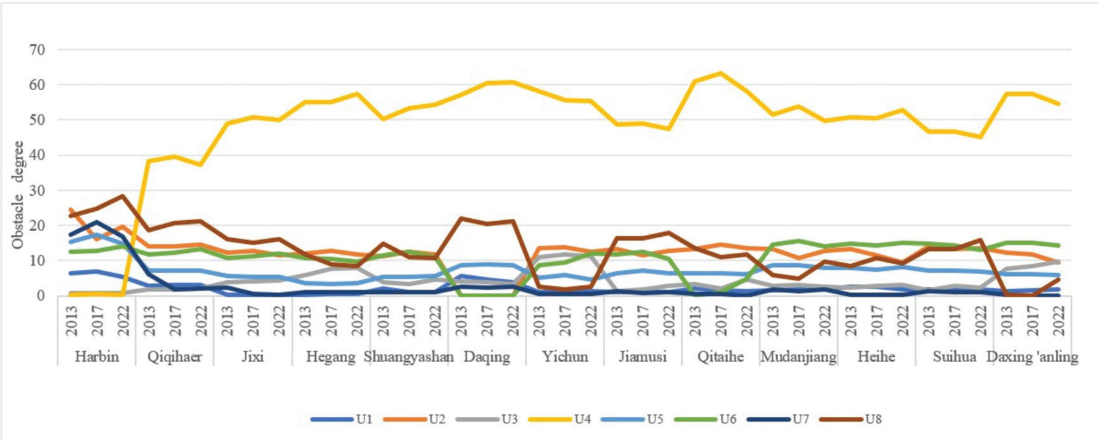

Figure 12. Obstacle degree of URI.

4. Discussion

4.1. Understanding of Coupling and Coordination Degree between LUF and URI

This study was based on the angle of view of the element–structure–function of land system operation. The land use function interacted with the urban–rural development [48]. The key point of URI development was not the spatial evenness but the achievement of a reasonable urban–rural flow and the efficient allocation of production factors such as land [15]. The analysis of the coupling and coordination degree between LUF and URI has significant meaning in promoting the coordination, fairness, and sustainability of regional development [20].

According to the results, there was a coupling relationship between LUF and URI in Heilongjiang Province, and the level of coupling coordination was significantly improved during the study period. Whether it relates to the promotion of LUF or the implementation of a URI development strategy, it will involve economic, social, ecological, and other aspects. The process is complex and the task is arduous [19,33,34]. The analysis of the coupling relationship between LUF and URI is bound to be a complex process. The change in LUF affects the multi-dimensional integration of the urban and rural economy, society, and ecology [7,13]. To scientifically evaluate the degree of integration of LUF and URI and clarify the spatial and temporal pattern of LUF and URI is critical for the formulation of URI policies. More consistent development patterns and differentiated mechanisms can be analyzed and used as a reference for other countries and regions.

The obstacle factors that hinder the development of the two systems have a close association. The obstacle factors should be properly handled, so that the coordination degree of LUF and URI can be improved and the urban–rural area can attain healthy and sustainable development [62–64].

4.2. Recognition of the Spatial–Temporal Characteristics of URI and LUF

In order to scientifically analyze the relationship between LUF and URI, we creatively constructed index systems to measure the level of LUF and URI on the basis of the element–structure–function of land system operation. We provided a methodological contribution for the quantitative measurement of levels of URI and LUF and the coupling coordination between LUF and URI. In addition, we provided a theoretical model for analyzing the relationship between LUF and URI. The results confirmed that the change in LUF affects the multi-dimensional integration of the urban–rural economy, society, and ecology. It is the basis for improving the systems, mechanisms, and institutions related to URI.

As one of the major agricultural provinces in China, Heilongjiang Province faces the prominent contradiction of a dual urban–rural structure. Therefore, it is of great significance to accurately evaluate the level of urban–rural integration in Heilongjiang Province to identify and promote its urban–rural integration development [65]. The overall level of URI in Heilongjiang Province has increased, but the range is small. Although the research data and methods are different, this study is basically consistent with the research conclusions of other studies [66]. This is closely related to the economic downturn in Heilongjiang Province under the structural background of the reform of the supply side, the difficulties inherent in the transformation and upgrading of traditional industries, and the outflow of human resources. The analysis of URI levels in a typical area in China may provide a reference for other countries that are also facing similar problems in URI development.

The composite utilization of land in Heilongjiang Province is closely related to the changes in its social, economic, and ecosystem functions. The analysis of LUFs at the municipal level in Heilongjiang Province was basically consistent with the evaluation results of the land use system in Heilongjiang Province [62]. The multi-functionality of land use is helpful in realizing a smooth transformation and upgrading of regional social–economic development [56]. The analysis of LUFs can provide a scientific basis for the comprehensive optimal allocation of land resources and sustainable social and economic development in Heilongjiang Province and provide reference experience for other land-resource-based provinces [67].

4.3. Limitations and Future Prospects

We used the comprehensive index model method to evaluate the LUF and URI levels of various areas in Heilongjiang Province in 2013, 2017, and 2022 and analyzed the coupling and coordination relationship between the two systems. The evaluation systems of LUF and URI selected both direct indicators and relevant indirect indicators. Because of the diversification of LUF and URI paths, the index system should be perfected in the future to analyze the spatial–temporal characteristics and differentiation rules, with the objective of revealing the interaction relationship between LUF and URI. The systematic characterization of the degree of coupling and coordination could provide a useful solution for the implementation of the URI strategy in Heilongjiang Province. We chose the comprehensive index model for evaluation because the evaluation method is simple and easy to operate. The results of calculations objectively reflect the real situations. However, some positive indicators for the evaluation of LUF and URI were passively abandoned due to the difficulty of obtaining data. Meanwhile, due to data limitations, the flow of factors is not fully reflected. In the future, the construction of a multi-source heterogeneous database for LUF and URI should be further strengthened, and the index of primary mobility characteristics (flow scale, direction, speed, frequency, network connection) should be enhanced in order to more accurately depict the essential connotation of regional LUF and URI.

5. Conclusion and Policy Implications

5.1. Conclusion

The urban–rural dual land management system in China has led to contradictions such as urban–rural segmentation and lagging rural development. From the point of view of the land system, it is necessary to improve the utilization functions of urban–rural land resources for URI development. Taking Heilongjiang Province as the research region, this study analyzed the spatial–temporal coupling characteristics of LUF and URI from 2013 to 2022. The quantitative evaluation of the relationship between URI and LUF is a methodological contribution. The results show the following:

(1) The comprehensive index of land use function in various regions in Heilongjiang Province showed an overall upward trend, but there was a large gap between the regions. The spatial distribution pattern is "high in the west and low in the east, high in the north and low in the south". Overall, it showed a trend of "ecological function > social function > economic function", and the change in land use function in Heilongjiang Province became more and more intense.

(2) The overall level of urban–rural integration in Heilongjiang Province is on the rise. The spatial distribution characteristics show "high in the middle and low in the east and west, high in the south and low in the north". Overall, there was a trend of "urban-rural ecology level > urban-rural public service level > urban-rural economic development level > urban-rural people's living standard".
(3) The coupling and coordination level of LUF and URI in Heilongjiang Province showed an increasing trend, except for Yichun and Harbin. The coupling coordination degree of the two systems shows a spatial distribution pattern of "high in the north and low in the south, high in the middle and low in the east and west".
(4) The obstacle degree analysis of LUF and URI in Heilongjiang Province shows that there is a close correlation of obstacle factors between the two systems. Properly handling the factors hindering the development of LUF and URI can effectively promote the coordinated development of LUF and URI.

The spatial distribution of LUF, URI, and their coupling and coordination relationship in different areas of Heilongjiang Province under different natural geographical locations and social–economic conditions shows an obvious heterogeneity in different time periods. This provides the references for putting forward the exact path to promote URI development. The interaction relationship between LUF and URI in China is shared among many developing countries. Thus, studies on the relationship between URI and LUF in this typical area in China may provide a reference for other countries that are also facing similar problems in URI development.

5.2. Policy Implications

The comprehensive study of this spatial–temporal law and the obstruction factors arising from LUF and URI are helpful in suggesting targeted reform measures and promoting the sustainable and coordinated development of the regional social economy.

Firstly, the advantages of ecological function should be fulfilled. Those regions with good ecological conditions should seize the positive opportunities for constructing an ecological civilization to strengthen environmental protection. Furthermore, the regions that are surrounded by mountains should overcome the negative impact of the transportation system, accelerate the layout of public service facilities such as science, education, culture, and health, and improve the utilization efficiency of tourism resources. The further improvement in the coupling and coordination levels of LUF and URI should create the impetus for regional sustainable development.

Secondly, industrial upgrading should be performed to accelerate the speed of urban–rural integration development. There is extensive scope for improvement in the regions with stable coupling coordination levels of LUF and URI, such as Harbin and Yichun. These regions should take full advantage of new industrialization and agricultural modernization to update the second and third industries in the urban areas and revitalize the industries in the rural areas. The regions should improve output efficiency and add the value of industries to the process of improving urban–rural residents' sense of acquisition.

Finally, the efficient flow of factors between urban and rural areas should be improved to optimize the relationship between LUF and URI. Policies to attract and encourage talent and investments in rural development should be enacted. The economic development gap between urban and rural areas is still the key factor affecting URI development, so support for rural areas should be increased. Rural advantages should be exerted to create new agricultural forms of commerce, such as rural e-commerce and the logistics industry. The integrated development model of production and marketing can reduce development costs and increase the economic benefits for farmers. Meanwhile, fair employment opportunities should be provided for urban–rural residents to narrow the income gap between urban and rural residents.

Author Contributions: Conceptualization, Q.L.; methodology, N.Z.; software, Y.Y. and L.W.; validation, N.Z. and Q.L.; formal analysis, Y.Y.; investigation, N.Z., L.W. and Y.Y.; resources, Q.L.; data curation, Y.Y.; writing—original draft preparation, N.Z.; writing—review and editing, N.Z., Y.Y., L.W. and Q.L.; visualization, N.Z. and Q.L.; supervision, N.Z. and Q.L.; project administration, N.Z.; funding acquisition, N.Z. All authors have read and agreed to the published version of the manuscript.

Funding: National Natural Science Foundation of China (41901208); China Postdoctoral Science Foundation (2021M700738); Heilongjiang Higher Education Teaching Reform Project (SJG20210079).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of the study are available from the corresponding author upon request. But the national administrative boundaries and land use data are not publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

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land

Article

Neighborhood Does Matter: Farmers' Local Social Interactions and Land Rental Behaviors in China

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Abstract: The transfer of farmland is an important area of rural development research; however, the impact of rural social networks has been neglected in studies. The aim of this study is to explore the effects, mechanisms, and heterogeneity of neighbors' behavior on the process of land renting by farmers. Based on the data of the China Family Panel Studies in 2018, this research empirically analyzes the impact of community-level, local social interactions on the land rental behavior of farmers and its mechanisms using a spatial probit model. The results of this study indicate that neighbors' land rental behavior positively and significantly affects that of other farmers in the same village. In addition, neighbors' land rental encourages other farmers in the same village to follow suit through an increase in the perceived importance of the Internet among the farmers. In addition, there is heterogeneity in neighborhood influence. Notably, the impact of social networks on the renting out of the land by farmers, as evidenced in this study, is a key factor in accelerating the circulation of rural land and promoting rural development, thus contributing to the process of rural revitalization and its recording in the literature.

Keywords: land transfer; peasant household; social embeddedness; neighbor behavior; spatial probit model

Citation: Gu, J. Neighborhood Does Matter: Farmers' Local Social Interactions and Land Rental Behaviors in China. *Land* **2024**, *13*, 76. https://doi.org/10.3390/land13010076

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 10 December 2023
Revised: 4 January 2024
Accepted: 8 January 2024
Published: 9 January 2024

1. Introduction

The issue of land ownership is the cornerstone of the stability and sustainability of development in rural areas. Activating rural land circulation is critical for optimizing agricultural land allocation, increasing agricultural performance, and promoting rural development. The transfer of rural land has always been one of the utmost priority issues for governments [1,2]. Indeed, the governments of several countries have introduced policies to encourage land transfesr in rural areas [3,4]. Unfortunately, the problems and challenges associated with rural land transfers remain serious issues to be resolved [5]. For instance, despite the various methods employed by governments to facilitate rural land transfers, farmers are often reluctant to participate in these measures. Some farmers prefer to leave their land idle or even abandon it rather than transfer it [6]. The per capita land resources of peasant families are small and scattered, and the land circulation period is short [7]. Most farmers have only oral agreements when transferring land, and few peasant households actually sign contracts, which can easily lead to disputes [8]. Thus, improving the willingness of peasant families to participate in land transfer and farmland circulation is still an urgent problem in agricultural land management and rural development.

Since the reform and opening up of China, the reform of rural land transfer has been high on the agenda. In 1984, the government proposed "encouraging the gradual concentration of land to capable farmers", marking the beginning of the reform of the transfer of rural land-use rights. In the late 1990s, the government encouraged the further development of the rural land transfer market in order to solve the problems of rural land abandonment and low productivity. In 2002, the Law of the People's Republic of China on Rural Land Contracting made specific provisions and enacted legislation on the subjects and forms of the transfer of rural land-use rights. This further accelerated the transfer of rural land and expanded the degree of large-scale operations. After entering the 21st century, policies on non-agricultural market transactions of rural land have undergone a shift from the previous total ban to allowing conditional transfers. In short, the market for the transfer of rural land-use rights has been initially established; however, it still suffers from a lack of vitality and operates on only a small scale [9].

In 2014, China introduced a policy of the "separation of three rights", whereby the ownership of rural land belongs to the collective, except for that which belongs to the state as stipulated by law, and the contractual and management rights of the land belong to farmers. The "separation of three rights" allows the right to operate the land to be used as an asset for collateralized loans, making land an even more valuable asset. In 2017, the government proposed a further rural revitalization strategy to deepen the reform of the rural land system, and in 2021, the government proposed a comprehensive promotion of rural revitalization with the goal of advancing the modernization of agriculture and rural areas. The reform of the land system is an important foundation for the realization of rural revitalization, and the agricultural land transfer policy is one of the important pivots for the implementation of this rural revitalization strategy [10].

Prior studies have explored factors influencing rural land transfer from different perspectives and levels, such as the family structure [11], asset level [12], financial literacy [8], social capital [13], personal attributes [14], and non-agricultural employment [15,16]. Existing studies have generally focused on the antecedents of rural land transfer, and this has been studied extensively. However, relevant studies have only been conducted based on the premise that farmers make their decisions on land transfer independently, without considering the mutual influence of farmers. That is to say, research on the connection between local social interaction and agricultural land transfer is sparse. The issue of agricultural land transfer is somewhat complex, as it does not only represent a market transaction of land but also involves interactions between geopolitics, kinship, neighborhoods, and human relations, and has its own logic. The concept of social embeddedness originated from the study of Polany [17] in 1944, which later led to an academic consensus that economic behavior is embedded in social structures [18,19]. Therefore, the core idea of social embeddedness is that the behavior of an economic agent is embedded in a social network, i.e., an individual's economic actions are always unfolding in interaction with others, and his or her decisions are always made in connection with others [20,21]. According to this social embeddedness theory, farmers' behavior is affected by both the "autonomy effect", which is related to individuals and emphasizes the impact of individual-level factors [22], and the "embeddedness effect", which is related to the farmers' social environment [23,24]. As previously mentioned, most of the studies on land transfer and farmland circulation have mainly focused on the autonomy effect while the embeddedness effect has been generally ignored. In existing studies, farmers are often regarded as independent decision makers who make decisions to maximize their interests under certain conditions [8,25,26]. However, rural societies are typically understood to be "acquaintance societies", meaning people are easily influenced by their neighbors in terms of their psychology and behavior [27,28]. Therefore, farmers' land transfer behaviors cannot be fully explained if the factor of the mutual influence among neighboring farmers is ignored.

The aim of this study is to explore the impact of behavioral spillovers between neighbors on renting out rural land from the perspective of local social interactions rooted in the community. This study contributes effectively to the existing literature and theories in the following three ways: First, this study expands on the existing literature in relation to the impact of neighbors' behavior on land transfers from the perspective of community-based social interactions. Second, it explores the path of neighbors' behavioral spillovers on land rental, which complements the research related to rural land transfers. Third, it provides a new perspective on how governments in developing countries can stimulate the micro-driving force of land transfers by guiding community opinions and demonstrating the benefits of land transfers to the farmers.

2. Theoretical Analysis and Hypotheses Development

Studies on farmers' peer effects show that individual farmers are not independent when making decisions, and their embedded social networks profoundly impact their decision-making behaviors [29–31]. It is apparent that the social network between neighbors can promote the collective action of farmers' transfer of farmland. This collective action occurs through the convergence of farmers' land rental under the potential influence of the social network that is rooted in the local village. Its specific mechanism can be summarized in three aspects. The first is the information–transmission mechanism. Farmers have a strong demand for information about land transfer prices and the demands of land leaseholders. However, due to inadequate information on the value of their land, farmers must incur high costs to collect that information [32]. The social networks within local communities can effectively promote the dissemination and sharing of relevant information, reducing farmers' information collection costs [33,34]. When farmers obtain reliable information through observation and learning of the land rental activities of neighboring farmers, they imitate their neighboring farmers' behaviors and make the same decision, which is what Rassenti et al. [35] call "the convergence of behavior". When farmers lack sufficient information, they are more inclined to use local social networks to collect information on land transfers, particularly on land rental, from their relatives, acquaintances, and other farmers, especially their neighbors, to make their own land transfer decisions [33].

The second mechanism is the social norm mechanism. Individual farmers dwelling in the same village share a common normative environment and know each other well [36]. In the process of land transfers among local farmers, a rental agreement is mostly an oral contract, and rent is often paid in favors; therefore, there is a potential credit risk [8]. However, once land rental becomes a common behavior among local villages, it will become a norm within the local social networks, which would help to reduce the opportunistic behavior of individual farmers and promote the convergence of farmers' behavior [36]. The final mechanism is the conformity mechanism. Since the classical experiments of Sherif [37] and Asch [38], many existing studies in this field of rural and agricultural development have documented the widespread presence of conformity in peasant families' decision making [39,40]. When renting out land in rural areas, farmers find it difficult to make accurate judgments because of their limited information. To avoid making mistakes when making decisions regarding land rental, farmers are likely to regard the information held by others (neighboring farmers) as their information sources and choose to be consistent with their behaviors (neighbor farmers), which is categorized as "farmers follow the herd" in the study conducted by Le Coent et al. [41].

In reality, information transmission, social norms, and conformity effects are often intertwined in the social networks of the local village, which together leads to the convergence behavior of farmers. Thus, when influenced by the local village's social network, farmers' land rental behavior converges, that is, "you rent out and I rent out". This hypothesis is therefore proposed:

Hypothesis 1 (H1): Neighboring farmers renting out their land encourages individual farmers to do the same.

With the rapid development in information technology, farmers' use and understanding of the Internet is likely to affect rural development [42]. In rural areas, neighbors' behavior can also effectively influence farmers' use and perception of the Internet [27]. When more farmers in the neighborhood rent out land, the local Internet network displays increasingly relevant information and views, which further spread through the local social network, thus shaping the network's public opinion [43]. This process can enable farmers to improve their perceptions of the importance of the Internet. When a neighbor rents out land, it arouses the curiosity of other farmers in the same village [34], as captured by the expression, "neighbors look over hedge with curiosity" [44]. These farmers will be likely to search for information about land transfers through the Internet, which will increase their perception of the importance and value of the Internet. Therefore, the following hypothesis is proposed:

Hypothesis 2 (H2): Neighbors' land rental behaviors have a positive effect on the farmers' perception of the importance of the Internet.

The use of the Internet can reduce the information asymmetry between those renting out and renting in farmland [45]. In the current situation, in which farmland transfer is not highly marketized, Internet use can significantly cut farmers' expenses and costs of looking for and transmitting information related to farmland transfers [46]. Farmers who have a clear and coherent realization of the importance of the Internet are more inclined to reduce information asymmetry in the local labor market through the use of the Internet. This, in turn, is conducive to timely access to more employment opportunities and increases the possibility of engaging in part-time production or migrant work [47,48]. Therefore, farmers with a higher perceived importance of the Internet are more inclined to lease agricultural land as it reduces farmers' dependence on land. Therefore, the following hypothesis is proposed:

Hypothesis 3 (H3): The perceived importance of the Internet positively affects individual farmers' land rental behavior.

According to the procedure of the mediating variable test [27,49], when Hypotheses 2 and 3 are both established, the perceived importance of the Internet mediates the relationship between neighbors' and individual farmers' land rental behaviors.

Referring to previous studies [50,51], the conceptual framework of this study is presented in Figure 1.

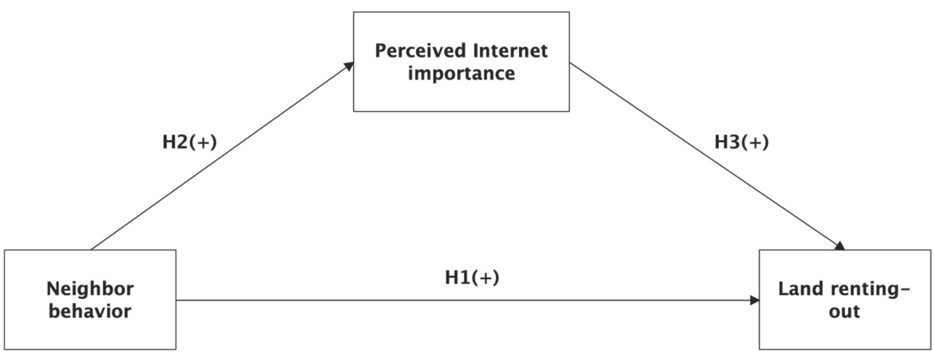

Figure 1. Conceptual framework.

3. Data, Variables, and Method

The microdata used in this study originated from the China Family Panel Studies (CFPS) in 2018, a nationwide panel survey that was organized and implemented by Peking University [52]. The survey covered 25 provincial administrations in China, including provinces, autonomous regions, and municipalities directly under the Central Government. All household members in each household were surveyed through four panels: adults, children, households, and communities. Therefore, these data points are both highly national and representative [53]. The CFPS uses a systematic probability sampling approach that is multistage, implicitly stratified, and proportional to population size [54]. Thus, the CFPS sample can be considered as a nationally representative sample [27]. In this study, the sample households are those peasant households engaged in any kind of agricultural work, such as farming, cultivating fruit trees, collecting produce, fishing, and raising fish/livestock, obtained from the CFPS household sample. These are traditionally rural peasant households. This screening process yielded 5036 peasant households, of which 3556 households were selected. Their heads of household ranged in age from 20 to 60 years old. After removing the missing values, a final sample of 3286 peasant households was obtained.

3.1. Explained Variable

The willingness and demand of farmers to lease agricultural land is one of the critical antecedents affecting and regulating the agricultural land-rental market activity in rural society [11]. Therefore, land rental has always been an important topic in the study of rural land transfers [8,12]. Here, agricultural land rental is taken as the explained variable. The following item in the questionnaire was used to operationally construct this variable: "Have you rented out the land collectively owned by your family to others in the past year?" Irrespective of whether a rent was charged, if the farmer hands over the land to other people for use, it was defined as "renting-out" and was assigned the value 1; if not, it was assigned a value of 0. Therefore, it is a binary variable consisting of 1 s and 0 s.

3.2. Explanatory Variables

Neighbors' behaviors can significantly impact individual decisions [55]. In the countryside, the influence of neighbors' behaviors is almost omnipresent in peasant families' decision making [34,56]. In accordance with the practices of Wang [56] and Skevas et al. [57], neighbors' behaviors can be construed as the spatial lag term of the explained variable, which is the result of multiplication of the constructed spatial weight matrix and land rental. A common method is to construct a spatial continuity weight matrix composed of 0 and 1 [58]. Therefore, this study also constructed a similar spatial continuity weight matrix: when two farmers were in the same village, the spatial weight between the farmers was 1; otherwise, it was 0. Following Gu [27], the spatial weight matrix was also spectrally normalized. In this study, neighbors' behavior specifically refers to the agricultural land rental behavior of neighboring peasant households in the same village.

3.3. Covariates

Rural labor mobility affects agricultural land-leasing behavior, and rural outmigration for work causes higher levels of farmland rental [59,60]. The rural outmigration variable was defined as whether any member of the family had migrated out for work: if at least one member of the family had migrated out for work, the variable value was 1; otherwise, it was 0. Rural families participating in non-agricultural entrepreneurial activities, including the operation of rural e-commerce and homestay, are more likely to rent out farmland, which has been confirmed in previous studies [16,61]. Therefore, it was necessary to consider farmer entrepreneurship as a covariable. The entrepreneurship variable is defined operationally by the number of farmers who are self-employed or private enterprises. Household-owned farm machinery negatively impacts farmers' land rental behaviors [12]. The machinery variable was defined operationally via the logarithmic value after adding 1 to the whole value of agricultural machinery and equipment that was owned by the farmer. Household size, household income, and farmers' land transfers are closely related [8,12,15]. Therefore, these two variables were also included in the empirical models.

Consistent with the previous literature on agricultural land transfer and rental [8,11,14], it is important to control factors at the level of household heads, including personal biological attribute variables such as gender and age, as well as individual social attribute variables such as years of education and marital status.

3.4. Mediator

Mediation is an important concept in the social sciences [62]. In this study, the study of the mediation effect helps in gaining a better understanding of the relationship and mechanism between social networks and land transfer in order to better manage the process of rural land transfer. By studying the mediation effect, the government and other relevant decision makers can better understand the behavior and motivation of farmers in renting out land so that they can formulate more effective management strategies to improve the overall efficiency of rural land transfer. In 2020, the Internet penetration rate in China's rural areas had skyrocketed to 55.9% [63]. The average global Internet penetration rate in both urban and rural areas was now 62% [64]. In the information age, the perceived value of the Internet widely affects people's decisions and behaviors [65,66] and also directly or indirectly affects farmers' decision making [27]. Based on previous studies [46,47], it is important to empirically test the perceived importance of the Internet as mediator by operationally defining it in terms of respondents' ratings of the importance of the Internet (1 = very unimportant to 5 = very important).

The descriptive information of the above variables is reported in Table 1.

Table 1. Descriptive information of variables.

Variable	Definition	Mean	Std. Dev.	Min.	Max.
Land rental	1 means the land is rented-out and 0 implies that the land is not rented-out	0.105	0.307	0	1
Neighbors' behavior	Spatial lag term of land rental	0.105	0.16	0	1
Labor outmigration	1 means that someone is migrating-out for work, 0 represents no outmigration	0.586	0.493	0	1
Entrepreneurship	Number of self-employed or private enterprises	0.1	0.328	0	3
Machinery	Logarithmic value after adding 1 to the whole value of agricultural machinery which is owned by the farmer (CNY)	4.061	4.188	0	13.459
Household size	Population size of the peasant households	4.365	1.867	1	16
Household income	Logarithmic value after adding 1 to the annual whole household income	10.729	0.898	0	14.146
Gender	Gender indicator with 1 for males and 0 for females	0.535	0.499	0	1
Age	Age	47.201	8.592	20	60
Education	Years of education (Year)	6.803	3.961	0	19
Marriage	Marital status with 1 for married and 0 for others	0.916	0.277	0	1
Perceived importance of the Internet	5-point scale with 1 for very unimportant and 5 for very important	2.608	1.569	1	5

3.5. Methods

According to Amaral et al. [67], the so-called spatial probit model (the spatial autoregressive probit model) can be modeled as follows:

$$Y^* = \rho W Y^* + X\beta + \epsilon \tag{1}$$

where $Y^* = \left(Y_1^*, \cdots, Y_N^*\right)'$; and Y_i^* is a latent variable. $W(N \times N)$ is a spatial continuity weight matrix composed of 1 and 0, which captures the structure of the social interactions between neighboring peasant households in the same village. X is the matrix of vectors of covariates. β is a parameter vector, and ρ is the key parameter on which this study focuses. $\varepsilon \sim N\left(0, \sigma^2 I_N\right)$. Here, $N = 3286$. Given that Y_i^* is not observable, the observed equation of the binary variable Y_i is as follows:

$$Y_\mathrm{i} = \begin{cases} 1, & \text{if } Y_i^* > 0 \\ 0, & \text{if } Y_i^* < 0 \end{cases} \tag{2}$$

If $\rho = 0$, this spatial probit model thus reduces to the standard probit model because there is no neighborhood interaction [53]. If $\rho \neq 0$, it means that there is a neighborhood interaction. Under these circumstances, the traditional estimators that are used in the standard probit model are biased because neighborhood interactions are systematically ignored [67,68]. Thus, the spatial probit model is preferred [69].

In general, the mediating variable test is conducted using a stepwise regression method consisting of three formulas [49]. When there is neighborhood interaction, referring to the practice set out in [27], the following two formulas can be added on the basis of Formula (1):

$$M^* = \rho W M^* + \gamma W Y^* + X\beta + \epsilon \tag{3}$$

$$Y^* = \rho W Y^* + \delta M^* + X\beta + \epsilon \tag{4}$$

where M^* denotes the vector of the mediating variable. If ρ in Formula (1), γ in Formula (3), and ρ and δ in Formula (4) are all significant, it indicates that M^* is a mediator.

Stata software (version 17.0, Stata Corp., College Station, TX, USA) was used to conduct the spatial probit analysis, and each hypothesis in the theoretical model was tested.

4. Results

Before conducting the spatial probit model regression, conducting a spatial autocorrelation test is necessary. Both Moran's I index (Moran) and Geary's C index (Geary) are commonly used methods to perform the spatial autocorrelation test [70]. Moran's I index of land rent-out is 0.126, and it is significant (p-value is 0.000). Geary's C index of land rent-out is 0.874, and it is significant (p-value is 0.000). Thus, in this study, the spatial probit model here is significantly better than the standard probit model.

4.1. Baseline Results

The empirical results of the spatial probit models and their related parameters are reported in Table 2. Specifically, columns (1) and (2) in Table 2 present the empirical results of the models that control for covariates at the household level. The latter results are controlled for provincial effects, whereas the former are not. On this basis, columns (3) and (4) add covariates at the household-head level. Column (4) controls for the provincial effects, while column (3) does not. All of the Hansen's J statistics in these models are not significant, indicating that these models are effective [69]. As reported in Table 2, the coefficients of neighbors' behavior in all the columns are both significant and positive. Thus, Hypothesis 1 is supported. Therefore, when neighboring farmers rent out land, this behavior spreads to other farmers in the same village through the neighbor-to-neighbor spillover. This spillover effect can effectively encourage and mobilize farmers to rent out agricultural land. The influence of this type of neighborhood spillover has been proven in many fields, such as the environment [71], urban development [72], real estate [56], and public health [73]. This is the first time that a neighborhood spillover effect has been confirmed in the field of agricultural land transfer.

In addition, the estimated coefficients of labor outmigration in all columns of the preceding Table 2 are significant and positive. Thus, labor outmigration in peasant households increases the probability and possibilities of agricultural land rental in rural areas. These empirical findings are clearly in line with the conclusions of previous research [59,60]. After controlling provincial effects, the coefficients of entrepreneurship are significantly positive. One potential reason for this is that farmers participating in non-agricultural activities are less dependent on the land [16,61]. Moreover, the negative impact of agricultural machinery owned by peasant families on the agricultural land rental behavior of farmers has also been confirmed [12]. The negative relationship between household size and farmers' land rental behavior has been confirmed, while the effect of household income is positive. The results in this study are roughly similar to some of the empirical results in previous research [8,12,15].

Table 2. Empirical results of baseline models.

	Explained Variable: Land Rental			
	(1)	**(2)**	**(3)**	**(4)**
Neighbors' behavior	0.684 ***	0.897 ***	0.734 ***	0.904 ***
	(3.49)	(3.94)	(3.9)	(4.32)
Labor outmigration	0.078 *	0.103 **	0.078 *	0.103 **
	(1.85)	(2.28)	(1.83)	(2.26)
Entrepreneurship	0.103	0.137 **	0.098	0.131 **
	(1.64)	(2.13)	(1.57)	(2.03)
Machinery	−0.024 ***	−0.024 ***	−0.022 ***	−0.023 ***
	(−4.87)	(−4.74)	(−4.59)	(−4.47)
Household size	−0.024 **	−0.038 ***	−0.016	−0.029 **
	(−2.18)	(−3.18)	(−1.45)	(−2.35)
Household income	0.122 ***	0.108 ***	0.123 ***	0.104 ***
	(4.62)	(3.88)	(4.56)	(3.70)
Gender			−0.025	−0.047
			(−0.61)	(−1.09)
Age			0.001	0.001
			(0.33)	(0.51)
Education			0.005	0.010 *
			(0.94)	(1.66)
Marriage			−0.261 ***	−0.269 ***
			(−3.40)	(−3.42)
_cons	−1.568 ***	−1.101	−1.370 ***	−0.93
	(−3.84)	(−1.59)	(−3.21)	(−1.29)
Provincial fixed effects	No	Yes	No	Yes
N	3286	3286	3286	3286
Hansen's J statistic	3.098	5.858	4.72	6.308
Hansen's J statistic (*p*-value)	0.542	0.21	0.787	0.613

z-statistics are in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

As for the factors of the household head, the influence of age and gender is not significant, and the number of years when the household head received education can improve the probability and possibilities of agricultural land rental from peasant households only when the provincial effects are controlled for. The empirical findings here roughly echo the empirical results of previous research [6,15]; however, they also differ in some aspects from the results of similar research [6,8], as they show that the household head's age has a significantly negative effect on agricultural land rental from peasant households, whereas the educational level of the household head has no significant impact. This indicates introducing neighbors' influence as a factor may change the influence of relevant factors on agricultural land rental from peasant households. Moreover, the household head's marital status inhibits farmers from renting out land, which was previously generally ignored.

4.2. Robustness Check

The CFPS has long used computer-assisted personal interviewing (CAPI) to conduct surveys. However, in 2020, due to the COVID-19 pandemic, CFPS switched to computer-assisted telephone interviewing (CATI) to conduct surveys. Changes in the way the surveys were conducted were likely to have an impact on the results. Therefore, it is necessary to carry out robustness tests here. Data from the CFPS in 2016 were used for the test, and the results are summarized in column (1) of Table 3. Then, data from CFPS in 2020 were used, and the results are summarized in column (2) of Table 3. Comparing the regression coefficients of neighbors' behavior in Table 3 with the regression coefficient of neighbors' behavior in column (4) of Table 2 shows that these coefficients are significantly positive. This suggests that the change in the survey method did not affect the findings of this study, i.e., the results of this study are robust.

Table 3. Robustness test.

	Explained Variable: Land Rental	
	(1)	**(2)**
Neighbors' behavior	1.136 ***	1.496 ***
	(6.18)	(5.74)
Labor outmigration	0.152 ***	0.078
	(3.58)	(1.54)
Entrepreneurship	0.209 ***	0.183 **
	(3.54)	(2.12)
Machinery	−0.016 ***	−0.012 **
	(−3.26)	(−2.03)
Household size	−0.008	−0.053 ***
	(−0.66)	(−3.36)
Household income	0.073 ***	0.151 ***
	(2.97)	(4.4)
Gender	−0.091 **	−0.04
	(−2.14)	(−0.75)
Age	0.002	0.003
	(0.85)	(1.06)
Education	0.015 ***	0.001
	(2.67)	(0.15)
Marriage	−0.173 **	0.08
	(−2.32)	(0.87)
_cons	−0.734	−1.666 *
	(−1.45)	(−1.7)
Provincial fixed effects	Yes	Yes
N	3692	2250
Hansen's J statistic	5.15	4.735
Hansen's J statistic (*p*-value)	0.881	0.786

z-statistics are in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.3. Path Analysis

How does neighbors' behavior affect the farmland rental behavior of other neighboring peasant families in the same community or village? To answer this question, the specific influence paths in this relationship must be examined. In the information age, the perceived value of the Internet influences individual decision making and behavior and often plays an important role in local social networks [42,45]. Therefore, the perceived importance of the Internet for farmers and peasant families in this study is used as the operationally mediating variable. Relevant results were obtained using the stepwise test method [27,49] and are summarized in Table 4. Columns (1), (2), and (3) correspond to Formulas (1), (3), and (4), respectively.

According to the results of column (2) in Table 4, the coefficient of neighbors' behavior (γ) is positive and significant. Thus, Hypothesis 2 is supported. When neighboring farmers rent out their land, this behavior attracts the attention of other farmers in the same village and encourages them to hunt for relevant information concerning land by surfing the almost ubiquitous Internet to facilitate their understanding of the situation [44]. Consequently, farmers' perception of the importance of the Internet increases. According to column (3), the regression coefficient of the perceived importance of the Internet (δ) is significantly positive. Thus, Hypothesis 3 is supported. The farmers' increased perceived importance of the Internet helps them find alternative employment opportunities, such as part-time jobs [47,48], thus reducing their dependence on the land and increasing the probability of land rental. In addition, the regression coefficients of neighbors' behavior (ρ) in columns (1) and (3) are significantly positive. Therefore, the Internet's perceived importance mediates the relationship between neighbors' and other farmers' behavior in the same village regarding land rental. Moreover, neighbors' behavior not only directly affects the land rental behaviors of other peasant families in the same community but also indirectly affects the farmers' behavior by influencing the Internet's perceived importance for other peasant families. The empirical results show clearly here that the direct and mediating effects have the same direction; therefore, the mediating effects here are complementary rather than competitive [74].

Table 4. Test of the mediating mechanism.

	Explained Variable		
	Land Rental	**Perceived Internet Importance**	**Land Rental**
	(1)	**(2)**	**(3)**
Neighbors' behavior (ρ)	0.904 *** (4.32)		0.935 *** (4.7)
Neighbors' behavior (γ)		0.307 ** (2.02)	
Perceived importance of the Internet (δ)			0.126 *** (2.75)
Variables controlled	Yes	Yes	Yes
Provincial fixed effects	Yes	Yes	Yes
N	3286	3286	3286
Hansen's J statistic	6.308	6.945	6.241
Hansen's J statistic (p-value)	0.613	0.643	0.716

z-statistics are in parentheses; ** $p < 0.05$, *** $p < 0.01$.

4.4. Heterogeneity Analysis

The influence of neighbors is often different in different situations. In accordance with the division practice of the Chinese Bureau of Statistics, the samples are partitioned into the two regional groups in China: the eastern and northern region, and the central and western region. Therefore, the results are correspondingly presented in Table 5. Please see Appendix A for information on the regions to which specific provincial administrative units belong. As shown in Table 5, the neighbors' impact on the agricultural land rental behavior of peasant households in two different areas is significant, but the impact in the eastern and northern region is clearly stronger than that in the central and western region. One reason for this phenomenon is that the interaction between neighbors and the social network in local communities in different regions is different [75]. In the rural areas of eastern and northern China, neighborhoods will be more closely knit and, as a result, the influence of neighbors will be greater.

Table 5. Empirical results of regional heterogeneity.

	Explained Variable: Land Rental	
	Region	
	(1)	**(2)**
	Eastern and Northern Region	**Central and Western Region**
Neighbors' behavior	0.896 ** (2.41)	0.829 *** (3.31)
Variables controlled	Yes	Yes
Provincial fixed effects	Yes	Yes
N	1052	2234
Hansen's J statistic	4.39	7.439
Hansen's J statistic (p-value)	0.82	0.49

z-statistics are in parentheses; ** $p < 0.05$, *** $p < 0.01$.

Government subsidies and agricultural machinery leasing can have an effect on land transfers in rural areas [12,26]. Therefore, the neighbors' impact on land rental may also differ depending on whether farmers receive subsidies or rent machinery. After grouping the samples, regression analysis was performed, and the empirical results of those tests are summarized in Table 6. As shown in column (1) and column (2) of Table 6, both effects of neighbors' behavior on land rental are significant, but the intensity of the effect is greater on farmers with subsidies than on those without subsidies. Government subsidies to encourage land transfers will create strong incentives for farmers to rent out their land and will encourage more neighboring farmers to rent out their land. As shown in columns (3) and (4), the effect of neighbors' behavior on land rental is only significant for farmers who have not leased agricultural machinery. Without sufficient agricultural machinery, farmers are more likely to follow their neighbors' practices and rent out the land.

Table 6. Results of subsidies and agricultural machinery leasing.

	Explained Variable: Land Rental			
	Subsidies		**Agricultural Machinery Leasing**	
	(1)	**(2)**	**(3)**	**(4)**
	Yes	**No**	**Yes**	**No**
Neighbors' behavior	0.449 ***	0.347 ***	−0.001	0.017 ***
	(2.68)	(2.62)	(−0.01)	(2.9)
Variables controlled	Yes	Yes	Yes	Yes
Provincial fixed effects	Yes	Yes	Yes	Yes
N	1010	2276	1498	1788
Hansen's J statistic	10.869	11.469	16.63	17.717
Hansen's J statistic (p-value)	0.998	0.998	0.968	0.973

z-statistics are in parentheses; *** $p < 0.01$.

Networks (Internet and social networks) are widespread factors that affect farmers' land transfer in rural areas [13,46]. In this study, the sample is divided into farmers with and without access to the Internet. As shown in column (1) and column (2) of Table 7, the effect of neighbors' behavior on land rental is only significant for farmers without access to the Internet. Without Internet access, such farmers rely more extensively on information from their neighbors and are, therefore, more likely to emulate their neighbors' behavior.

Referring to previous practices [76], households are classified into two groups based on their total annual expenditure on social activities and social interaction. If the total annual expenditure on social activities and social interaction is zero, such families are labeled as having no social networks. Other families are labeled as having social networks. The empirical results of those tests are summarized in column (3) and column (4) of Table 7. The empirical results here show that the neighbors' influence on farmland rental in rural areas is only significant for peasant families with solid social networks in the same community or village. Farmers with no social networks are essentially outside or on the fringes of the local social network. Consequently, their behaviors are less influenced by those of their neighbors.

Table 7. Empirical results of Internet-related heterogeneity among household heads.

	Explained Variable: Land Rental			
	Access to the Internet		Social Network	
	(1)	(2)	(3)	(4)
	Yes	No	Yes	No
Neighbors' behavior	0.014	0.032 ***	0.014 ***	−0.007
	(1.43)	(4.59)	(3.36)	(−0.14)
Variables controlled	Yes	Yes	Yes	Yes
Provincial fixed effects	Yes	Yes	Yes	Yes
N	1491	1795	3124	162
Hansen's J statistic	25.806	15.096	22.673	3.204
Hansen's J statistic (*p*-value)	0.731	0.993	0.861	0.999

z-statistics are in parentheses; *** $p < 0.01$.

5. Discussion

5.1. Theoretical Implications

Ethnomethodology holds that social interactions among group members are governed by some folk rules [77]. However, in research on farmers' land transfer behaviors, those folk rules hidden in the social interactions between neighbors are generally ignored. Folk rules permeate rural daily life and carry a high degree of acceptance in village social life. Folk rules possess a catalytic mechanism that helps land transfer to be fully integrated into the daily life of the village, which will increase the motivation of farmers to transfer land. To fill in this obvious knowledge gap, the current research attempted to find the micro-driving force of land transfers generated through social interaction at the community or rural village level from a novel and insightful perspective of neighbor interactions. In this regard, the current research makes important theoretical contributions.

First, the current research enriches the literature on agricultural land transfers from the perspective of local social interactions in rural villages. As for the factors affecting the transfer of rural land, the existing literature mainly analyzes factors such as non-agricultural employment and relevant characteristics at the family and village levels [11,25,60]. In contrast to the previous research, this study deliberately focused on the effect and impact of village-based local social interaction on farmland rental. The results and empirical evidence of the current research indicate that the interaction between neighboring peasant families in the same village and the resulting demonstrative effect can promote farmland rental. Hence, this study shed light on the importance of local social interactions in promoting farmers' land transfer behaviors, providing a deeper understanding of the rapidly emerging research area of rural land transfers, which has, thus far, been widely ignored by scholars [8,78].

Second, this research contributes effectively to the agricultural land literature on neighborhood spillovers by exploring the mechanisms through which neighboring farmers and peasant families rent out agricultural land [56,73]. To this end, this study examined the perceived importance of the Internet as a mediator. Specifically, when neighboring farmers' land is rented out, it not only directly increases other farmers' probability and possibilities of renting out land in the same village but also indirectly increases the probability of farmland rental by improving the perceived value and importance of the Internet among other farmers and peasant families in the same village. As far as the existing land transfer situation is concerned, information asymmetry is the main influencing factor leading to the inefficiency of land transfer in rural China. In the past, farmers mainly obtained land information through face-to-face communication with relatives and friends in the village; however, this method is defective in terms of the timeliness of information exchange and the potential range of dissemination. Through the Internet, farmers can not only break through the information asymmetry barrier inherent in neighborhood communication [79] or enhance the information exchange efficiency of both sides of the transfer to reduce transaction costs [80] but also broaden the spatial and temporal scope of farmers within the market so as to further deepen the depth and breadth of the transactions within the land transfer market. Moreover, the direct and mediating effects show the same direction; therefore, the mediating effect is complementary rather than competitive [74]. Thus, the development of the Internet not only helps promote land transfers [46] but can also produce a social multiplier effect to accelerate the transfer of rural land [27,58]. This finding provides a new perspective for comprehensively and accurately assessing the impact of the social interaction and spatiotemporal integration of physical space–time and Internet-based virtual space–time on rural land transfer.

Finally, by analyzing heterogeneity, this study more comprehensively examined how local social interactions influence land rental in rural areas. This study showed that the neighborhood effect on land transfers is not significant for rural households with leased agricultural machinery and households that are dissociated from the local social network (farmers with access to the Internet but no social network). Indeed, this finding deepens the research on land transfers in rural areas [25,26,61]. It provides empirical evidence and theoretical guidance for stimulating the micro-driving force of land transfers in rural areas.

5.2. Practical Implications

Combining the findings and empirical evidence of this current research, this study proposes some targeted policies and practical recommendations based on three aspects. First, concerning rural governance, the government should provide farmers with opportunities to participate in any local social network and promote positive interactions between the village committee and the farmers' social network to achieve a consensus on land transfer through consultation. Second, the formation and operation of the farmers' local social network in the context of land transfers depend on the role played by rural elites and agricultural leaders. Therefore, the government should vigorously publicize land transfer policies, guide farmers to learn from rural elites and agricultural leaders, improve their willingness to transfer land and ensure an effective land supply in rural areas. Finally, the government should actively cultivate stable farmers' cooperative organizations to facilitate the growth of social networks. As long as they are well-designed and thoroughly implemented, these policies can achieve good results. There will always be resistance and challenges to the implementation of any policy, and the key is to ensure that the policy is popular and its implementation is well-planned. While these policy recommendations are designed for the Chinese context, they can also serve as a reference for facilitating agricultural land transfers in most developing countries. Of course, when applying China's experience in other countries, the cultural and institutional differences need to be fully taken into account.

5.3. Limitations and Future Research

Owing to features of the data and other constraints, the current research inevitably has some deficiencies. This study only utilized data from China, which prevents international comparative research. In the future, relevant data from other regions and developing countries should be collected systematically and analyzed by comparing different countries. In addition, to construct a spatial weight, this study adopted the method of attributing an equal weight in the same village. However, even if farmers live in the same area of the countryside, the influence of different neighbors is different; that is, the weight is different. Therefore, in the future, scholars should aim to construct spatial weight matrices with different weights to describe neighborhood relations. Fourth, because the data for this study came from the CFPS, there is limited information on rural land transfers. In the future, a more in-depth and complementary study should be conducted in conjunction with other data. Finally, the directionality of the neighbor spillover effect in the process of land transfer is worth further investigation.

6. Conclusions

During the transformation and upgrade of the mode of agricultural production for agricultural modernization, stimulating farmers' participation in land transfers and guiding large-scale production operations are crucial steps. Accordingly, based on the 2018 CFPS micro database, this study examined the farmers' neighbor effect in the process of land rental. The empirical evidence of this current study shows that the land-leasing behavior of neighboring peasant families has a significantly positive impact on the agricultural land rental behavior of other peasant families in the same village. This, in turn, indicates that neighborhood interaction based on the local social network of the village influences farmers' willingness to rent out agricultural land. In terms of the mechanism of the local social network, this study found that the Internet's perceived importance is an important mediating variable for neighbors' mutual influence on land rental behavior. Moreover, farmers show a heterogeneous neighborhood effect while renting out land. Overall, the neighborhood effect is significant; however, for rural households that lease agricultural machinery and farmers who have access to the Internet but lack a social network, the neighborhood effect is not significant. Undoubtedly, these results provide important empirical evidence and theoretical guidance for stimulating the micro-driving force of land transfers in rural areas through local social networks.

Funding: The authors disclose receipt of the following financial support for the research, authorship, and/or publication of this article: This research is funded by the National Social Science Foundation of China (17BSH122).

Data Availability Statement: The data presented in this study are available on request from the author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Regional division of provinces.

The Eastern Region (10 Provincial Administrative Units)	The Central Region (6 Provincial Administrative Units)	The Western Region (12 Provincial Administrative Units)	The Northeast Region (3 Provincial Administrative Units)
Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan.	Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan.	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang;	Liaoning, Jilin and Heilongjiang.

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Article

The Impact of Land Transfer-In on Crop Planting Structure and Its Heterogeneity among Farmers: Evidence from China

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Abstract: The crop planting structure in the world has shown a trend of "non-grain", which will shake the foundations of global food security in the long run. As a basic and important production factor, changes in land will have an impact on farmers' crop planting decisions. In this paper, we take China, a country that is experiencing land transfer, "non-grain" production, and farmer differentiation, as the research area, use the household survey data at the national level, and adopt the methods of Propensity Score Matching (PSM) and multiple regression models to reveal the impact of land transfer-in on the crop planting structure and its heterogeneity among farmers. The results showed that land transfer-in can drive the crop planting structure to tend to be "non-grain" in China. The research conclusion was still valid after the robustness tests of expanding the sample size, increasing the number of control variables, and introducing endogenous problem management. The heterogeneity analysis indicated that the negative impact of land transfer-in on the planting of grain crops mainly exists for large-scale farmers and farmers with agriculture as the main source of income. Based on these findings, the Chinese government should formulate targeted policies to prevent the "non-grain" tendency of crop planting structure after land transfer-in.

Keywords: land transfer-in; crop planting structure; food security; PSM; China

Citation: Chen, Y.; Cai, M.; Zhang, Z.; Li, M. The Impact of Land Transfer-In on Crop Planting Structure and Its Heterogeneity among Farmers: Evidence from China. *Land* **2024**, *13*, 87. https://doi.org/10.3390/land13010087

Academic Editor: Hossein Azadi

Received: 5 December 2023
Revised: 7 January 2024
Accepted: 9 January 2024
Published: 11 January 2024

1. Introduction

At present, world security is facing various challenges, such as local conflicts, trade frictions, and frequent extreme weather events [1–5]. In this context, the importance of food security is becoming more and more prominent [6–8]. Ensuring a stable supply of food rations is the key to ensuring food security [9,10]. However, with the development of the economy and urbanization, people's demand for high-value and high-quality food has increased, and the planting structure has shown a trend of "non-grain". According to the data from FAOSTAT, from 1980 to 2021, the global harvested area of oilseeds, vegetables, and fruits expanded by 108.4%, 68.1%, and 126.5%, respectively. However, the harvested area of the main ration crops (rice and wheat) expanded by only 1.1%, and its share of the total harvested area of crops decreased from 34.5% to 26.3% [11]. In the long term, this change in crop planting structure will affect the supply capacity of food rations and shake the foundations of global food security [12–15].

Essentially, whether to plant grain crops or cash crops is a behavioral decision made by the business entity to maximize production profit and labor productivity [16,17]. The principal basis for this decision is the factors of production such as land, labor, and capital owned by the business entity [18]. Of all the factors of production, land is the most basic and important [19,20]. The amount of land owned largely determines the mode of agricultural production and management [21,22]. Therefore, changes in the scale of land management, such as land transfer-in (farmers take over the transferred land, and the land management scale expands), will inevitably have an impact on the crop planting decisions of the business entities [23,24].

The impact of land transfer-in on cropping structure is still controversial among scholars. On the one hand, some scholars believe that land transfer-in will lead to the "non-grain" of planting structures. There are two main theoretical logics. Firstly, the business entity usually pays rent for the land that is transferred-in, thus increasing the land and total production cost. In order not to cut profits, business entities may prefer to plant cash crops with relatively higher returns [25–27]. Secondly, with the transfer-in of land and the expansion of the land operation scale, the cost of labor and land has gradually become apparent, and the objectives of business entities have become more and more profitable [28–30]. As a result, the tendency to plant cash crops with higher returns has become stronger.

On the other hand, there are many scholars who hold the opposite view, arguing that land transfer-in will drive the planting structure to be "grain-oriented" [31–35]. The main theoretical logic lies in the fact that compared with the cash crops that are labor-intensive, difficult to be replaced by machinery for manual operation, and have high mechanization application cost, grain crop planting has more mature mechanization technology and socialized service technology [25]. With the land transfer-in and the expansion of land scale, more labor force is required. Under the constraints of the decreasing amount and rising cost of agricultural labor, business entities tend to grow grain crops that make it easier to replace labor with machinery [36]. At the same time, with the expansion of the operation scale, the agricultural production activities such as cultivation, planting, and harvesting are usually outsourced when the operation scale exceeds the cultivation capacity of the farmer's labor. Grain crops are more likely to be involved in the socialized service system [33,37]. As a result, with the rapid development of the agricultural productive service market, grain crops are more likely to be the plant choice of most business entities [38].

By combing through the literature of scholars, it can be found that most of the data sources for these studies were farmer surveys in one or several provinces. The natural, social, and economic conditions of different regions vary greatly, so the results of the research were regional and diverse. Moreover, the type of farmer household is not distinguished, so the ignorance of farmer differentiation may be an important reason for the controversy of the existing results. With the process of industrialization and urbanization, the differentiation of rural development has accelerated, and the differentiation of peasant households has also gradually emerged [39–41]. Some peasant households have more resources, higher production and management capacity, and gradually develop into large farmers or family farms. Some peasant households seek non-agricultural employment in the cities and return to the countryside to engage in agricultural production only when needed, thus becoming part-time farmers. There are also farmers who still maintain traditional agricultural production due to inertial thinking [29]. Different types of farmers have different resources, and the consideration of planting choices is correspondingly different. Based on this, we take the whole of China, a country that is experiencing farmer differentiation and land transfer, and where the phenomenon of "non-grain" production is intense, as the research area. Then, we adopt the data from the Chinese Family Database (CFD) of ZheJiang University and China Household Finance Survey (CHFS) conducted by the Survey and Research Center for China Household Finance at the Southwestern University of Finance and Economics (SWUFE) [42], to reveal the impact of land transfer-in on the crop planting structure and its heterogeneity among farmers through the methods of Propensity Score Matching (PSM) and constructing multiple econometric models.

There are two possible contributions to this article. Firstly, the data used in this paper are derived from a representative national database of farmer surveys covering almost all provinces, so this work can provide a nationwide and stable conclusion on the impact of land transfer on the crop planting structure in China. Secondly, although China's land transfer policy is relatively mature, there is still a lack of management policies for different types of farmers. Considering the reality of farmer differentiation, we divide farmers into four types according to their operation scale and income structure. By analyzing their differences in planting choices after the land transfer-in, this work can provide decision-making support for China's more targeted land transfer policies.

2. Materials and Methods

2.1. Variable Selection

The explained variable in this paper is the crop planting structure of farmers. Taking into account the availability of data, we measured this variable using the ratio of the planting area of grain crops to the total planting area of grain crops and cash crops (GR). According to the questionnaire, grain crops include six major types: rice, wheat, maize, potato, sweet potato, and pulses. Cash crops include four major types: peanuts, rape, cotton, and tobacco. An increase in the value indicates that the crop planting structure shows a trend of "grain-oriented", and a decrease in the value indicates that the crop planting structure shows a tendency of "non-grain".

The core explanatory variable in this paper is land transfer-in, which is measured by two indicators. One is the dummy variable, i.e., whether the farmer owns the cultivated land that transferred-in (Trans_in). The other is a continuous variable, i.e., the ratio of the area of cultivated land that transferred-in to the total area of cultivated land owned by farmers (Trans_rate).

Farmers' planting decisions will be affected by many factors, including natural conditions, agricultural production conditions, farmers' household characteristics, agricultural production costs and benefits, etc. [38]. In order to ensure the unbiased simulation results, this paper selects topographic conditions (Topography), the amount of agricultural labor (Labor), area of cultivated land (Land), agricultural machinery usage (Machine), cost and profit of grain production (Cost, Profit), and farmer's income level (Income) as control variables, considering the availability of data and referring to the existing literature [25,33,43–48].

The definitions of all variables are shown in Table 1.

Table 1. Definition of each variable.

Variables	Definition	Unit
GR	Proportion of the planting area of grain crops to the total planting area of grain crops and cash crops	%
Trans_in	A dummy equal to 1 if the farmer owns transferred-in land, and 0 otherwise	–
Trans_rate	The ratio of the area of cultivated land that transferred-in to the total area of cultivated land owned by farmers	%
Topography	A dummy equal to 1 if the farmer is located in a plain, and 0 otherwise	–
Labor	Amount of agricultural labor force per household	Person
Land	Area of cultivated land per labor force	Hectare/person
Machine	The proportion of the area of cultivated land with machinery use to the total area of cultivated area	%
Cost	Production cost per planting area of grain crops *	Thousand CNY/hectare
Profit	Net profit per planting area of grain crops *	Thousand CNY/hectare
Income	Disposable income per labor force	Thousand CNY/person

Note: * average value of rice, wheat, and maize.

2.2. Data Sources and Descriptive Statistics

2.2.1. Data Sources

The data used in this study came from the China Family Database (CFD) of Zhejiang University, and its data were obtained through the China Household Panel Survey (CHPS). The sample of the CHPS is distributed in 29 provinces (autonomous regions and municipalities directly under the central government; excluding Xinjiang, Tibet, Hong Kong, Macao, and Taiwan). The survey content includes the basic structure of urban and rural households, employment situation, income and expenditure structure, household wealth, agricultural production and operation, land use and transfer, population migration and urbanization, financial behavior, health and social security, education and training, etc. [49]. The survey has been conducted every two years since 2011 and has so far conducted 5 rounds. However, the 2019 data are only available to researchers at Zhejiang University, so we can only obtain data up to 2017. According to the data in 2017, the number of family samples was 40,011, including 127,012 individual samples and 608 community samples. Based on the purpose of the study, we screened the samples. Invalid samples, incomplete data samples, and extreme value samples were deleted. Finally, 2334 valid samples were obtained and 2% tail reduction was carried out. Among them, the number of households with land transfer-in was 295.

2.2.2. Descriptive Statistical Analysis

Table 2 reports the average value of the main variables for the whole sample as well as for the grouped sample. According to the data, the average GR of all sample farmers was 91.51%, which is higher than that of the official statistics in China. This is partly due to the fact that the crop types in the CHPS questionnaire only include six main grain crop types and four major cash crop types. On the other hand, it may also be due to the fact that most of the samples selected by CHPS are farmers who grow grain crops. The average GR of farmers with land transfer-in was 89.16%, which was significantly lower than that of the whole sample and the farmers without land transfer-in. It indicates that land transfer-in may cause a decrease in GR. From the perspective of different types of farmers, the GR of small-scale farmers was significantly lower than that of large-scale farmers, while the GR of farmers with agriculture as their main income source is similar to that of farmers with a non-agricultural main income source.

Table 2. The average values of the main variables.

Variables	All Samples	Land Transfer-In		Operation Scale		Main Income Source	
		Yes	No	Small	Large	Agriculture	Non-Agriculture
GR	91.51	89.16	91.85	90.87	92.10	91.58	91.46
Trans_in	0.13	1.00	0.00	0.06	0.19	0.16	0.10
Trans_rate	5.02	38.78	0.00	2.38	7.47	6.43	4.04
Topography	0.44	0.43	0.47	0.32	0.56	0.49	0.41
Labor	1.94	2.04	1.92	1.85	2.03	1.98	1.92
Land	0.29	0.53	0.26	0.10	0.46	0.37	0.23
Machine	55.28	59.79	54.62	45.18	64.62	59.58	52.25
Cost	16.91	20.29	16.42	17.70	16.19	18.52	15.78
Profit	922.51	902.01	925.43	1062.26	796.75	970.51	890.65
Income	26.03	25.70	26.07	27.71	24.47	13.55	34.79

Note: Bounded by the median of the operation scale of all samples, if the operation scale of the farmer is larger than this value, they are considered a large-scale farmer. Otherwise, they are a small-scale farmer. If the agricultural income of a farmer accounts for more than 50% of their total income, they are considered to be a farmer with agriculture as their main source of income. Otherwise, they are considered to be a farmer with a non-agricultural main source of income.

The average Trans_rate of the whole sample of farmers was 5.02%, which is lower than that of the official statistics in China. This may be due to the fact that the sample size of households with land transfer-in surveyed by CHPS is not large. The average Trans_rate of farmers with land transfer-in was 38.78%, which is close to China's official statistics for the same period. From the perspective of different types of farmers, the average value of Trans_rate of small-scale farmers was significantly lower than that of large-scale farmers, while the average value of Trans_rate of farmers with agriculture as their main income source was significantly higher than that of farmers with a non-agricultural main income source.

2.3. Methods

2.3.1. Propensity Score Matching (PSM)

Farmers' planting behavior is affected by a variety of factors, so there may be a problem of selectivity bias in the sample data. In order to reduce the interference of sample selectivity bias and overcome the shortage of land transfer samples, the Propensity Score Matching (PSM) method proposed by Rosenbaum and Rubin [50] was used to process the samples. The PSM method makes the observations as close as possible to the random experimental data by matching and resampling [51]. Its analysis steps are as follows. First, the samples were divided into a treatment group (farmers with land transfer-in, D = 1) and untreated group (farmers without land transfer-in, D = 0). Secondly, considering the control variables, the propensity score of the sample farmer, i.e., the probability that a farmer is willing to accept land transfer-in, was calculated. In the third step, according to the propensity scores of each sample farmer, the methods of nearest neighbor matching, radius matching, and kernel matching were used to match the samples. Then, the balance and validity of the match results were checked. Finally, the Average Treatment Effect on Treated (ATT), that is, the change in the GR brought about by land transfer-in, was calculated.

2.3.2. Regression Model

In order to systematically reveal the relationship between land transfer-in and crop planting structure, we constructed the following multiple linear regression model after matching the samples.

$$GR_i = \beta_0 + \beta_1 Landtransfer_i + \sum \beta_k Control_i^k + \varepsilon_i \tag{1}$$

where GR_i is the explained variable, i.e., the proportion of the planting area of grain crops to the total planting area of grain crops and cash crops of farmer *i*. The $Landtransfer_i$ is the core explanatory variable, representing the situation of the land transfer of farmer *i*, and is measured by either the land transfer-in dummy or the rate of land transfer-in. $Control_i^k$ represents each control variable, as shown in Table 1. β_0 is the constant term. β_1 is the coefficient of the core explanatory variable. β_k is the coefficient of the control variable *k*. ε_i is the random error term. At the same time, in order to clarify the heterogeneity of farmers in the impact of land transfer-in on crop planting structure in China, we also constructed a corresponding regression model based on the data of each farmer type, and the model form was the same as that of Equation (1).

3. Results

3.1. PSM Estimation Result

Table 3 reports the results of the balance test for the explanatory variables. It can be seen that from pre-matching to post-matching, Pseudo R^2 decreased significantly from 0.075 to 0.001~0.005, the LR statistic decreased significantly from 126.01 to 0.86~4.01, and the significance test result shown by the *p* value changed from highly significant to non-significant. It indicates that the null hypothesis was rejected, that is, there was no significant difference in the influencing factors between the treatment group and the untreated group after matching. Moreover, the mean bias decreased dramatically from 15% to 3.3~5.9%, and the median bias decreased from 8.2% to 3.1~6.2%. The test results showed that the overall bias of the samples was greatly reduced after matching, the characteristics of the samples were similar between the two groups, and the matching results were ideal.

Table 3. Equilibrium test results of explanatory variables before and after matching.

Matching Method	Pseudo R^2	LR	p	Mean Bias	Med Bias
Before matching	0.075	126.01	0.000	15.0	8.2
Nearest neighbor matching	0.005	3.60	0.825	5.4	5.6
Radius matching	0.002	1.52	0.982	4.0	3.8
Kernel matching	0.001	0.86	0.997	3.3	3.1

Table 4 reports the GR of farmers in the treatment group and untreated group, as well as the difference between the two groups. It can be noted that the results obtained by the three matching methods are relatively similar, indicating that the matching results are robust. The results show that for farmers with land transfer-in, the average GR is 89.53%. However, if these farmers do not accept land transfer-in, the average GR will rise to 92.59%. That is, due to the land transfer-in, the GR of these farmers decreased by 3.06%. This suggests that the land transfer-in can promote the "non-grain" of farmers' crop planting structure.

Table 4. The overall effect of land transfer-in on GR.

Matching Method	Treatment Group	Untreated Group	ATT
Nearest neighbor matching	90.47	93.60	−3.13 **
Radius matching	88.90	92.08	−3.18 **
Kernel matching	89.21	92.09	−2.88 **
Mean value	89.53	92.59	−3.06

Note: ** $p < 0.05$.

3.2. The Impact of Land Transfer-In on Crop Planting Structure

In order to further confirm the impact of land transfer-in on crop planting structure, we constructed multiple regression models and estimated the regression coefficients using Stata software version 15.1. The results are presented in Table 5. In Model 1 and Model 2, we simulated only the effects of the core explanatory variables Trans_in and Trans_rate on the explained variable GR, respectively. Then, we added all the control variables to Model 1 and Model 2 and obtained Model 3 and Model 4, respectively. The results show that the coefficients of the core explanatory variables Trans_in and Trans_rate change little with or without control variables, and both of them are significantly negative at the 1% level. This indicates that the proportion of the planting area of grain crops to the total planting area will decline with the land transfer-in. That is, land transfer-in can drive the crop planting structure to tend to be "non-grain". On average, the occurrence of land transfer-in can lead to a decrease of 3.47% in the proportion of the planting area of grain crops to the total planting area of grain and cash crops. For every 1% increase in the ratio of the land transfer area to the total land area, the proportion of the planting area of grain crops to the total planting area decreased by 0.1%.

3.3. Robustness Test

In order to verify the validity and robustness of the estimation results, a number of robustness tests are performed in this paper.

3.3.1. Expand the Sample Size

The samples in the model are farmers who grow only grain crops and cash crops. To test the robustness of the models, we expanded the sample size to farmers who grow all types of crops. After that, the samples were screened by the PSM method, and the regression model was simulated again. The results showed that the coefficients of Trans_in and Trans_rate were significantly negative at the 1% level (Table 6, Model 5 and Model 6), which was consistent with the previous conclusion.

Table 5. Simulation results of the regression models.

Variables	Model 1	Model 2	Model 3	Model 4
Trans_in	−3.1994 ***	–	−3.4667 ***	–
	(−2.62)	–	(−2.90)	–
Trans_rate	–	−0.0928 ***	–	−0.0986 ***
	–	(−3.51)	–	(−3.82)
Topography	–	–	4.8277 ***	4.8027 ***
	–	–	(3.95)	(3.94)
Labor	–	–	−0.3319	−0.4420
	–	–	(−0.41)	(−0.55)
Land	–	–	0.0161	0.0836
	–	–	(0.01)	(−0.07)
Machine	–	–	0.0157	0.0164
	–	–	(0.98)	(1.02)
Cost	–	–	−0.0309 ***	−0.0320 ***
	–	–	(2.82)	(2.92)
Profit	–	–	−0.0014 ***	−0.0014 ***
	–	–	(−4.09)	(−4.15)
Income	–	–	0.0011	0.0011
	–	–	(0.06)	(0.07)
Cons	93.6580 ***	93.8224 ***	92.3138 ***	92.7082 ***
	(123.79)	(131.73)	(40.81)	(41.25)
N	698	698	698	698
R^2	0.106	0.170	0.266	0.274

Note: *** $p < 0.01$.

Table 6. Results of robustness test.

Variables	Model 5	Model 6	Model 7	Model 8	Model 9
Trans_in	−2.5116 ***	–	−2.8279 **	–	–
	(−2.88)	–	(−2.32)	–	–
Trans_rate	–	−4.0530 **	–	−0.0857 ***	−2.6021 ***
	–	(−2.07)	–	(−3.29)	(−2.77)
Control Variables	Yes	Yes	Yes	Yes	Yes
N	2254	2254	659	659	698
R^2	0.195	0.193	0.269	0.276	0.167

Note: ** $p < 0.05$, and *** $p < 0.01$.

3.3.2. Increase the Number of Control Variables

When farmers choose whether to plant grain crops, their decisions are usually affected by the cost and profit of cash crops in addition the cost and profit of grain crops. Therefore, we bring the cost and net profit of cash crops into the model for re-simulation. The regression results show that the coefficients of land Trans_in and Trans_rate (Table 6, Model 7 and Model 8) change little compared with Model 3 and Model 4, which indicates that the previous conclusion is robust.

3.3.3. Endogenous Problem Management

Although the PSM method can solve the endogeneity problem of selectivity bias to a certain extent, the model may also have the endogeneity problem of reverse causality, as farmers' planting situations may also affect their willingness to transfer land [38]. For example, the cultivation of cash crops requires more human input, and it is difficult for left-behind farmers to accept land transfer-in under the existing technical conditions [52]. In this paper, the instrumental variable (IV) method is used to solve the endogeneity problem. Referring to the practice of Luo et al. [53], the average rate of the land transfer area to the total land area of each province was chosen as the instrumental variable. On the one hand, the rate of the land transfer area to the total land area of each farmer is closely related to the average rate of the land transfer area to the total land area of the province where the farm is located. On the other hand, the planting behavior of farmers is not affected by the average rate of the land transfer area to the total land area at the provincial level. Using this instrumental variable, the two-stage least squares (2SLS) method is adopted to re-simulate the model. The result shows that the estimation coefficient of the instrumental variable in the first stage passes the significance test, and the F-value of the weak-instrumental variable test is 19.56. The value is largely greater than 10, indicating that the instrumental variable is valid [38]. The coefficient of Trans_rate is significantly negative at the level of 1% (Table 6, Model 9), which is consistent with the previous result. It indicates that after considering the possible endogeneity, the land transfer-in still significantly promotes the crop planting structure to have a "non-grain" trend, which verifies the robustness of the conclusion again.

3.4. The Heterogeneity of the Impact among the Farmers

Table 7 reports the estimate results for different types of farmers. For small-scale farmers, the coefficients of Trans_in and Trans_rate did not pass the significance test (Model 10 and Model 11), indicating that land transfer-in does not have any significant impact on the crop planting structure of small-scale farmers. For large-scale farmers, the coefficient of Trans_in and Trans_rate was significantly negative at the 5% and 10% level, respectively (Model 12 and Model 13). It indicates that land transfer-in had a negative impact on their tendency to grow grain crops, i.e., driving the "non-grain" cropping structures. For farmers with agriculture as their main source of income, the coefficient of Trans_in and Trans_rate was significantly negative at the 5% level (Model 14 and Model 15), indicating that land transfer-in had a negative impact on their tendency to plant grain crops, that is, driving the "non-grain" planting structure. For farmers with a non-agricultural main source of income, the coefficients of Trans_in and Trans_rate both failed the significance test (Model 16 and Model 17), implying that land transfer-in did not have a significant impact on the planting structure of these farmers.

Table 7. The estimation results of different types of framers.

Variables	**Small-Scale Farmers**		**Large-Scale Farmers**		**Farmers with Agriculture as Their Main Income Source**		**Farmers with a Non-Agricultural Main Income Source**	
	Model 10	**Model 11**	**Model 12**	**Model 13**	**Model 14**	**Model 15**	**Model 16**	**Model 17**
Trans_in	−1.2508	–	−2.6495 **	–	−5.3423 **	–	0.9094	–
	(−0.46)	–	(−1.97)	–	(−2.55)	–	(0.45)	–
Trans_rate	–	−0.0997	–	−0.0551 *	–	−0.0975 **	–	−0.0575
	–	(−1.40)	–	(−1.82)	–	(−2.57)	–	(−1.50)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	512	512	171	171	346	336	352	344
R^2	0.183	0.182	0.063	0.082	0.109	0.178	0.072	0.082

Note: * $p < 0.1$, and ** $p < 0.05$.

4. Discussion

4.1. Comparison with Previous Studies

Based on data of the China Household Panel Survey at the national level, this paper analyzed the impact of land transfer-in on farmers' crop planting structure. The results show that land transfer-in can drive the crop planting structure of farmers to tend to be "non-grain". The conclusions of this study are partially consistent with those drawn by Zeng et al. [25], Bi et al. [28], and Luo et al. [53]. These studies are based on the survey of rural households in different provinces, and the results show that when the labor force is sufficient and the land area does not reach a moderate scale of operation, the more land transfer-in, the greater the tendency of a "non-grain" cropping structure. However, these scholars believe that there is a threshold effect on the impact of land transfer or operation scale on the "non-grain" cropping structure. When the operation scale exceeds the moderate scale, it is difficult for household labor to complete the production of cash crops. With the high cost of agricultural labor and the moral hazard, farmers will tend to plant grain crops that are more convenient for machinery use [54,55]. That is, when the scale of operation reaches or exceeds the moderate scale, farmers will rationally choose to plant more grain crops, and the planting structure will tend to be "grain-oriented".

However, how large is the moderate operation scale? There is still no unified understanding. Many scholars provide diverse results based on different evaluation standards [56–58], and the moderate scale of different business entities in different regions should also be different. A representative view is that "the scale of land operation is equivalent to 10 to 15 times the average contracted land area of local households, and the income from agriculture is equivalent to the income of local workers in the secondary and tertiary industry", as proposed in a Chinese government document. According to the data from the Annual Statistical Report of China's Rural Policy and Reform [59], the number of farmers with an operating scale of more than 3.33 hectares (50 mu) accounted for only 1.65%, and the number of farmers with an operation scale of more than 6.67 hectares (100 mu) accounted for only 0.59% in 2020. The average operating scale of the samples selected for this study is 0.3 hectares (Table 1). This indicates that the current scale of land management in China is far from reaching a moderate operation scale. Therefore, at this stage, land transfer will drive the planting structure to tend to be "non-grain", and the conclusion of this paper also confirms this.

4.2. Explanation of the Results of This Study

There are many explanations for this conclusion, but the most critical crux is the high cost of land transfer, and the root cause is the low comparative returns of grain crops [60]. According to the data of the National Compilation of Costs and Benefits of Agricultural Products [61], from 2003 to 2020, the average land rent of the three main grain crops (paddy, wheat, and maize) in China increased from 56.1 CNY/hectare to 660.15 CNY/hectare, an increase of 10.8 times. At the same time, the proportion of land rent to the total production cost of the three main grain crops has risen from 0.99% to 3.93%. In addition, there are also costs in collecting transaction information [26,62], negotiating, and rights protection in the process of land transfer [63–65]. With the increase in land transfer costs, the average cost of grain crops continues to increase, and the net profit is further compressed. From 2016 to 2019, the net profit was even negative. That is, farmers would lose money when growing grain. In 2020, the net profit of grain crops turned positive, but it was only 707.10 CNY/hectare. As a comparison, the average net profit of the two main oil crops (peanut and rapeseed), sugarcane, tobacco, and vegetables was 2378.25, 3976.5, 1176.9, and 61,965 CNY/hectare, respectively, which was 3.4, 5.6, 1.7, and 87.6 times that of grain crops, respectively. Farmers are economically rational people who will make rational decisions by comparing various factors including input, profit, risk, etc. [66,67], and the results of the decisions are ultimately reflected in the planting structure. Motivated by economic interests, farmers are more willing to plant cash crops, resulting in a trend of "non-grain" in the crop planting structure.

At the same time, the results of this paper also show that the negative impact of land transfer-in on the rate of grain crop planting area mainly exists for large-scale farmers and farmers with agriculture as their main source of income. This is mainly due to the fact that small-scale farmers often cultivate the land to meet their needs for grain rations [68]. Through rational comparison, smallholder farmers are more inclined to grow grain crops to obtain grain rations. With the transfer-in of land and the expansion of operation scale, the operation model will transition from self-sufficiency to commercialization and marketization. Farmers will pay more attention to the commercial attributes of land products and the economic benefits they bring, and profit has become the principal pursuit of their business activities [18,28]. As a result, they are more inclined to grow cash crops with higher economic returns. Farmers with a non-agricultural main source of income usually allocate most of their labor force to the non-agricultural work, and their dependence on agriculture is low. However, they still maintain small-scale agricultural operations because there is still agricultural labor in the family, or to protect against the risk of unemployment. Such farmers have less labor allocated to agriculture and are therefore more disposed to grow grain crops that require less labor force. Farmers with agriculture as their main source of income are more dependent on agricultural income and allocate more labor to agriculture in pursuit of maximizing agricultural returns. Therefore, when other factors were controlled, they prefer to grow cash crops with higher profits.

4.3. Dialectical Understanding of the "Non-Grain" Planting Structure

From the perspective of farmers, choosing to grow more cash crops is understandable. They are rational economic beings, and their fundamental behavioral orientation is to pursue profit maximization under the condition of given resource endowment. Taking into account factors such as land, labor, policy, market, risk, and profit, they will make the choice of growing grain crops or cash crops. In fact, the "non-grain" planting structure is not a constant trend in China. For example, according to official statistics, the proportion of the planting area of grain crops to the total planting area of agricultural crops in China increased from 65.22% to 71.42% during 2003–2016 (Figure 1). The expansion of the grain planting area has benefited from many factors, such as the abolition of agricultural taxes, the introduction of agricultural subsidies, the establishment of a minimum procurement price policy, and the increase in agricultural infrastructure construction and scientific and technological services [69,70]. These measures have greatly enhanced the enthusiasm of farmers to grow grain crops. Moreover, from an international perspective, the "non-grain" planting structure is not unique to China. It also occurs in many agricultural countries, such as India, Bangladesh, and Myanmar. According to the FAOSTAT, from 1978 to 2021, the proportion of the planting area of grain crops to the total planting area of agricultural crops in India, Bangladesh, and Myanmar showed a downward trend, decreasing by 5.83%, 5.54%, and 5.18%, respectively (Figure 1). Agricultural production in these three countries is also dominated by smallholder farming, and farmers are also profit-oriented [71,72]. As these three countries are undergoing a shift in diets [73], the increasing demand for non-grain foods such as vegetables and fruits has also contributed to the change in the crop planting structure.

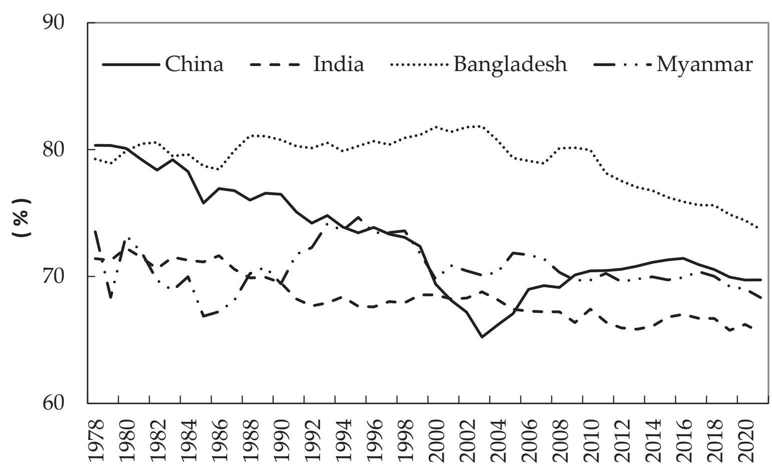

Figure 1. Proportion of planting area of grain crops to total planting area of agricultural crops in China, India, Bangladesh, and Myanmar during 1978–2021.

However, from the perspective of national food security, the trend of "non-grain" production must be prevented. Over the past two decades, China's self-sufficiency rate in grain rations has remained above 100% and the self-sufficiency rate in cereals has remained above 95%. The relatively high and stable grain self-sufficiency rate is due to the tremendous achievements in grain production. However, the growth rate of China's grain yield has been declining, with an average growth rate of less than 1% in the past decade. In the face of numerous challenges such as such as land and water resource constraints and climate change, it is becoming more and more difficult to further improve grain yields in the future. For example, the wheat yield has stagnated or decreased in more than 20% of counties in the North China Plain, while the maize yield has stagnated or decreased in more than 80% of counties [74,75]. In this context, it is becoming increasingly important to maintain the planting area of grain crops, and it is urgent to take measures to prevent the "non-grain" tendency of crop planting structures.

4.4. Policy Recommendations

Based on the above discussion, the Chinese government should formulate targeted policies to prevent the "non-grain" trend of crop planting structures after land transfer-in, and we put forward the following policy recommendations.

Firstly, improve the land transfer market and curb the excessively rapid rise in land rents. On the one hand, it is necessary to speed up the improvement of the construction of the land transfer service platform. This measure can provide more convenient information release and access services for both the supply and demand sides of land transfer, and thus reduce the cost of information transmission and promote the transfer of land. On the other hand, it is necessary to formulate a more reasonable guidance price for land transfer and explore the establishment of a reasonable rent formation mechanism for land transfer. Government intervention should be associated with market regulation to curb the excessively rapid rise in land transfer rents and promote the rationalization of land transfer rents.

In addition, improve the grain subsidy system and increase farmers' income from growing grain. On the one hand, it is necessary to make it clear that grain subsidies are linked to the actual grain planting area, so that grain subsidies will be tilted in favor of those who cultivate more grain, and increase the income and enthusiasm of the land operators. On the other hand, it is necessary to strengthen education and technical training for business entities, popularize advanced technology and management experience among them, and improve their operational and management standards. Through these measures, they can reduce the production costs and increase the income from growing grain. As a result, the profit gap between grain crops and cash crops may be narrowed, and the problem of "non-grain" production will be fundamentally alleviated.

Lastly, enhance the quality of land transfer and promote moderate-scale operation. On the one hand, local governments should actively explore forms such as land shareholding, land trusteeship, land exchange and mergers, and other innovative forms of transfer. For the purpose of centralizing and connecting land, the government should promote the transformation of land transfer from "decentralized transfer" to "large-scale transfer", so as to effectively promote the expansion of the land management scale. On the other hand, according to the local actual situations, local governments should actively cultivate new agricultural business entities, develop new agricultural business models, and promote moderate-scale operation. When the land scale reaches a moderate range, farmers will rationally choose to grow grain crops [53].

4.5. Research Limitations and Future Directions

In addition to the possible contributions, this research also has some limitations. For example, due to data usage limitations, we are unable to obtain the most recent data for 2019, which are only available to researchers at Zhejiang University. Probably due to the impact of the COVID-19 epidemics, the data for 2021 have not been released. Long-term series studies are of great significance to draw a more comprehensive and reliable conclusion. Therefore, we will conduct more updated farmer surveys in the future and systematically reveal the influence mechanism and results of land transfer-in on farmers' crop planting structure.

Moreover, based on data statistics and theoretical analysis, we deduced that the increase in land transfer rent is an important reason for the "non-grain" production after land transfer-in. However, we did not systematically explore the driving forces of the increase in the land transfer rent due to the unavailability of the data. Identifying this problem is helpful to optimize the rent of land transfer and prevent the "non-grain" production after land transfer. Therefore, it is necessary to conduct more systematic research on the land transfer rent in the future, such as its change characteristics, driving factors, and optimization countermeasures.

5. Conclusions

In this paper, we take China as the research area, use the household survey data at the national level, and adopt the methods of Propensity Score Matching (PSM) and multiple regression models to reveal the impact of land transfer-in on the crop planting structure and its heterogeneity among farmers. The results showed that land transfer-in can drive the crop planting structure to tend to be "non-grain". The research conclusion was still valid after the robustness tests of expanding the sample size, increasing the number of control variables, and introducing endogenous problem management. The heterogeneity analysis indicated that the negative impact of land transfer-in on the planting of grain crops mainly exists for large-scale farmers and farmers with agriculture as their main source of income. Based on these research results, the Chinese government should formulate targeted policies to prevent the "non-grain" trend of crop planting structures after land transfer-in.

Author Contributions: Conceptualization, Y.C. and M.L.; methodology, Y.C.; software, Y.C.; validation, Y.C., M.L. and Z.Z.; formal analysis, Y.C.; investigation, Y.C. and M.C.; resources, Y.C.; data curation, Y.C. and M.C.; writing—original draft preparation, Y.C.; writing—review and editing, Y.C.; visualization, Y.C.; supervision, M.L.; project administration, M.L. and Z.Z.; funding acquisition, M.L. and Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Tianjin Philosophy and Social Science Research Planning Project (Grant number TJGL21-030).

Data Availability Statement: The associated dataset of the study is available upon request to the corresponding author.

Acknowledgments: We thank the Social Science Experiment Center of Zhejiang University for providing the data.

Conflicts of Interest: The authors declare no conflicts of interest.

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Optimizing Land Use for Carbon Neutrality: Integrating Photovoltaic Development in Lingbao, Henan Province

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Abstract: This study aims to examine the impact of land use variations on carbon emissions by incorporating the development of photovoltaics as a scenario. To meet this end, we investigate the carbon emissions fluctuations resulting from different development scenarios: natural development, low-carbon strategies, and widespread adoption of photovoltaic technology. We identify important influencing factors related to these changes and utilize multi-objective optimization and the PLUS model to simulate land use patterns in Lingbao City projected for 2035, with a focus on achieving carbon neutrality. Through multiple scenarios, we analyze differences in carbon emissions, economic benefits, ecological impacts, and land use allocations. Our findings demonstrate that the photovoltaic scenario leads to a substantial 3500-ton reduction in carbon emissions and boosts overall benefits by RMB 85 million compared to the low-carbon scenario. This highlights the significant role of photovoltaic systems inefficient land utilization, meeting carbon emission targets, and generating economic gains. This research explores the relationship between land use alterations and carbon emissions, aiming to achieve ambitious carbon reduction objectives by integrating photovoltaic applications across diverse land types. It provides fresh perspectives for examining urban land utilization and strategies to reduce carbon emissions.

Keywords: land use optimization; carbon emission; photovoltaic; county-level cities; scenario simulation

Citation: Xie, X.; Deng, H.; Li, S.; Gou, Z. Optimizing Land Use for Carbon Neutrality: Integrating Photovoltaic Development in Lingbao, Henan Province. *Land* **2024**, *13*, 97. https://doi.org/10.3390/land13010097

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 13 December 2023
Revised: 6 January 2024
Accepted: 12 January 2024
Published: 15 January 2024

1. Introduction

Research Background

In recent years, global warming has triggered a series of extreme weather disasters that have severely impacted overall human survival. As the world's largest emitter of carbon dioxide, China's carbon neutrality goal has a profound impact on global ecosystem stability [1]. To cope with this worldwide challenge, many countries have made carbon-neutral commitments [2]. From the perspective of emission reduction, land use change affects atmospheric CO_2 concentration and is recognized as the second largest source of carbon emissions, right after fossil fuel combustion [3–5]. Moreover, changes in land type, intensity, and structure profoundly affect the carbon cycling process in the terrestrial ecosystem. It can be said that land use change is one of the key factors altering carbon emissions from terrestrial ecosystems. However, most of the existing studies have explored the relationship between carbon emissions and cities from an energy perspective while paying insufficient attention to the changes in carbon emissions due to land use. Therefore, studying and analyzing carbon emissions from the perspective of land use changes is of important significance for governing urban carbon emissions and achieving carbon neutrality goals.

Changes in land use are the result of multiple contributing factors. For example, the scale and location of urban power plants are examples of the impact of urban energy structures on urban land use change. According to statistics, the annual carbon dioxide emissions from the power sector in China account for about half of the national energy carbon emissions [6]. Transforming energy structures will be one of the most significant factors in helping Chinese cities achieve carbon neutrality at the land use level.

Studies have indicated that photovoltaic (PV) systems can effectively help the global energy sector achieve carbon reduction goals [7]. As of 2020, China's installed PV capacity reached 253 GW, while solar PV power generation accounted for only 3.42% of the total power generation (NEA, 2021). In order to further reduce carbon emissions and achieve energy structure transformation. China plans to have a total installed capacity of over 1.2 billion kilowatts of wind and solar energy by 2030. This will lead to a decrease of over 65% in carbon dioxide emissions per unit of China's gross domestic product compared to 2005, with non-fossil fuels accounting for about 25% of primary energy consumption and forest storage increasing by 6 billion cubic meters compared to 2005. Among PV systems, distributed photovoltaics are the preferred choice for implementing carbon reduction measures at the land use level in the future due to their wide applicability, relatively low peak demand, ease of implementation locally, fewer transmission issues, relatively independent and safe control methods, and ease of real-time monitoring [8]. However, previous studies have overlooked the impact of photovoltaic development on land use change and carbon emissions.

This study focuses on studying the impact of distributed photovoltaic systems on urban land use change and carbon emissions. By proposing new photovoltaic penetration scenarios, it may be found that the large-scale popularization of photovoltaics is beneficial for optimizing urban land use patterns and achieving carbon emission targets. This study aims to (1) analyze in depth the factors influencing carbon emissions from land use based on the land use data of Lingbao from 2000 to 2020. (2) take multiple factors of urban ecology, economy, and carbon emission demand into full consideration to obtain various land use demands under natural development (ND), low carbon emissions (CE), and PVP scenarios based on multi-objective optimization and visualize the scenarios by using patch-generating land use simulation (PLUS). Multi-objective optimization is mainly used to find the optimal solution of the objective function when influenced by multiple factors. The PLUS model is a cellular automaton (CA) model based on raster data that can be used for simulating patch-scale land use/land cover (LULC) changes. (3) compare the differences in economic benefits, carbon emissions, and ecological benefits under different scenarios and propose the optimal development scenario suitable for the future development of Lingbao. The objectives (1) and (2) of the article mainly focus on multi-objective optimization of methods and the PLUS model section. Goal (3) is presented in the Results and Discussion section of this article.

2. Literature Review

2.1. Impact of Land Use Changes on Spatiotemporal Patterns of Carbon Emissions

Land use change is an essential link between ecosystems and human activities and a significant factor in the escalation of urban carbon emissions. In recent years, more and more scholars have been considering changes in land use from the perspective of carbon emissions. Currently, studies in this field mainly focus on analyzing the impact of land use on the spatiotemporal patterns of carbon emissions [9], as shown in Table 1.

At the national level, Wan Yee calculated the increase in carbon emissions in each country due to changes in farmland areas based on statistics from 1885 countries [10]; Yang estimated the carbon emissions from historical land use changes based on China's 300-year historical land use/cover change (LUCC) dataset [11]. Tang quantified the impact of land use and landscape pattern changes on carbon emissions from a regional perspective [12]. At the provincial and city cluster levels, Chen and Gui analyzed the spatiotemporal evolution characteristics of carbon emissions in Guangdong Province and Northwest China, respectively [13,14]. Ye analyzed the evolution characteristics of land use carbon emissions (LUCEs) in Zhejiang Province from 2000 to 2020 and analyzed the impacts of various factors on LUCEs using Kaya identity and LMDI decomposition methods [15]. Cao proposed a water-energy-carbon spatial optimization strategy for land use in urban agglomerations based on cities in the middle reaches of the Yangtze River [16]. At the city level, Zhang analyzed the factors influencing land use changes [17]. Ke established a hybrid network framework and revealed the role of different types of land in the low-carbon development of megacities [18]. Moreover, many scholars have also conducted research on ecologically sensitive areas such as lake regions and watersheds. For example, Rong analyzed the spatiotemporal characteristics of carbon emissions at the watershed scale [19]. This indicates that under the system of research on the relationship between land use and carbon emissions, land use at the macro (national, provincial, and urban agglomeration) and meso levels (city and watershed) is relatively complete, while studies at the micro (county and village) levels are scarce.

Table 1. Research on the impact of land use changes on carbon emissions.

Research Scope	Research	Research Direction	Usage Method	Advantages and Disadvantages	Source
Macro	33 countries	Farmland changes, carbon emissions	PAS2050-1	Advantages: Demonstrated a consistent, globally applicable spatial approach to estimating land use changes and carbon emissions associated with crop production. Disadvantages: Temporary carbon sequestration is not considered for data reasons.	[10]
	United States	Agricultural production, carbon emissions, and land use changes	CARD model, dynamic nonlinear programming model, FASOM	Advantages: Expounded the impact of the carbon tax on U.S. agriculture and global commodity trade. Disadvantages: Issues such as rising costs due to climate change are not included in the scope of problems.	[20]
	China	Estimation of carbon emissions from land use	Estimation of carbon density based on vegetation in the historical LUCC dataset	Advantages: Re-estimated carbon balance in Chinese terrestrial ecosystems from 1700 to 1980 and updated the table function of carbon loss and gain. Disadvantages: The data cannot reflect the secondary fluctuations of LUCC in different years.	[11]
	Yangtze River Economic Belt, China	Land use, landscape pattern, and carbon emissions	Direct measurement method, material balance calculation method, and emission factor method	Advantages: Explored the impact of changes in land use and landscape patterns on carbon emissions from a regional perspective. Disadvantages: The spatial scale of the study focuses on the whole Yangtze River Economic Belt, while the heterogeneity of specific regions is insufficiently explored.	[12]
	Guangdong Province, China	Estimation of the land use carbon emission factor	Exploratory spatiotemporal data analysis (ESTDA)	Advantages: Estimated carbon emissions of 122 county-level administrative regions in Guangdong Province. Disadvantages: No feasible emission reduction path is proposed for the spatiotemporal evolution of carbon emissions.	[14]
	Zhejiang Province, China	Land use carbon emission estimation, carbon emissions, scenario simulation	The direct calculation method and the indirect proxy method for energy consumption	Advantages: Applied the multi-scenario analysis method to simulate future carbon emission changes. Disadvantages: The Random Forest algorithm itself is defective; The large span of the study area is not considered, leading to certain inaccuracies in carbon emission estimation.	[15]
	Yangtze River Delta, China	Optimization of land use allocation, carbon emissions	Multi-objective particle swarm optimization (MOPSO), TOPSIS	Advantages: Incorporate land use suitability into the multi-objective objective function to improve the scientific nature of the decision function. Disadvantages: GDP and carbon emissions were set as positively correlated in the study, simplifying the model but leading to errors.	[21]
	Northwest China	Land use changes, carbon emissions	NSGA-II, INVEST model, direct measurement method, energy consumption analysis method	Advantages: Proposed multiple scenarios for optimizing carbon emissions from land use. Disadvantages: The model references a gray prediction model, which may introduce errors in practical applications.	[13]

Table 1. *Cont.*

Research Scope	Research	Research Direction	Usage Method	Advantages and Disadvantages	Source
Meso levels	Cities of different tiers in Hubei Province, China	Land use changes	Descriptive statistical analysis, transition matrix analysis of land use/cover change, and OLS regression	Advantages: Analyzed the factors influencing land use changes in different urban systems. Disadvantages: The impact of economic and social factors on the expansion of urban construction land has been addressed in previous studies, but the differences between different tiers of cities have not been effectively identified.	[17]
	Shenzhen, China	Land use changes, carbon emissions	Hybrid network framework	Advantages: Constructed a hybrid network framework integrating carbon emission accounting, environmentally extended input-output tables, and land matrix data. Disadvantages: The division of land use across different sectors is insufficiently refined.	[18]
	Shanghai, China	Optimization of land use allocation, carbon emissions, and scenario simulation	Decomposition analysis of kaya identity drivers Multi-objective genetic algorithm (MOGA), decomposition analysis of kaya identity drivers	Advantages: Innovatively introduced the systematic research methodology of "carbon emission accounting–peak scenario analysis–objective optimization under carbon emission constraints–multi-objective land use optimization simulation". Disadvantages: The energy statistics of Pudong New Area are incomplete and need to be converted based on the land carbon emission intensity in Shanghai. The complexity of the planning content leads to the relative dispersion of the land layout output results.	[22]
	Bortala Mongol Autonomous Prefecture, China	Optimization of land use allocation and ecological footprint	Back propagation neural network (BPNN), multi-objective genetic algorithm (MOGA)	Advantages: Proposed an integrated framework combining ecological footprint, BPNN, MOGA, and PLUS models. Disadvantages: Factors, including social dimensions, are not incorporated into the optimization objectives.	[23]
	Yellow River Basin, China	Land use change and carbon emissions	Social network analysis, PLUS model	Advantages: Simulated and predicted future land-use patterns at the watershed scale in 2030. Disadvantages: The impact of policy factors is not considered.	[19]
Micro	Changxing, China	Optimization of land use allocation and carbon emissions	NSGA-II, LC-MLUA optimization model	Advantages: Proposed an improved algorithm, NSDE, based on NSGAS-II. Disadvantages: Study cases are insufficient.	[24]

2.2. Predicting Carbon Emission Scenarios

In the field of carbon emission scenario prediction, some scholars combine carbon emissions from land use with indicators from other fields [22], such as socio-economic [15,19], ecological [25,26], and energy [27,28] indicators. However, as a complex system, changes in urban land use are affected by a variety of factors, making it difficult to gain insight into the mechanisms and drivers of changes from a single aspect. In recent years, some scholars have begun to predict future land use patterns under different scenarios based on the coupling of multi-objective optimization and land use simulation models, as shown in Table 2. For example, Chen optimized the future land use structure of Northwest China in 2060 by proposing three objectives (ecological conservation, economic development, and carbon emissions) and setting four development scenarios, namely, natural development (ND), low carbon emission (CE), high carbon sequestration (CS), and carbon neutrality (CN) [13]. Zhang proposed a low-carbon development scenario by integrating multiple carbon emission identification models and combining them with an improved multi-objective genetic algorithm, and he gave layout suggestions for the optimization of land-use allocation in Pudong New Area, Shanghai [22]. Liu built a patch-based low-carbon multi-objective land use allocation (LC-MLUA) optimization model through the improved NSGA-II algorithm [24]. Fatemeh proposed six scenarios to optimize land use changes for the Ilam urban watershed in the northern part of Ilam province, western Iran, including food production (FP), water yield (WY), sediment retention (SR), recreational quality (RQ), aesthetic quality (AQ), and habitat quality (HQ), which provided new perspectives for land development in ecologically-oriented cities [29]. Wang proposed a LULC optimization scenario for the Bortala Mongol Autonomous Prefecture region in China by combining the ecological footprint, back propagation neural network (BPNN), multi-objective genetic algorithm (MOGA), and PLUS model. Compared with the ND scenario, this scenario can effectively improve the ecological carrying capacity of the local land in the future [23]. With the development of the new energy industry, PV systems have become one of the most critical factors for urban decarbonization. The appropriate location for PV installation is also closely related to land use changes in cities. Although existing studies have thoroughly analyzed the impact of land use changes on carbon emissions and comprehensively considered other factors influencing urban development based on the goal of urban carbon emissions, very few studies have included PV in the factors influencing land use changes.

Table 2. Research on carbon emissions scenario prediction.

Research Area	Research Topic	Research Method	Scenario Setting	Source
Northwest China	Multi-objective optimization, scenario simulation	Multi-objective genetic algorithm (NSGA-II)	Natural development scenario (ND), low carbon emission scenario (CE), high carbon sequestration scenario (HS), carbon neutral scenario	[13]
Shanghai, China	Multi-objective optimization, scenario simulation	Multi-objective genetic algorithm (MOGA)	Low carbon development scenario	[22]
Zhejiang Province, China	Scenario simulation	STIRPAT model, LMDI decomposition method	Natural development scenario, energy conservation and emission reduction scenario, energy structure adjustment scenario	[15]
Hainan Province, China	Scenario simulation	(LPM), Markov chain Linear programming model (LPM), Markov chain	Natural development scenario (ND), spatial planning (SP), low carbon emission (LE), and high carbon sequestration (HS)	[30]
Shenzhen, China	System dynamics, scenario simulation	System dynamics model (SD)	A business-as-unusual (BAU), carbon-neutral action (CNA)	[31]

In summary, existing studies have not adequately addressed the impact of PV system development on land use changes at the county scale. In this study, we hope to predict the changes in urban energy structure due to PV development and further assess its impact on urban land use, which may provide a new perspective for future research on urban and county-level land use reduction.

3. Data and Methods

3.1. Research Area

Lingbao City is located at the western edge of Henan Province, between latitude 34°07′10′′–34°44′21′′ N and longitude 110°21′18′′–111°11′35′′ E, with a total area of 3011 km^2 and a resident population of 653,800. There are many mountains and ravines in the city, with the small Qinling Mountain Range and Xiaoshan Mountain Range in the south, the Yellow River and valley plain in the north, and loess hills in the center. However, the national ecological and environmental protection policy of 2016 completely banned the development of gold mines in Lingbao territory, which led to a sharp drop in income and a serious loss of population in the city [32]. The terrain is high in the south and low in the north, and the ground elevation gradually rises to 2413.8 m from 308 m in the Yellow River in the north to the south, with a relative elevation difference of up to 2105.8 m and an average natural gradient of 34.4‰. The details of the research area are shown in Figure 1.

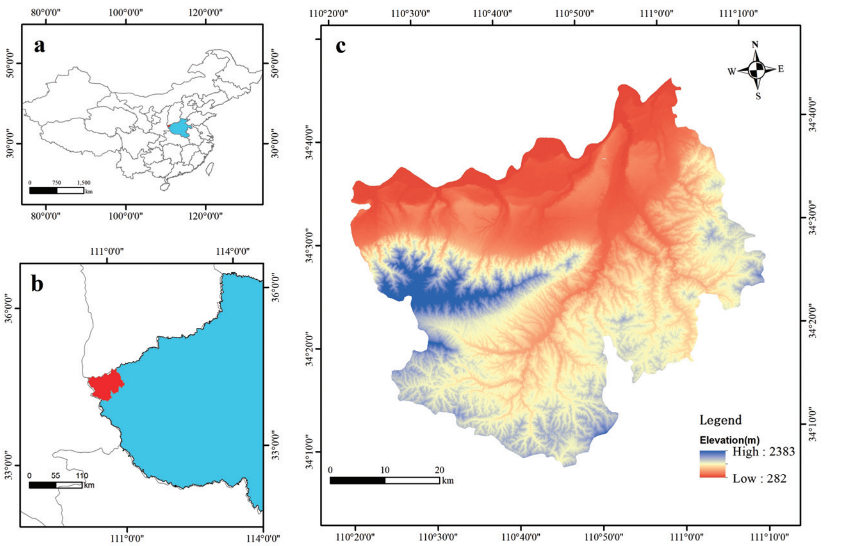

Figure 1. Location of the research area and digital elevation model (DEM), (**a**) Location of Henan Province, (**b**) Location of Lingbao in Henan Province, and (**c**) Digital elevation model (DEM) of Lingbao.

3.2. Data Sources

Based on the research method and content, the data involved in this study include three aspects: data required for PLUS model simulation, multi-objective optimization, and carbon emission factor correction.

Meteorological, soil type, and socio-economic data involved in the PLUS model simulation: Meteorological data came from the National Earth System Science Data Center (including yearly average rainfall and temperature data from 2000 to 2020) [33]. Soil-type data were from the FAO/UNESCO Soil Map of the World [34]. Socio-economic data, such as population, GDP, and public (railway) road distribution, was from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (CAS) and the National Catalogue Service for Geographic Information [35,36]. All the data were parsed and processed by Arcgis10.8, and the coordinate system was uniformly converted to the CGCS2000 latitude and longitude coordinate system.

Multi-objective optimization requires the following data: Yearly output value of primary, secondary, and tertiary industries, as well as agriculture, forestry, fishery, and animal husbandry from 2000 to 2020 in Lingbao, was obtained from the Statistical Bulletin on the National Economy and Social Development in Lingbao [37] to calculate the economic benefit coefficient. Data on the sown area, yield per unit area, and price of grain crops in Lingbao from 2000 to 2020 was obtained from the Statistical Bulletin on the National Economy and Social Development in Lingbao and the National Agricultural Product Cost-Benefit Data Compilation [37,38] to calculate the ecological efficiency coefficient. Data on the energy structure of Lingbao from 1978 to 2007 was obtained from [39] to calculate the carbon emission factor. The carbon emission factor correction data are mainly related to PV systems, including building roof vector datasets [8].

3.3. Methods

In this study, based on the coupled NSGA-II and PLUS, future multi-scenario simulation and carbon reduction analysis were conducted for Lingbao, a county-level city in Henan Province, China. The framework of this paper mainly includes three parts (Figure 2). First, three objectives were set based on the ecological conservation, economic development, and carbon emissions of Lingbao. The multi-objective genetic algorithm NSGA-II was utilized to solve the land-use demand for each type of land use when the objective benefits were maximized. Second, given the impact of PV power generation on the urban energy structure, the area of land suitable for PV installation in Lingbao was first estimated, followed by solving the PV power generation capacity for the area and then converting the PV power generation capacity and correcting the carbon emission factor in the multi-objective optimization. Finally, the Markov model was used to predict the land use pattern of Lingbao in the natural state under the natural development scenario in 2035. At the same time, the land use demand obtained from multi-objective optimization before and after PV correction was inputted into the PLUS model to obtain the land use pattern under the energy conservation and emission reduction scenario and the PV development scenario, respectively.

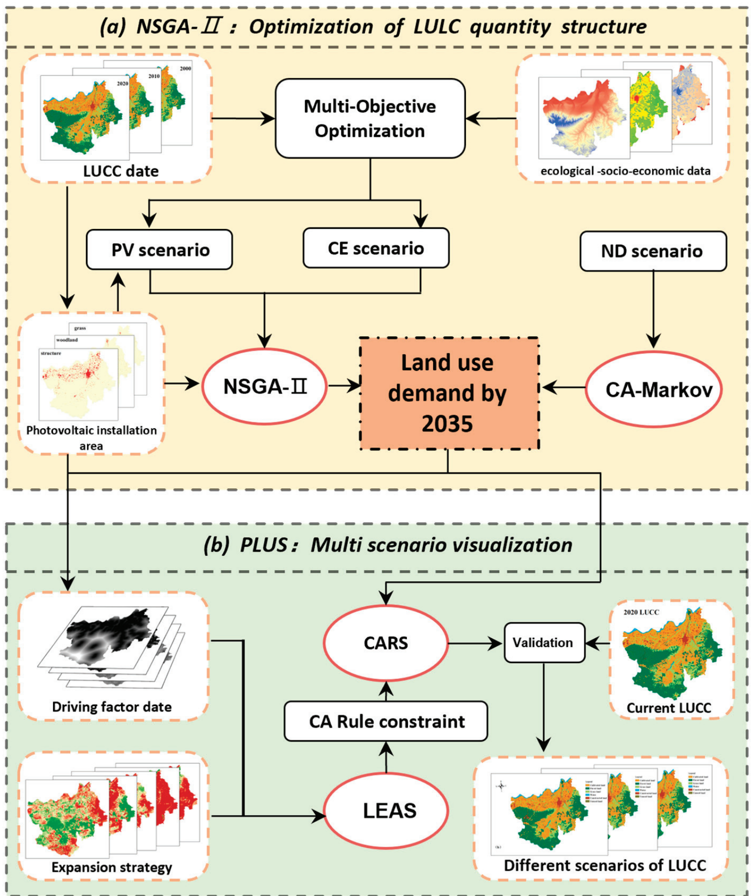

Figure 2. Research framework. (**a**) Optimization of LULC quantity structure. (**b**) Multi scenario visualization.

3.3.1. Predicting Land Use Demand

(1) Estimation method for carbon emissions

The estimation method for carbon emissions in this paper mainly refers to the Intergovernmental Panel on Climate Change's (IPCC) carbon inventory estimation method, which mainly categorizes carbon emissions into direct and indirect emissions [40]. Direct emissions can be directly calculated from the area and carbon density data on five types of land use [41], with the formula as follows:

$$E_a = \sum Cg\delta g \tag{1}$$

where E_a denotes the cumulative direct carbon emissions, Cg denotes the spatial extent of LULC type g, and δg denotes the carbon emission factor specific to LULC type g, which is derived with reference to the results of previous studies, as shown in Table 3.

Table 3. Carbon emission factors for different LULC types.

Land Use Type	Farmland	Woodland	Grassland	Waters	Unused Land
Carbon emission factor	0.36	−11.02	−5.76	−7.71	−3.87

Indirect carbon emissions, mainly from construction land, are calculated based on the energy structure data of construction land [39], with the formula as follows:

$$E_b = \sum_{i=1}^{n} m_i \times q_i \times \varphi_i \times 44/12 \tag{2}$$

where E_b denotes the total carbon emissions from the consumption of various types of fossil energy; i is the type of energy; m_i is the consumption of energy i, and its determination method is mainly based on [39]; and q is the standard coal equivalent coefficient for energy i; φ_i is the carbon emission factor, which is equal to the product of three indicators (average low heating value, carbon content, and oxidation rate) of various energy sources; 44/12 indicates the ratio of CO_2 to the molecular weight of carbon. The calculation of the carbon emission factor and standard coal equivalent coefficient for each energy type refers to the IPCC Guidelines for National Greenhouse Gas Inventories and China Energy Statistics Yearbook [42,43], as shown in Table 4.

Table 4. Energy carbon emission factor and standard coal equivalent coefficient.

Energy Name	Raw Coal	Coke	Crude Oil	Gasoline	Diesel	Fuel Oil	Liquefied Petroleum Gas (LPG)	Natural Gas	Electricity
Carbon emission factor (t/t)	0.5183	0.7801	0.8237	0.7978	0.8443	0.8647	0.8458	0.5897	0.928
Standard coal equivalent coefficient (kg standard coal/kg)	0.7143	0.9714	1.4286	1.4714	1.4571	1.4286	1.7143	1.33	0.1229

Total carbon emission is denoted by E_c, including direct and indirect carbon emissions, with the calculation formula as follows:

$$E_c = E_a + E_b \tag{3}$$

(2) Estimation method for economic benefits

Based on the economic output data per unit area of each land type from 2000 to 2020, the economic benefit coefficients of each land use in 2035 were calculated based on the gray prediction model GM (1, 1). The principle of the gray prediction model is a prediction method that establishes a mathematical model and makes predictions based on a small amount of incomplete information [44,45]. Among them, farmland, woodland, grassland, waters, and artificial surfaces are expressed as agricultural output value, forestry output value, pasture output value, fishery output value, and secondary and tertiary industry output value, respectively; wetland and unused land are not calculated as they do not directly produce economic value [46]. The calculation results are shown in Table 5.

Table 5. Economic benefit equivalent.

Land Use Type	Farmland	Woodland	Grassland	Waters	Construction Land
Equivalent factor (10,000 yuan/ha)	38.12	0.18	5.59	1.53	1351.20

(3) Estimation method for ecological benefits

Different from economic benefits, ecological benefits focus on the valuation of the goods and services provided by different ecosystems, directly or indirectly, that satisfy human needs. Their value is usually quantified in the form of economic terms based on their prices in the market or the prices of alternative goods and services [47,48]. In this study, the ecological benefits per unit area of each land type were calculated using the economic value of the annual natural grain yield of farmland with the national average yield per hectare as one standard equivalent [49]. The gray prediction model GM (1, 1) was used to obtain the ecological benefit coefficient of each land use scenario in 2035 based on the data from previous years. The calculation results are shown in Table 6.

Table 6. Ecosystem service value equivalent per unit area in Lingbao.

LULC Type	Farmland	Woodland	Grassland	Wetland	Waters	Construction Land	Unused Land
Equivalent factor (10,000 yuan/ha)	0.52	2.63	1.61	52.02	11.84	0.00	0.09

Gray prediction model, GM (1, 1)

Gray system theory (GST) is used to describe, predict, decide, and control incomplete information systems [44], and the GM (1, 1) formula is shown as follows [45]:

$$z^{(1)}(k) = \sum_{l=1}^{k} x^{(0)}(l) \tag{4}$$

$$\frac{dz^{(1)}}{dt} + \alpha z^{(1)} = \mu \tag{5}$$

$$z^{(1)}(k+1) = \left[z^{(0)}(1) - \frac{\mu}{\alpha}\right]e^{-\alpha k} + \frac{\mu}{\alpha} \tag{6}$$

$$z^{(0)}(k+1) = z^{(1)}(k+1) - z^{(1)}(k) \tag{7}$$

Assuming the amount of raw data on carbon emissions is v, the raw data on carbon emissions is $z^{(0)}$ = {z(0)(i), l = 1, 2, ..., n}, the new sequence $z^{(1)}$ = {z(1)(k), k = 1, 2, ..., n} is obtained by accumulation according to Equation (4). x represents a new set of sequences. $x^{(0)}$ be raw series, $x^{(1)}$ is said to be the one order accumulated generating operation series of $x^{(0)}$. Then, from the $z^{(1)}$ sequence, the time response sequence of differential Equation (6) is derived after least squares estimation of the values for parameters α and μ. Subsequently, the generated sequence is accumulated and recovered to determine the prediction formula for the recovered sequence, as shown in Equation (7). The final calculated factors for each type of land use are shown in Table 7.

Table 7. Carbon emissions per unit area, economic and ecological benefits in 2035 for each land type.

Factor	Farmland	Woodland	Grassland	Wetland	Water Bodies	Land Used for Construction	Unused Land
Economic benefits/10,000 yuan	38.1272	0.1856	5.5989	1	1.5301	1351.203	1
Ecological benefits/10,000 yuan	0.5186	2.6259	1.6082	23.45	11.8403	0	0.0867
Carbon emissions (CE scenario)/t	0.3570	−11.0179	−5.7549	0	−7.7113	74,095.4050	−3.8359
Carbon emissions (PV scenario)/t	0.3570	−11.0181	−5.7554	0	−7.7113	74,095.3964	−3.8675

Function construction

The NSGA-II algorithm generates a series of Pareto-optimal solutions based on fast sorting and elite strategies. It can achieve a balance between multiple optimization objectives and, therefore, has outstanding performance in solving multi-objective land use and land cover optimization problems [50]. In this study, the NSGA-II algorithm was used to solve the demand for each type of land that is most suitable for the development of Lingbao in 2035 based on a full consideration of the factors influencing urban development. Given the context of national PV development and the socio-economic development and ecological conservation requirements of Lingbao, this study proposes three prospective LULC development scenarios with the primary goal of achieving carbon neutrality.

ND scenario: The quantity structure of LULC for various types of land use in Lingbao in 2035 is predicted by the CA-Markov module in the PLUS model. This is an inertia scenario based on past land use data without considering any policy conditions.

CE scenario: The socio-economic development and ecological conservation objectives of Lingbao are taken into consideration while minimizing carbon emissions. The objective function is expressed as follows:

$$F_1(X) = Max\sum\nolimits_{j=1}^{7} A_g X_g \tag{8}$$

$$F_2(X) = Min\sum\nolimits_{j=1}^{7} B_g X_g \tag{9}$$

$$F_3(X) = Max\sum\nolimits_{j=1}^{7} C_g X_g \tag{10}$$

$$F_4(X) = MaxF_1(X) - MinF_2(X) + MaxF_3(X) \tag{11}$$

where $F_1(X)$, $F_2(X)$, $F_3(X)$ denote the economic value factor (yuan·hm^{-2}), the carbon emission factor (t·hm^{-2}), and the ecological value factor (yuan·hm^{-2}). The variable Xg denotes the area of a particular land use type (hm^{-2}). The variable j represents different types of land use, where j_1 to j_7 represent cultivated land, forest land, grassland, wetland, water area, construction land, and unused land, respectively.

PV scenario: Given the impact of new energy development on the urban energy structure, it is assumed that Lingbao will be fully covered with PV on all lands suitable for PV installation in 2035. The objective function of this scenario is obtained by estimating the power generation capacity of PV systems on various land use types and correcting the carbon emission factor of the CE scenario. First, the areas of farmland, woodland, grassland, water, and unused land for PV installation should be determined. In general, locations with slopes greater than 5° are not suitable for solar panels, and areas with solar radiation below 5400 MJ/m^2 are also considered unsuitable [51]. Moreover, the land use policy restrictions in China are considered, i.e., permanent basic farmland and high-cover woodland and grassland are not allowed for PV project development. Water and unused land are not calculated as they are quite small in relation to the total shared area and scattered. Low-cover woodland, grassland, and roof land for construction are mainly selected as PV installation lands in this study. Among them, the PV installation area of woodland and grassland is obtained in Arcgis10.8 based on the overlay analysis of annual average rainfall, year-by-year solar radiation, and DEM data. The roof area of land for construction in Lingbao in 2035 is calculated with reference to [8]. The formula for estimating the power generation capability of a PV system is as follows [52]:

$$Sp = G\left[\frac{\text{kWh}}{\text{m}^2 y}\right] * Area\left[\text{m}^2\right] * eff[\%] * PR[\%] \tag{12}$$

where G denotes the average value of solar radiation over the surface area, area denotes the area of the façade or roof (m^2), eff denotes the efficiency (%) of the PV module, and PR denotes the performance ratio. As this study focuses on investigating the impact of PV on land use change, it is assumed during calculation that the efficiency of the PV module is set to 21% and the PR is set to 80% [53–55].

Setting constraints

Total area constraint: The total area under each scenario assumption should be consistent.

$$\sum_{g=1}^{7} X_g = 299,555 \tag{13}$$

Economic growth constraint: Ensure that the economic value of the optimized scenario is greater than or equal to the economic growth target of Henan Province in 2035 and that the economic value of the optimized scenario is greater than that under the ND scenario. The value of $\sum_{g=1}^{7} W_g A_g$ is shown in Table 8.

$$\sum_{g=1}^{7} X_g A_g \geq \sum_{g=1}^{7} W_g A_g \tag{14}$$

Table 8. Comparing the current situation in 2020 and the changes in different land use types under different scenarios (10^{3}hm^2).

Scenario	Farmland	Woodland	Grassland	Waters	Land for Construction	Unused Land
Status quo in 2020	114,922.8	109,490.22	54,139.32	6451.29	14,267.7	283.86
ND	7852.59	2256.03	−11,394.61	446.85	2513.97	3.42
CE	1608.8	2125.55	−3732.34	0.20	−0.70	−1.52
PVP	2067.16	646.57	−2712.43	−0.29	−0.70	3.42

Carbon emission constraint: Ensure that the carbon emissions of the optimized plan are lower than those under the ND scenario.

$$\sum_{g=1}^{7} X_g B_g \leq \sum_{g=1}^{7} W_g B_g \tag{15}$$

Area constraints for each type of land: The area constraints for each type of land shall be determined based on the current value and the ND scenario as the upper and lower limits and adjusted for different land types according to the development demands.

$$114,922 \leq X_1 < 122,775; 109,490 \leq X_1 < 111,746; 40,744 \leq X_3 < 54,139; 6451 \leq X_5 < 6898; 14,267 \leq X_6 \leq 16,781; X_7 < 285$$

3.3.2. Multi-Scenario Land Use Simulation Based on the PLUS Model

The PLUS model combines a rule mining framework using the Land Expansion Analysis Strategy (LEAS) module with a CA model based on various random seeds (CARS). The LEAS module is conducive to depicting spatiotemporal differentiation patterns in LULC, while the CARS module employs meta-cellular automata based on LULC data and drivers for efficient spatial simulation [49].

Model input settings

The LEAS module assesses the contribution of various types of influencing factors to land use changes by extracting the changes in LULC over two periods. This can help analyze the growth potential of different land types in the research area. In addition, the CARS module can simulate LULC competition at the urban patch level. It uses adaptive factors, neighborhood effects, and development probabilities to determine the direction of expansion of various land types in different scenarios.

Accuracy verification

In this study, the PLUS model was used to predict the LULC land pattern of Lingbao in 2020, and its accuracy was verified through comparison with the current LULC data in 2020. The overall accuracy generated by verification was 0.83, and the Kappa coefficient was 0.75, indicating that the model met the accuracy requirements for simulating future LULC in the research area [56].

Visual expression of scenarios

Land demand for the ND, CE, and PVP scenarios was inputted into the model. The land use patterns of the three scenarios in Lingbao in 2035 were visualized through the CARS module of the PLUS model.

4. Results

4.1. Comparison of LULC Changes in Different Scenarios

From 2020 to 2035, the LULC changes under various scenarios in Lingbao showed significant differences (Table 9 and Figure 3). Under the ND scenario, land areas for construction and farmland increased significantly. Significant changes in land use are exemplified by Figure 3e–h. Woodland, water, and unused land showed no significant increase, while those of grassland in the central and southern parts of the research area decreased significantly. Under the CE and PVP scenarios, the expansion of construction land in the central part of the research area and farmland in the southern part of the research area was restricted. The grassland in the central and southern parts of the research area was better protected (Figure 3), and the areas with various types of land did not significantly increase or decrease. This suggests that the two low-carbon development scenarios have shown remarkable results in restricting carbon sources, such as farmland and land for construction, and protecting carbon sinks, such as woodland, grassland, and watersheds, which highlights the concept of low-carbon urban development in the future.

Table 9. Comparison of relative value (absolute value) of benefits in different scenarios.

Type	Economic Benefits/10^8 Yuan	Carbon Emissions/10^4	Ecological Benefits/10^8 Yuan	Total Value/10^8 Yuan
Status quo in 2020	2399.38	105,564.33	51.06	32,783.28
	0.0	0.0	0.0	0.0
ND	2761.62	124,196.85	50.43	27,420.34
	362.24	18,632.52	−0.63	−5362.91
PVP	2400.36	105,560.00	50.90	32,785.40
	0.98	−4.33	−0.16	2.15
CE	2399.73	105,560.35	50.79	32,784.55
	0.35	−3.98	−0.27	1.30

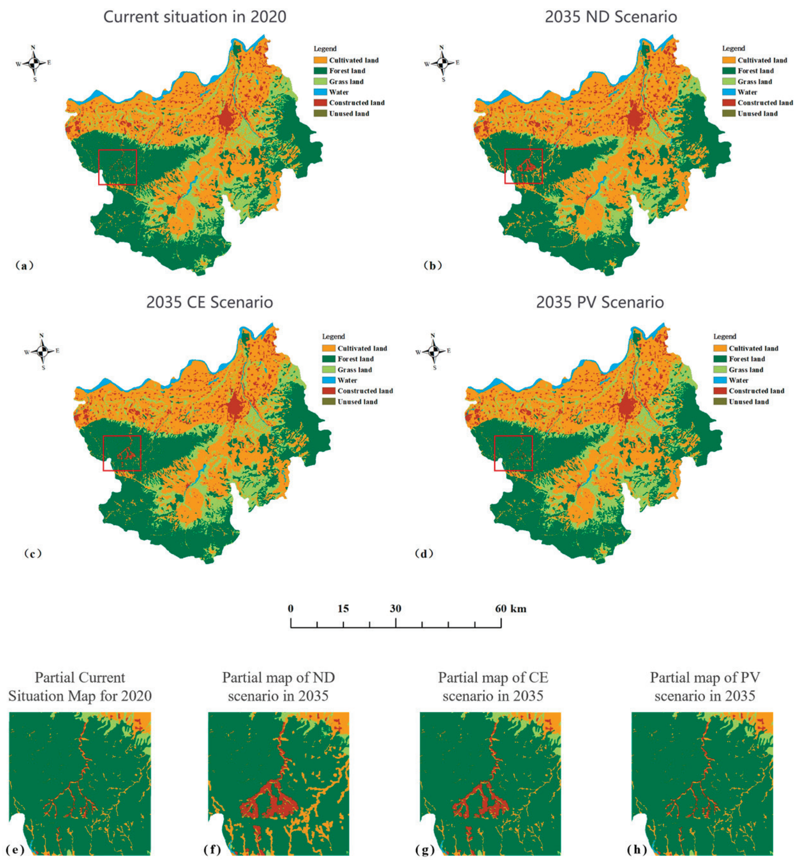

Figure 3. Land use patterns under different scenarios, (**a**) Current land use in 2020; (**b**) Natural development scenario; (**c**) Energy conservation and carbon reduction scenario; (**d**) PV penetration scenario. (**e**) Partial current Situation for 2020; (**f**) Partial map of ND scenario in 2035; (**g**) Partial of CE scenario in 2035; (**h**) Partial map of PV scenario in 2035.

Compared with the CE scenario, the PVP scenario presented a slight increase in the farmland area and a further decrease in woodland and grassland area, which might be related to the installation of distributed PV in woodland and grassland. The smaller reduction in the grassland area is mainly due to the conversion of part of the woodland to grassland in the south because the gentle slopes in the woodland part are more suitable for the installation of distributed PV compared to the grassland part of Lingbao (Figure 3). Overall, the ND scenario showed a substantial increase in farmland, land for construction, and woodland, while the extent of grassland decreased significantly at the same time. This change is mainly attributed to the low output value of the animal husbandry industry in Lingbao, which is often accompanied by encroachment on the grassland area due to urban development. Conversely, in the optimized scenarios (CE and PVP), more attention is paid to the protection of carbon sinks.

4.2. Comparison of Comprehensive Benefits and Carbon Reduction Analysis

The comprehensive benefits of various LUCC scenarios in Lingbao in 2035 differ significantly (Table 9). Compared with the ND scenario, the CE and PVP scenarios showed less carbon emissions, with carbon neutral contributions of 18,636.86 $\times$ 10^4 t and 18,636.5 $\times$ 10^4 t, respectively. At the same time, there was also a significant increase in ecological value, which saw overall value increase by RMB 5365.1×10^8 and RMB 5364.2×10^8, respectively. In the PVP scenario, the ecological benefits and carbon emission reductions were maximized. In summary, although the ND scenario has high economic benefits, it also leads to massive carbon emissions. By converting the carbon emissions into economic benefits in the form of standard coal, it was found that, compared with the other two types of scenarios, the total economic benefits of the ND scenario presented a negative growth trend over the status quo in 2020. Comparing the two types of low-carbon scenarios indicated that the PVP scenario had higher economic benefits, lower carbon emissions, and higher ecological benefits than the CE scenario.

5. Discussion

5.1. PV Development Contributions to Emission Reduction at the Land Use Level

PV solar power generation is an essential part of the future decarbonized energy economy [57] and an important direction to be considered for China's energy restructuring. In this study, the penetration of PV systems is included in the consideration of factors influencing urban development based on the previous CE scenario [13]. Through comparing the PVP sand CE scenarios, it is verified that the penetration of PV systems, to a certain extent, can bring additional economic benefits to the city while mitigating the pressure on urban ecological conservation and carbon emissions (Table 9). The main reason for the reduction of carbon emissions may be due to the fact that PV systems make full use of urban roofs and unused land for power generation [57], which lowers the pressure of power generation in the city and reduces carbon emissions from energy consumption. In one respect, the increase in economic aggregate is directly attributable to the generation of electricity by PV systems. However, the replacement of conventional fossil energy generation with PV cuts the cost of power generation and carbon reduction in the city [22], which further reduces the land demand for urban economic growth. The reduced demand for construction land is shifted to other land types, such as farmland and woodland, which generates new economic and ecological benefits. Overall, the method proposed in this study to correct the carbon emission factor based on the PV penetration scenario is feasible for investigating the effect of new energy development on land use changes and carbon reduction. In addition, there is still great potential for further exploring the effects of future PV systems on land use changes [58].

5.2. Trends in Land Use Changes in Lingbao in the Context of Carbon Neutrality

Changes in LULC have a material impact on carbon emissions from terrestrial ecosystems [59]. At the same time, changes in urban carbon emissions will indirectly affect changes in LULC through necessary factors influencing urban development, such as energy structure adjustment and constraints on ecological conservation targets [60]. In recent years, new energy systems represented by PV have developed rapidly and gradually become one of the key considerations required in urban planning. This study thoroughly analyzed the factors influencing land use changes from 2000 to 2020 and proposed three development scenarios (ND, CE, and PVP) in conjunction with two national and local policies (carbon neutrality goal and PV revitalization). Through scenario comparison, the complex influence mechanisms between urban LULC changes and economic development, ecological conservation, and carbon emissions were revealed. Specifically, under the ND scenario, the total area of farmland and construction land increases by 8%. The expansion of land for construction and farmland promoted rapid socio-economic development and farmland cultivation, while it was also accompanied by elevated energy consumption, possibly leading to more carbon emissions [61–63]. At the same time, increased land for construction and farmland encroached on the grassland area (25% reduction). Less grassland implies a decreased carbon absorption capacity of the city, which indirectly increases urban carbon emissions (Table 9). Under the CE and PVP scenarios, the growth in construction land and total farmland areas was under control, while woodland and grassland were better protected. The comparison of scenarios verified the strong correlation between changes in specific land types and urban development benefits, even at the county scale. This indicates that in the future, more attention should be paid to the expansion rate of land for construction in land use management in Lingbao while making full use of the natural background resources, such as farmland and woodland, to dynamically develop planting and forestry [64]. Moreover, it is also necessary to ensure the robust growth of the urban economy while reducing carbon emissions.

5.3. Research Deficiencies

Firstly, due to the classification limitation of the land use data used in this study, the area of wetland was counted as a watershed, which may lead to some errors in the calculation of the ecological benefit function. Secondly, the land use characteristics of Lingbao, with numerous mountains, gullies, and scattered construction land, may also lead to bias in the PLUS model simulation. Furthermore, the calculation of carbon emissions from PV systems is a complex process that requires not only the consideration of the whole life-cycle carbon emissions of PV panels when manufacturing them but also the assessment of farmland when selecting suitable land for PV installation. However, due to the strict restrictions on the use of farmland in China, where PV construction is prohibited on permanent basic farmland, and the difficulty of accessing such data, the carbon emission factor for farmland was not corrected in this study.

6. Conclusions

In this paper, with Lingbao, Henan Province, as an example, the impact of PV development on land use changes at the county level was thoroughly explored. The study constructed a multi-objective LUCC coupled model with carbon neutrality at its core, set three LUCC scenarios based on carbon emissions, and assessed the differences in the comprehensive benefits of different scenarios. The study results indicated that the farmland, woodland, grassland, and land for construction in Lingbao changed significantly under the three scenarios in 2035. Comparing the ND scenario with the two low-carbon CE and PV scenarios suggested that the intensive and carbon-reducing land-use pattern could cut over $18{,}600 \times 10^4$ t carbon emissions in Lingbao. It was also observed that changes in LULC were highly correlated with those in carbon emissions, which verified that the low-carbon development pattern also had a relatively significant impact on the changes in urban land use at the county level. Moreover, compared with the ND scenario, carbon reduction benefits from the PV and CE scenarios were $18{,}636.9 \times 10^4$ t and $18{,}636.6 \times 10^4$ t, respectively; the total added value was increased by RMB 5365.1×10^8 and RMB 5364.2×10^8, respectively. The PVP scenario reached the maximum value for carbon reduction benefits, ecological benefits, and total added value. This configuration became the optimal LUCC model among the three scenarios in Lingbao and highlighted the key role of reasonable LUCC optimization in achieving carbon neutrality goals and driving sustainable urban development while verifying that the development of PV was conducive to optimizing the urban land use structure and ensuring the achievement of carbon neutrality goals.

Author Contributions: Conceptualization, X.X. and H.D.; methodology, X.X. and H.D.; validation, X.X. and H.D.; formal analysis, H.D.; investigation, H.D.; data curation, H.D. and S.L.; writing—original draft preparation, X.X., H.D. and Z.G.; writing—review and editing, X.X. and Z.G.; visualization, H.D.; supervision, X.X.; funding acquisition, X.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Major project of National Natural Science Foundation of China (Grant No. 42293273) and the National Natural Science Foundation of China Youth Science Fund Project (Grant No. 52208068).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to thank the reviewers for their valuable comments and suggestions, which played a positive role in improving the content of our paper.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

BAU	Business-as-unusual
BPNN	Back propagation neural network
CE/LE	Low carbon emissions
CNA	Carbon-neutral action
ESTDA	Exploratory spatiotemporal data analysis
FASOM	Forest and agricultural sector optimization model
HS	High carbon sequestration scenario
IPCC	Intergovernmental Panel on Climate Change
LC-MLUA	Low carbon multi-objective land use allocation
LMDI	Logarithmic mean divisia index
LPM	Linear programming model
LUCC	Land use/cover change
LULC	Land-use/Land-cover
MOGA	Multi-objective genetic algorithm
MOPSO	Multi-objective particle swarm optimization
ND	Natural development
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PV	Photovoltaic
PVP	Photovoltaic penetration
PLUS	Patch-generating land use simulation
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
OLS	Ordinary least squares

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Article

Impact of Urbanization on the Sustainable Production of Regional Specialty Food: Evidence from China's Potato Production

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Abstract: The rapid urbanization process has gradually deepened its role in the sustainable development of agriculture, especially in the sustainable supply of food in poor areas, and has attracted more attention from international academic circles. However, the impact mechanism of different dimensions of urbanization on food sustainability in poor areas has not yet been fully unpacked. Therefore, this study focuses on potatoes as a specialty food mainly grown in poor areas of China, explores the impact mechanism of urbanization on the carbon emission intensity of potato production (CEIPP) with the spatial Durbin model, and compares with the carbon emission intensity of staple grain (CEISG) results. The main conclusions are as follows: the urbanization of main potato-producing areas developed rapidly from 2002 to 2020, which is in line with the decrease in CEIPP. The decrease in CEIPP has a significant impact on slowing down the growth of total carbon emissions and has greater potential for reduction, especially in Central and Western China, which has a large poverty-stricken population. Compared with traditional staple grain, urbanization has become a key factor influencing CEIPP. The results indicate that different dimensions of urbanization have varying degrees of impact on the sustainable production of regional specialty foods in China. The improvement of comprehensive urbanization, population urbanization, and economic urbanization reduces CEIPP, while land urbanization increases CEIPP. Therefore, to reduce CEIPP and promote its sustainable development, it is necessary to improve population urbanization and economic urbanization, properly avoid the disorderly expansion of land urbanization, and improve the quality and level of comprehensive urbanization.

Keywords: urbanization; carbon emission intensity; potatoes; poor areas; spatial Durbin model

Citation: Ni, Y.; Li, Z.; Li, J.; Jian, Y. Impact of Urbanization on the Sustainable Production of Regional Specialty Food: Evidence from China's Potato Production. *Land* **2024**, *13*, 147. https://doi.org/10.3390/land13020147

Academic Editors: Xueru Zhang, Yaqun Liu and Xingyuan Xiao

Received: 22 December 2023
Revised: 20 January 2024
Accepted: 22 January 2024
Published: 26 January 2024

1. Introduction

Recent climate change, frequent pests and diseases, COVID-19 pandemics, and regional conflicts have posed serious challenges to global food security, threatening the lives and livelihood of people in all countries around the world, especially those in vulnerable groups [1–3], and may lead to a failure to achieve the "zero hunger" goal (SDG 2) on schedule [4]. In 2019, 144 million children under the age of five had developmental delays due to hunger and malnutrition [5], and 47 million children were emaciated [6]. Children with developmental delays are mainly found in Asia and Africa, accounting for 95% of the world total [7]. Meanwhile, urbanization in poor areas such as Asia and Africa has also rapidly increased. The rapid urban sprawl promotes not only economic development but also generates enormous environmental burdens and ecological pressures, leading to a series of ecological and environmental problems [8,9]. Does the ecological environment, especially carbon emissions caused by urbanization, affect food production in poor areas? What is the impact mechanism of the rapid urbanization process in poor areas on the sustainable development of regional food? This paper attempts to discuss these issues.

According to gradient theory, the rural population flows massively to cities during urbanization [10,11], and the land scale expands in a disorderly manner, leading to the restructuring of production factor inputs [12], changes in food production methods [13], and technological efficiency [14,15]. This exacerbates the aging of the rural population [16] and leads to the loss of arable land, structural shortage of labor, and the non-agricultural conversion of farmland [17–19], which ultimately affects regional food security [20]. Urbanization also promotes the growth of farmers' non-agricultural income and the diversification of agricultural product consumption structure. This results in non-agricultural conversion of grain production structure [21], which has a crowding-out effect on grain production. The regional imbalance in urbanization causes a serious imbalance in food production [22]. Meanwhile, urbanized areas are generally leaders in the comprehensive green and low-carbon transformation of the economy and society, as well as in the innovation and promotion of green and low-carbon technologies, so they play a crucial role in promoting carbon reduction and improving carbon emission efficiency.

China has experienced the most massive urbanization in human history in the past 40 years. The urban permanent population has increased by 730 million, and the urbanization rate has increased from 17.9% in 1978 to 50.0% in 2010 and then surged to 65.2% in 2022 [23]. Joseph E. Stiglitz observed that the two most significant events of the 21st century were technological progress in the United States and urbanization in China, which fully demonstrates the historical significance and profound impact of urbanization in China [24]. There is no denying, however, that urban population growth and regional expansion in areas with high poverty rates may be more likely to cause systemic damage to the food system. Against the dual background of China's new urbanization and rural revitalization, the transformation of agricultural production in poverty-stricken areas not only requires attention to the future livelihood status of small farmers [25] but also actively explores ways to achieve sustainable agricultural development.

Potatoes are more stress-resistant, environment-friendly, and more widely used compared with traditional staple grains. They play an important role in increasing grain production and farmers' income, as well as improving soil, making significant contributions to ensuring sustainable food security in poor areas. Due to the above advantages, potatoes have become the third largest food crop for global cultivation and consumption [26]. Global statistics show that Asian countries are becoming regions with strong growth in potato production [27], and potato production in China has also experienced stable growth for nearly half a century [28]. It has initiated the strategy of developing potatoes as a staple food since 2014 [29] to promote the cultivation and consumption of potatoes [30]. The advantageous potato-producing areas in China are located in Northwest and Southwest China, with a trend of spatial concentration [31]. Urbanization in Central and Western China has accelerated in recent years, driven by major strategies such as the Western Development Strategy and the construction of the "Belt and Road". However, the typical characteristics of the environment in these regions include many unfavorable factors [32], making it easier for them to concentrate on poverty-stricken populations [33]. Therefore, a comprehensive analysis and assessment of the impact of urbanization in poor areas on carbon emissions from potatoes, as well as food security, is of great significance for a correct understanding of the relationship between urbanization and sustainable food production.

Urbanization is changing the food systems of countries around the world. Previous research on the impact of urbanization on food security has mainly focused on individual aspects of food production or consumption [34,35], with little attention paid to the analysis of urbanization on sustainable food production. Moreover, there is a lack of exploration of the relationship between urbanization and low-carbon production of specialty food in poor areas. Firstly, this study matched the distribution of main potato-producing areas with poverty-stricken counties in China and used the staple grain-producing areas as a control to determine the area of research of this study. Secondly, the urbanization levels and carbon emission intensity of potato production (CEIPP) were calculated based on the multi-dimensional urbanization framework of "economy-population-land", and an improved potato production carbon emission model, and then evolutions of their spatiotemporal patterns were analyzed. Thirdly, the impact mechanism of urbanization on CEIPP was explored with the spatial Durbin model (SDM). A comparison was made with the results of carbon emission intensity of staple grains (CEISG) to highlight the significance of this study in achieving sustainable food production in poor areas. Finally, targeted urbanization strategies are proposed. The study is also expected to provide empirical references for other middle-income or developing countries and ultimately contribute to achieving global food security and sustainable development.

2. Materials and Methods

2.1. Construction of Urbanization Indicators

Urbanization is a very complex economic phenomenon, which not only means the flow of rural population to cities but also implies changes in lifestyle, land use, and economic development models. This study measures urbanization with indicators of three dimensions: population urbanization (PU), land urbanization (LU), and economic urbanization (EU). Based on this, this paper proposes the concept of a whole set of variables by drawing on Li [36] and obtains the indicator of comprehensive urbanization (CU) by combining the Analytic Hierarchy Process and Entropy Method. Referring to Liu et al. [37], this study defines the indicators of urbanization as follows: PU mainly measures the proportion of the urban population to the total population at the end of each year in each province, LU measures the proportion of built-up areas to the administrative area in each province, and EU measures the proportion of the output value of the secondary and tertiary industries to the GDP in each province.

The weight coefficient of CU is obtained by combining the Analytic Hierarchy Process and Entropy Method, and the comprehensive weight is expressed as:

$$w_i = \frac{\left(w_i^a \times w_i^b\right)^{1/2}}{\sum_{i=1}^{n} \left(w_i^a \times w_i^b\right)^{1/2}} \tag{1}$$

where w_i^a is the weight obtained through the Entropy Method, and w_i^b is the weight obtained through the analytic hierarchy process.

$$w_i^a = (1 - e_j) / \sum_{j=1}^{n} (1 - e_j) \tag{2}$$

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{3}$$

$$p_{ij} = a_{ij} / \sum_{i=1}^{m} a_{ij} \tag{4}$$

$$a_{ij} = \frac{x_{ij} - Min(x_j)}{Max(x_j) - Min(x_j)} \tag{5}$$

where p_{ij} is the characteristic proportion of evaluation object i under indicator j, e_j is the entropy value of indicator j, a_{ij} is the standard value of positive indicators, and max (x_j) and min (x_j) represent the maximum and minimum values in indicator j, respectively.

$$w_i^b = \frac{1}{n} \sum_{j=1}^{n} \left(b_{ij} / \sum_{k=1}^{n} b_{kj}\right) \tag{6}$$

$$B = (b_{ij})_{n \times m} \tag{7}$$

where, b_{ij} represents the importance of i.

2.2. Calculation of Carbon Emission

Carbon sources of potato production can be classified into six categories: fertilizers, pesticides, agricultural plastic films, diesel fuel consumption, crop irrigation, and tillage. Therefore, the formula of total carbon emissions from potato production (TCEPP) and CEIPP is:

$$TCEPP_i = \sum_{\gamma=1} E_{i,\gamma} = \sum_{\gamma=1} (\delta_{i,\gamma} \cdot T_{i,\gamma}) + E_i^{ACH} + E_i^{ICR} \tag{8}$$

$$CEIPP_i = E_i^{tol} / Y_i \tag{9}$$

where $TCEPP_i$ is the total carbon emission of potatoes, Y_i is the production of potatoes, $E_{i,\gamma}$ is the emission of carbon source γ, $T_{i\gamma}$ is the usage (or production) of each carbon source, and $\delta_{i,\gamma}$ is the carbon emission coefficient of each source. $CEIPP_i$ is obtained by dividing total carbon emission by production. E_{ij}^{ACH} is carbon emission from pesticides. E_i^{ICR} is carbon emission from irrigation and drainage. In the context of ensuring food supply security, the continuous increase in potato production leads to an increase in total carbon emissions in the short term. Therefore, a study of the impact mechanism on CEIPP rather than on TCEPP is more in line with the concept of low-carbon transformation and sustainability of food production. Referring to Tian et al. [38], Zhang and Wang [39], and Wang et al. [40], corresponding emission coefficients are obtained for the following five types of carbon sources. The carbon emission coefficient of fertilizers is 0.897 kg/kg, pesticides 4.9341 kg/kg, agricultural film 5.180 kg/kg, agricultural diesel 0.593 kg/kg, and agricultural tillage 3.126 kg/hm^2.

The formula for calculating the carbon emission from potato pesticides is:

$$E_{ij}^{ACH} = \delta^{ACH} \cdot (COS_{ij}^{CH} / \overline{P}_{ij}^{CH}) \cdot ARE_{ij} \tag{10}$$

where E_{ij}^{ACH} refers to the pesticide carbon emission of potatoes in province j, and COS_{ij}^{CH} refers to the pesticide cost per Chinese mu in province j, $\overline{P}_{ij}^{CH}$ is the average price of potato pesticides in province j, and ARE_{ij} is the planting area of potatoes in province j.

The formula for calculating carbon emission from potato irrigation and drainage is:

$$EIR_{ij} = [(COS_{ij} - WAR_{ij}) / PEL_j] \cdot ARE_{ij} \tag{11}$$

$$E_{ij}^{IRC} = \partial \cdot PV_j \cdot EIR_{ij} \cdot \delta_{ce} \tag{12}$$

where E_{ij}^{IRC} is the carbon emission from irrigation and drainage of potatoes in province j, EIR_{ij} is electricity consumption for irrigation and drainage in province j, COS_{ij} is the cost of irrigation and drainage in province j, WAR_{ij} is water fees in province j, PEL_j is the average cost of electricity for agricultural irrigation in province j, ARE_{ij} is the planting area of potatoes in the province j, PV_j is the proportion of thermal power in province j, δ_{ce} is the carbon emission coefficient of standard coal, with a value of 0.69 (US Energy Information Administration, EIA), ∂ is the coefficient of converting electricity into standard coal, with a value of 0.1229 kg of standard coal/KWH (derived from the China Electricity Statistical Yearbook).

2.3. The Impact Mechanism of Urbanization on Carbon Emissions from Potato Production

This study draws on the research on the impact of urbanization on agricultural carbon emissions to explore the mechanism of its impact on carbon emissions of potato production.

There is an inherent correlation between the changes in economic, social, and resource factors brought about by urbanization and the changes in carbon emissions from agricultural production [41,42]. Factors such as the transfer of rural labor to urban areas, the upgrading of residents' consumption structure and the rapid development of rural areas driven by urban radiation may all lead to changes in agricultural productivity and resource utilization efficiency. Therefore, urbanization is an important factor affecting carbon emissions from agricultural production. Extensive research has been conducted on the relationship between urbanization and carbon emissions from agricultural land use, and it can be summarized that urbanization may affect carbon emissions in the following ways: (1) In terms of PU, urbanization promotes the transfer of agricultural labor. Employment in the primary industry in China has decreased from a peak of 390.98 million in 1991 to 177.15 million in 2021. After the successful rural reform, a large number of young and middle-aged rural laborers migrated to cities to work, leaving aged agricultural labor [43]. The reduction of agricultural labor has multiple impacts on carbon emissions. On the one hand, it increases land use intensity, with increased input of such factors as fertilizers and pesticides, which poses greater pressure on agricultural land carbon emissions. On the other hand, it promotes the development of new agricultural management entities and agricultural production trusteeship and expands the land management scale, which has a negative impact on the input of agricultural chemicals, thereby suppressing agricultural carbon emissions [44]. (2) In terms of LU, the massive expansion of urban land has encroached on agricultural land [45]. For a long time in the past, urbanization in China basically followed a path of outward expansion, characterized by high consumption, high emission, and high expansion, which is non-green extensive development [46]. This model has a high demand for new construction land. With cities constantly expanding to peripheral rural areas, a large amount of arable land is converted into construction land [47], intensifying the scarcity of arable land resources [48]. (3) In terms of EU, the rapid development of the secondary and tertiary industries provides technical and financial support for low-carbon agriculture. The improvement of technology and labor brought about by EU drives the improvement of agricultural productivity and promotes the transformation toward low-carbon and green agricultural production [49]. Based on the analysis above, the impact mechanism of urbanization on carbon emissions from potato production is shown in Figure 1.

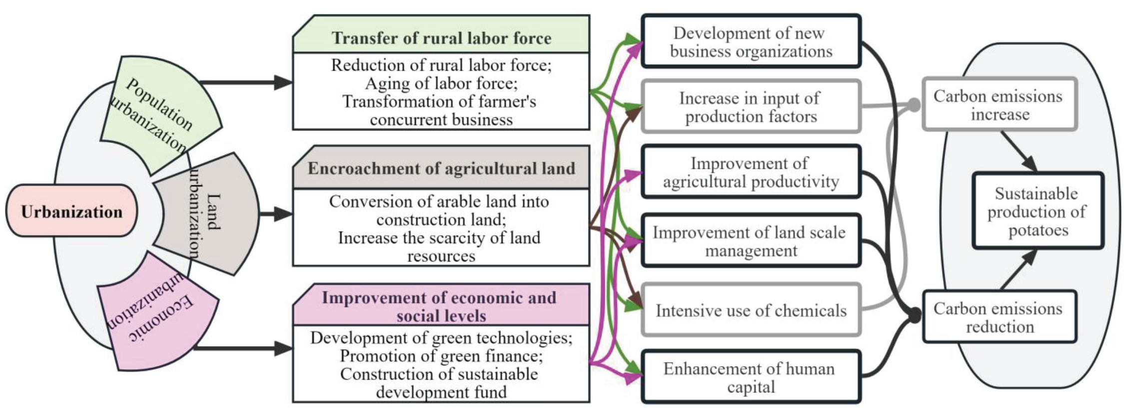


Figure 1. Impact mechanism of urbanization on carbon emissions from potato production.

2.4. Spatial Econometric Model

2.4.1. Moran Index

Spatial characteristics are important factors that must be taken into consideration in the study of urbanization [50]. The commonly used method for measuring spatial correlation is the Moran index, which includes the Global Moran Index and local Moran index. The former is used to analyze the overall spatial agglomeration, while the latter focuses on the spatial agglomeration in a region. This study uses the Global Moran Index to explore the spatiotemporal characteristics of CEIPP in China. The Global Moran Index is:

$$GMI = \frac{n}{S_0}\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}z_i z_j}{\sum_{i=1}^{n} z_i^2};\ z_i = (x_i - \overline{x}),\ z_j = \left(x_j - \overline{x}\right) \tag{13}$$

$$S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j};\ Z_I = \frac{I - E[I]}{\sqrt{V[I]}} \tag{14}$$

$$E[I] = -1/(n-1);\ V[I] = E\left[I^2\right] - E(I)^2 \tag{15}$$

where $w_{i,j}$ is the spatial weight. The value range of the Global Moran Index is $[-1, 1]$. Among them, a value greater than zero indicates a positive correlation, less than zero indicates a negative correlation, and zero indicates no correlation. A value close to 1 indicates clustering of identical attributes, while that close to -1 indicates clustering of distinct attributes.

2.4.2. Spatial Panel Model

A spatial panel model of provinces in China is constructed to explore the regional differences in the impact of factors on CEIPP, and to further analyze its impact mechanism. The spatial panel model is:

$$\begin{cases} F_{it} = a + \tau F_{i,t-1} + \rho w_i F_{it} + \beta_i \sum_{j=1}^{k} X_{i,j,t} + \delta_i w_i \sum_{j=1}^{k} X_{i,j,t} + \eta_t + \mu_i + \varepsilon_{it} \\ \varepsilon_{it} = \lambda m_i \varepsilon_i + v_{it} \end{cases} \tag{16}$$

where $X_{i,j,t}$ is the influencing factor j in a module in region i, w_i is row i of the spatial weight matrix, and W is constructed to include distance weight, economic weight, and carbon emission weight, η_t is time effect, $(\mu_i + \varepsilon_{it})$ is a composite disturbance term, m_i is row i of the disturbance spatial weight matrix M. When $\tau \neq 0$, the equation is a spatial panel model, and when $\lambda = 0$, it is SDM.

2.5. Selection of Control Variables and Data Sources

2.5.1. Selection of Control Variables

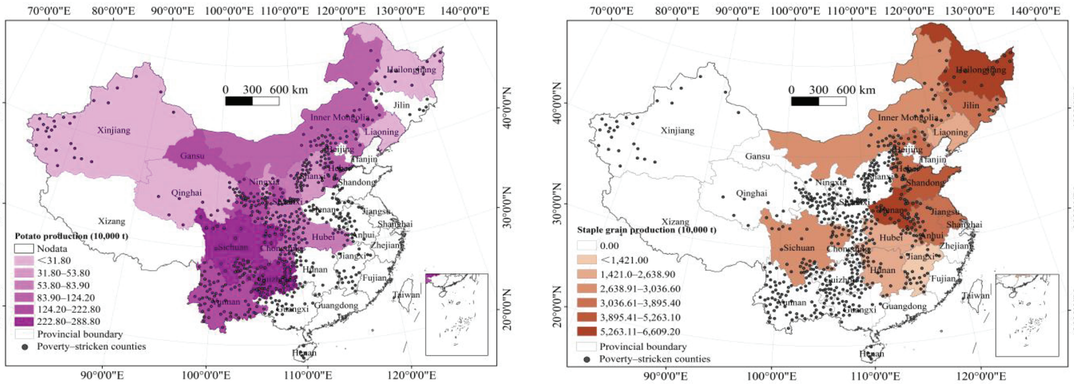
Besides urbanization, there are many other factors affecting carbon emissions from food production. Some studies show that economic growth is an important factor affecting agricultural carbon emissions by verifying the inverted U-shaped relationship between agricultural carbon emissions and economic growth in China [37,51]. Agricultural soil and water resources and per capita arable land are inhibitory factors of agricultural carbon emissions [38]. Agricultural policies are negatively related to agricultural carbon emissions [39]. Agricultural technological progress and efficiency are considered important factors in suppressing carbon emissions [40], and agricultural carbon emissions are negatively correlated with mechanization [43]. The scale of agricultural land management has both direct and indirect impacts on carbon emissions [44]. These studies provide important references for the calculation of carbon emissions from potato production and the influencing factors analysis in this study.

Production technical efficiency (PTE) is calculated by drawing on the EBM model proposed by Tone [45], and this study takes potato planting area, direct cost, indirect cost, and labor quantity as input indicators and potato production as the output indicator. Compared with traditional DEA methods, the model advantages in relaxing the "proportional changes in factor inputs" assumption and makes the results more realistic. Per capita agricultural output (PCAO) is calculated by dividing the total agricultural output value by the number of employees in the primary industry. The proportion of disaster areas (PDA) is measured by the proportion of potato disaster-affected areas to total planting areas. Potato industrial structure (PIS) is measured with the proportion of potato output value to the total food output value. Agricultural openness (AO) is measured by the proportion of the total agricultural import and export value of each province to the added value of agriculture. Production agglomeration levels (PAL) are used in the location entropy calculation method, and the specific formula is PAL = (output value of potatoes of each province/total output value of each province)/(total output value of potatoes in the country/total output value in the country). The proportion of agricultural fiscal expenditures (AFE) is measured with the proportion of agricultural fiscal expenditures to the total regional fiscal expenditure. The proportion of environmental protection fiscal expenditure (EPFE) is measured with the proportion of environmental protection fiscal expenditure to the total regional fiscal expenditure.

2.5.2. Data Sources

Over 90% of the 592 national-level poverty-stricken counties in China grow potatoes, and 192 out of 393 main potato planting counties in China are nation-level poverty-stricken counties, which means there is a strong correlation between them, as shown in Figure 2a. This article draws on Li et al. [52] and selects 15 regions as the main potato-producing areas, including Hebei, Shanxi, Inner Mongolia, Liaoning, Heilongjiang, Hubei, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. Potato production in these 15 regions was 16.539 million tons in 2020, accounting for 91.97% of the total in China, so they are highly representative. Potatoes are more profitable than other staple grains in poor areas due to their strong adaptability and stress resistance. The "Guiding Opinions on Promoting the Development of the Potato Industry" has developed the potato industry into a specialty industry in Western China [53], helping poverty-stricken households to overcome poverty. In addition, data on the cultivation of Chinese staple grains (wheat, corn, and rice) are introduced to highlight the necessity of this study. Heilongjiang, Jilin, Liaoning, etc., are classified as staple grain-producing areas according to SCPRC [16]. The distribution of staple grain production in the main producing areas is shown in Figure 2b. In a comparison of a and b in Figure 2, it can be concluded that there are very few poverty-stricken counties in major producing areas of stable grain, while most poverty-stricken counties are located in non-major producing areas of stable grain. Therefore, a study of the carbon emissions from potato production in these regions is of great significance for promoting the achievement of SDG 1, SDG 2, and SDG 12. This study ultimately selects a sample from 2002 to 2020 to calculate TCEPP and CEIPP in 15 regions, including Hebei, Shanxi, Inner Mongolia, etc., due to the availability of data.

Data on potato planting areas, potato production, total population, urban population, rural population, agricultural disaster-affected areas, local fiscal expenditure, local agricultural fiscal expenditure, and local environmental protection fiscal expenditure are from the National Bureau of Statistics. Data on the input of potatoes are from the "National Compilation of Agricultural Product Cost and Benefit". Data on employment in the primary industry, output value of the tertiary industry, GDP, built-up area, and administrative area are from statistical yearbooks of each province. The total food output value and potato output value come from the "China Rural Statistical Yearbook". Data on the import and export volumes of agricultural products are from the China Customs database. The electricity prices for agricultural production are from the State Grid website (www.sgcc.com.cn, accessed on 5 February 2023). Diesel prices come from the Wind database. The guidance on the use of potato pesticides is from the Ministry of Agriculture and Rural Affairs of China, and data on the price of pesticides are from Century Pesticide Network (www.nongyao001.com, accessed on 7 February 2023). Value data, such as local fiscal expenditure, local agricultural fiscal expenditure, and local environmental protection fiscal expenditure, are deflated with deflators (GDP deflator, CPI deflator, agricultural product production price index, and agricultural means of production price index), taking 2001 as the base period to obtain comparable data. The descriptive statistics of the main variables are shown in Table A1.



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

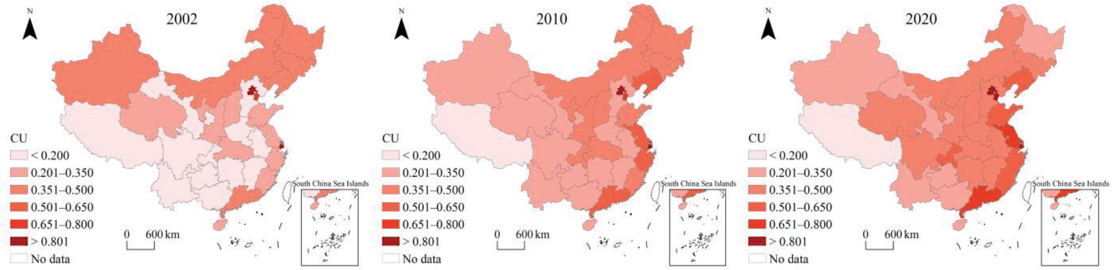
Figure 2. Spatial distribution of potato-producing areas, staple grain-producing areas, and national poverty-stricken counties in China: (**a**) Potato production in main potato-producing areas and distribution of national poverty-stricken counties; (**b**) Staple grain production in major producing areas of stable grain and distribution of national poverty-stricken counties. Note: The base map is sourced from the Standard Map Service System of the Ministry of Natural Resources, with the base map review number GS (2019) 1822 [54]; the data on potato production and staple grain production are from the National Bureau of Statistics.

3. Results and Analysis

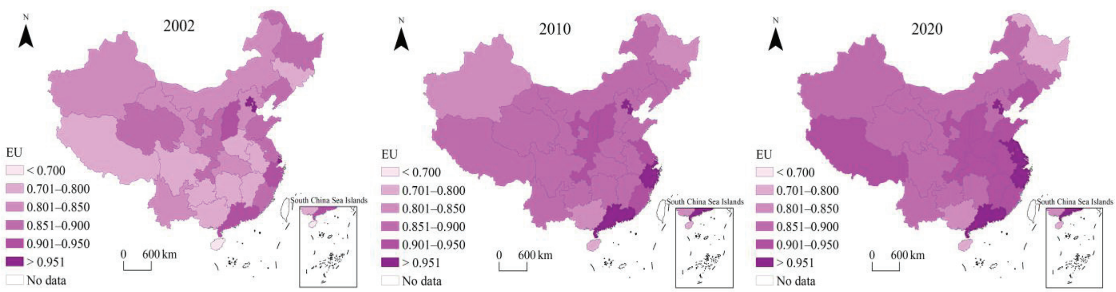
3.1. Spatial Evolution Characteristics of Urbanization in China

Overall, China's CU has shifted from the eastern coastal areas in 2002 to the central and western regions in 2020, and the gap between and within regions has gradually narrowed, as shown in Figure 3a. In 2020, China's CU showed a decreasing trend from the eastern coastal areas to the central and western regions. CU of the Southwest and Northwest China are close to each other, while they significantly lag behind that of the Eastern regions. Meanwhile, the CU of the main potato-producing area located near the Hu Huanyong Line developed rapidly from 2002 to 2020, under the strategy of the Rise of Central China and the Western Region Development.

The high-value areas of EU gradually gathered toward the eastern coastal areas from 2002 to 2020, as shown in Figure 3b. The average EU in the main potato-producing areas reached a high level of 0.883 in 2020, with Sichuan and Guizhou, which have the highest potato production, experiencing the highest EU growth. The high-value areas of PU in China evolved from concentrated distribution in the north to belt distribution along the coast, as shown in Figure 3c. The average PU in the main potato-producing areas reached 0.611 in 2020, and the average PU in Chongqing, Sichuan, and Guizhou, which have higher potato production, are significantly higher than that of other provinces. The high-value areas of LU in China evolved from the agglomeration in the eastern coastal areas to the coordinated development of the central and eastern regions, as shown in Figure 3d. The average LU in the main potato-producing areas in 2020 increased by 124.242% compared with that in 2002, and the LU in Sichuan and Guizhou, which have the highest potato production, increased by 165.574% and 249.379%, respectively. Therefore, the changes in urbanization of the main potato-producing areas contribute to the spatial evolution of urbanization in China.



(**a**)



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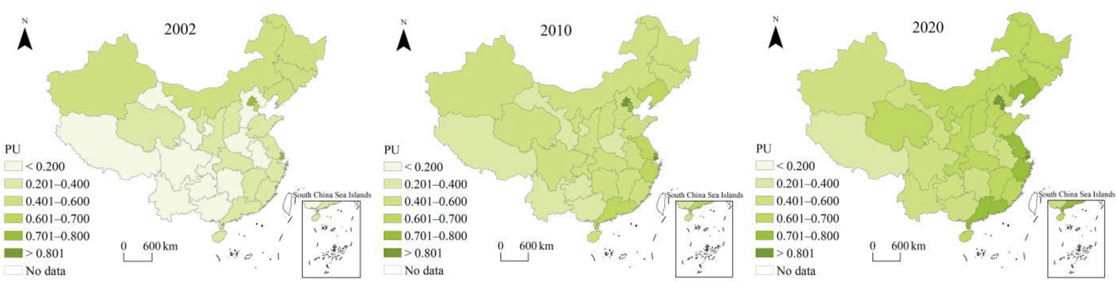
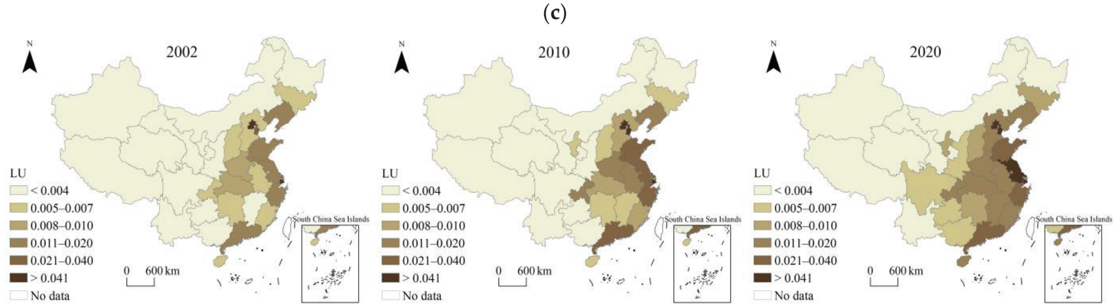


(**c**)



(**d**)

Figure 3. Spatial evolution characteristics of urbanization in China: (**a**) Spatial evolution of CU; (**b**) Spatial evolution of EU; (**c**) Spatial evolution of PU; (**d**) Spatial evolution of LU.

3.2. Spatial Evolution Characteristics of Carbon Emissions from Potato Production

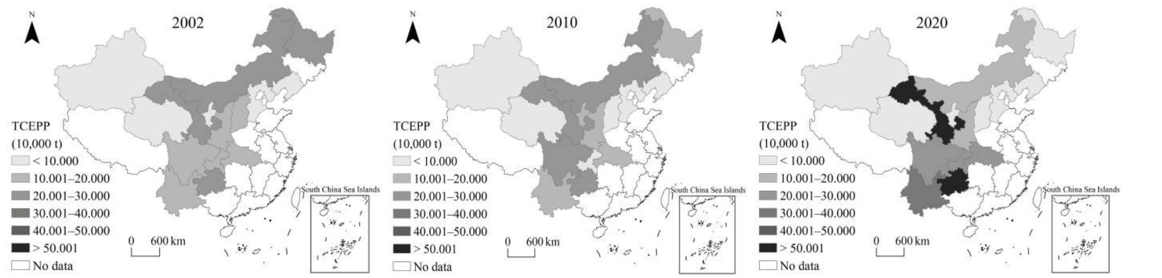
TCEPP showed a V-shaped trend from 2002 to 2020, as shown in Figure 4a. In terms of spatial distribution, the high carbon emission concentration areas shifted from the Northeast, North China, and Southwest China in 2002 to Southwest and Northwest China in 2020. During the same period, the average CEIPP showed a fluctuating downward trend, decreasing from 2672.742 kg/t in 2002 to 2550.977 kg/t in 2020. In terms of spatial distribution, CEIPP gradually shifted from Northeast and North China to Northwest, Southwest, and Hubei, as shown in Figure 4b. Combining the data of TCEPP and CEIPP, we can see that the decrease in CEIPP has an effect on the slowing down of the TCEPP growth rate. Moreover, comparison with urbanization data shows that CEIPP has significantly decreased in provinces such as Sichuan, Hebei, and Ningxia, which are experiencing rapid urbanization. Therefore, the development of urbanization has an impact on carbon emissions from potato production.

TCESG showed a fluctuating decline trend from 2002 to 2020, with high-value areas shifting from the Yangtze River and East China to North China and Heilongjiang, as shown in Figure 4c. CEISG showed a decreasing trend from 2002 to 2020, and its high-value areas gradually shifted from North China to the Northwest, as shown in Figure 4d. CEISG of Hebei Province decreased the most, corresponding to its largest decrease in TCESG in China. Therefore, it can be concluded from the spatial evolution of TCESG and CEISG in China that the decrease in CEISG in North China and the provinces in the middle and lower reaches of the Yellow River is the main reason for the slowing down of TCESG growth in these regions. These regions are not the main distribution areas of poverty, but the above analysis also provides us with some inspiration.

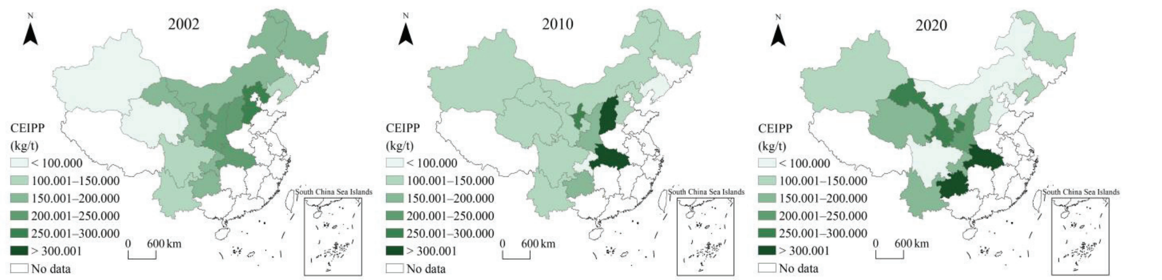
The average CEIPP in the main potato-producing areas decreased from 178.183 kg/t in 2002 to 170.065 kg/t in 2020, a decrease of 4.556%, while the average CEISG in the region decreased from 181.793 to 128.930 kg/t, a decrease of 29.079%, far exceeding CEIPP. Compared with the decrease of CEISG, potato carbon emission has greater potential for future reduction, especially in Central and Western China that have higher CEIPP (such as Guizhou, Chongqing, Gansu, Shaanxi, etc.) and are the main areas of poverty. Recently, the input of production factors has been gradually digitalized and green because of the improvement of potato technology and the development and transformation of the industry. Accordingly, carbon emissions from potato production will be significantly reduced in the future, which contributes to the sustainable development of the potato industry. It can be inferred that there is a significant potential for potato carbon emission decrease, and to some extent, it can also have a significant impact on carbon emissions from food production, thereby promoting sustainable and safe food production in China. Therefore, a study of the carbon emissions from potato production in these regions is of great significance for promoting the achievement of SDG 1, SDG 2, and SDG 12.

3.3. Analysis of the Impact of Urbanization

The spatial correlation of CEIPP is examined with spatial econometric models before empirical analysis. This study tests the spatial correlation of CEIPP from 2002 to 2020 with the Global Moran Index, and the results are shown in Table A2. The spatial correlation of CEIPP is moderately significant under the adjacency matrix, and it is remarkably significant under the distance matrix, economic matrix, and emission matrix. Therefore, this study constructs spatial panel models of the adjacency matrix, distance matrix, economy matrix, and emission matrix. Drawing on Elhorst and Chen [55,56], using Wald and Lratio tests to determine the model's suitability (SAR, SAC, SEM, SDM), and uses Hausman test to determine whether it is fixed effects or random effects, and the test results are shown in Table A3. A fixed effect SDM model is selected, and STATA is adopted for regression of the influencing factors of CEIPP under the adjacency spatial matrix, distance spatial matrix, economic spatial matrix, and carbon emission spatial matrix, respectively. The results are shown in Tables A4 and 1. Based on the significance of spatial autoregressive coefficients of the matrix and integrating the significance of variable parameters and Log-likelihood, the SDM models under the carbon emission spatial matrix are finally selected to analyze the influencing factors of CEIPP.



(**a**)



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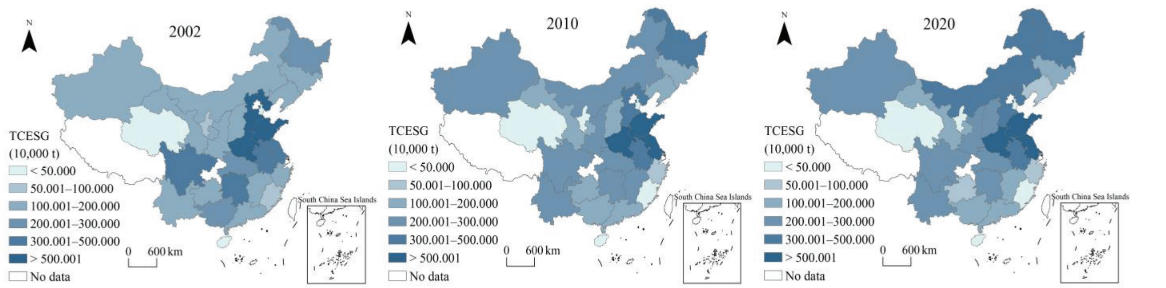

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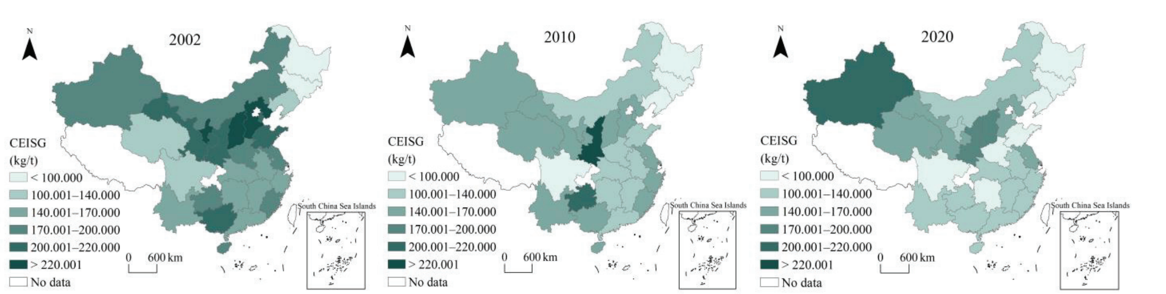

(**d**)

Figure 4. Spatial evolution characteristics of carbon emissions from food production: (**a**) Spatial evolution of TCEPP; (**b**) Spatial evolution of CEIPP; (**c**) Spatial evolution of TCESG; (**d**) Spatial evolution of CEISG.

Table 1. Results of factors influencing CEIPP under the economic matrix and emission matrix in SDM.

Variable	Economic Matrix				Emission Matrix			
CU	−8.1560 ** (3.8198)	—	—	—	−6.6033 *** (1.8330)	—	—	—
PU	—	−5.6442 (5.8748)	—	—	—	−5.8359 *** (2.1286)	—	—
LU	—	—	13.1694 (13.1261)	—	—	—	15.1825 * (8.0461)	—
EU	—	—	—	−0.8002 * (0.4657)	—	—	—	−3.6589 ** (1.8157)
PTE	−1.1470 * (0.6980)	−1.1453 * (0.6967)	−1.1674 * (0.6792)	−1.1718 * (0.7239)	−0.9207 *** (0.2837)	−0.9169 *** (0.2802)	−0.9693 *** (0.2872)	−0.9505 *** (0.3177)
PCAO	0.0371 (0.0568)	0.0537 (0.0679)	0.0218 (0.0494)	0.0361 (0.0395)	0.0234 (0.0378)	0.0295 (0.0260)	0.3812 (0.3675)	0.0227 (0.0277)
PDA	−0.1484 (0.2278)	−0.1716 (0.2351)	−0.1468 (0.2287)	−0.1721 (0.2310)	0.1033 (0.1559)	0.5184 ** (0.2411)	0.3564 * (0.2062)	0.2211 ** (0.1057)
PIS	0.8605 (1.1080)	0.7874 (1.0586)	0.6376 (0.9317)	0.6154 (0.9441)	−0.0466 (0.8951)	0.7075 (0.5947)	0.7505 (0.6101)	0.6835 (0.6614)
AO	−0.1275 (0.3506)	−0.0973 (0.3102)	−0.1792 (0.3717)	−0.1243 (0.3380)	−2.0896 * (1.2094)	−1.9327 * (1.1169)	−1.9928 * (1.2893)	−1.7308 * (1.0252)
PAL	−0.0414 (0.1233)	0.6896 * (0.3435)	0.9199 * (0.5178)	1.0771 * (0.6292)	0.5125 ** (0.2498)	0.8757 * (0.5011)	0.5780 * (0.3320)	0.0354 (0.0748)
AFE	0.5585 (1.5064)	0.6093 (1.5414)	0.7969 (1.5349)	0.4660 (1.5594)	0.4578 (1.1996)	2.7671 (1.4519)	1.3540 (1.0021)	1.7748 (2.1858)
EPFE	−2.0634 (2.3053)	−1.4826 (2.2909)	−1.5932 (2.3653)	−1.7387 (2.4121)	−1.5771 * (0.9043)	−1.9311 * (1.1304)	−0.8969 ** (0.4425)	−1.7860 * (1.1219)
W·CU	8.3907 ** (3.8226)	—	—	—	6.8300 *** (1.9291)	—	—	—
W·PU	—	5.5337 ** (2.7024)	—	—	—	5.8700 *** (2.1262)	—	—
W·LU	—	—	—	—	—	—	−17.2351 ** (8.5926)	—
W·EU	—	—	—	—	—	—	—	7.6009 * (4.0343)
W·PDA	—	—	—	—	—	0.4993 * (0.3023)	0.4216 * (0.2389)	—
W·PIS	—	—	—	—	0.7935 ** (0.3908)	—	—	—
W·AO	—	—	—	—	2.1416 * (1.2808)	2.0368 * (1.1902)	1.9961 (1.4888)	1.5131 ** (0.7196)
W·PAL	−0.7445 * (0.4145)	−0.7709 * (0.5161)	−0.9419 * (0.5362)	−1.092 * (0.6333)	—	—	—	—
Spatial	0.1887	0.3914 **	0.2001	0.1751	0.3822 **	0.3849 **	0.3683 **	0.3634 **
R^2	0.4174	0.4245	0.5055	0.4411	0.6393	0.6884	0.7108	0.6432
Log-likelihood	−152.4583	−152.4356	−152.6347	−152.8957	−141.0648	−139.8980	−136.8646	−140.6961

Note: the standard error of coefficient estimation is shown in brackets, '*', '**', '***' represent the significance levels of 10%, 5% and 1%, respectively; "—" represent no data.

3.3.1. Analysis of the Impact of Urbanization on CEIPP

CU has a significant negative impact on CEIPP (Table 1). Urbanization is not only a process of agglomeration of industries and population and rapid economic and social development but also a leader in the comprehensive green and low-carbon transformation, as well as in innovation and promotion of green and low-carbon technologies. Southwest and Northwest China, where the main potato-producing areas are located, are the main spillover areas of urbanization. Green production becomes the primary choice in these areas due to the poor production and living conditions and low environmental carrying capacity and has gradually become the key to the transformation of economic development mode [57]. Moreover, as an important food and economic crop in the region, potato production and resource utilization efficiency are easily affected by general productivity. Therefore, the transformation into green production brought about by the improvement of CU has a significant spillover effect on the sustainable production of potatoes.

PU has a significant negative impact on CEIPP (Table 1). A likely explanation is that the areas with a higher degree of population agglomeration tend to be more developed economically, and they are more active in implementing the environmental protection system to achieve energy conservation and emission reduction [58,59]. The large-scale transfer of rural labor to cities and the improvement of population quality have made large-scale operations in agriculture realistic. The intensive and efficient use of agricultural capital reduces carbon emission intensity. Qinghai, Gansu, Inner Mongolia, and Yunnan in Western China, where the rural population accounts for a high proportion, are experiencing rapid urbanization. According to the Yunnan Provincial Bureau of Statistics, Yunnan Province has been promoting a new type of people-oriented urbanization since 2010, featuring steady growth of the population and a rise in the urbanization rate. In 2020, 5.477 million of the population have a university education (college and above), and the focus on education has shifted to a higher level [60], which will reduce CEIPP by increasing human capital levels.

LU has the largest positive impact among all variables (Table 1). The improvement of LU is accompanied by a decrease in agricultural land, posing greater pressure on agricultural land use. Therefore, agricultural producers have to increase multiple cropping and increase the input of chemical fertilizers, pesticides, and other production factors to substitute for the decrease of land and the transfer of rural labor, causing an increase in carbon emissions. The main potato-producing areas are located in the Northwest and Southwest China. China's Western Development Strategy, especially the implementation of the Targeted Poverty Alleviation Strategy, provided these areas with a large amount of capital, which led to rapid urbanization of land and a decrease in arable land area. Statistics show that China invested 1.6 trillion yuan in financial special poverty alleviation funds at all levels from 2012 to 2020. For example, Guizhou province has completed the relocation of 1.92 million people in poor areas, accounting for nearly one-fifth of that in the nation [61]. The relocation of poor people and poverty alleviation can improve production mechanization, management, and intensive use of land resources in the long run, but in the short term, the reduction of farmland and the mismatch of resources leads to an increase in carbon emissions in potato production.

EU has a significant negative impact on CEIPP (Table 1). The main potato-producing areas, such as Southwest and Northwest China, have low EU, and they are in the stage of accelerated development. With the advancement of EU, the proportion of the output of the tertiary industry in GDP increases, and the capital investment in technological research and development increases accordingly. The technological effects spill over to rural areas. Green, ecological and low-carbon production technologies penetrate into the agricultural sector, and environment-friendly ecological resources replace petrochemical products, which reduces carbon emissions. The green economy in poor areas such as Northwest and Southwest China has developed rapidly, especially with the support of digital technology. For example, the use of the Internet of Things Network and sensor technology for real-time monitoring in potato production enables modern management and precise input of production factors. This not only reduces costs and improves efficiency but also reduces carbon emissions. The introduction of digital monitoring and an early warning system for potato late blight helps to avoid the abuse of drugs in the prevention and control of the disease, thus reducing environmental pollution and providing a strong guarantee for the sustainable development of the potato industry.

3.3.2. Effect Decomposition of Urbanization on CEIPP

The results are shown in Table 2. The direct effect of CU on CEIPP is significantly negative (−2.5818), the indirect effect is significantly positive (1.9283), and the total effect is negative, indicating that CP reduces carbon emissions from potato production in the region but not in adjacent regions. Generally, however, it inhibits carbon emissions from potato production. The direct effect of PU on CEIPP is significantly negative (−2.9479), the indirect effect is significantly positive (1.0661), and the total effect is negative, indicating that agglomeration of population to cities enhances large-scale, mechanized, information and green production in agriculture, which reduces CEIPP. However, the siphon effect of large cities in adjacent regions hinders PU, leading to the opposite effect. Both the direct and indirect effects of LU on CEIPP are positive, but the estimates did not pass the significance test, reflecting that current LU in the main potato-producing areas could not effectively reduce CEIPP. This is because the reduction of agricultural land results in an increase in the substitution of agricultural inputs, excessively intensive use of agricultural land and other negative effects, thus hindering the decline of CEIPP. The direct effect of EU on CEIPP is significantly negative (−1.0210), the indirect effect is significantly positive (1.9355), and the total effect is positive, indicating that the improvement of EU reduces CEIPP in the region but not in adjacent regions. It also reflects that the impact of EU on CEIPP in adjacent regions is higher than that in the locality.

Table 2. Effect decomposition of factors influencing CEIPP under emission matrix.

Variable	Direct Effect				Indirect Effect			
CU	−2.5818 *** (0.8126)	—	—	—	1.9283 *** (0.3949)	—	—	—
PU	—	−2.9479 ** (1.3979)	—	—	—	1.0661 *** (0.2444)	—	—
LU	—	—	11.8540 (14.596)	—	—	—	6.2697 (1.6931)	—
EU	—	—	—	−1.0210 * (0.5693)	—	—	—	1.9355 *** (0.4396)
PTE	−1.4241 *** (0.2446)	−1.3767 * (0.8057)	−1.5022 *** (0.3391)	−1.3159 ** (0.5916)	−0.1831 *** (0.0617)	−0.10066 ** (0.0493)	−0.1093 * (0.0601)	−0.1391 * (0.0789)
PCAO	0.0416 (0.0622)	0.3329 (0.2940)	0.0148 (0.3764)	−0.0202 (1.0466)	−0.5026 (0.4065)	−0.4472 (0.3056)	−0.9271 * (0.4396)	−1.0613 * (0.5648)
PDA	0.6428 ** (0.2964)	0.8406 * (0.4830)	1.1784 (0.8165)	1.0901 (0.8064)	−0.5059 (0.3608)	0.5060 (0.3270)	0.5833 (0.6650)	0.6810 (0.9707)
PIS	0.9436 * (0.5173)	0.9043 * (0.5248)	1.0157 ** (0.4898)	0.5865 * (0.3372)	−0.8151 ** (0.4019)	−0.6136 ** (0.2875)	−0.8382 * (0.4846)	−0.3237 *** (0.1031)
AO	−0.5109 * (0.3471)	0.1387 (0.7181)	−0.2427 (1.1515)	−0.0819 (1.3026)	0.4952 ** (0.2434)	0.2250 (0.5786)	0.1208 (2.0381)	0.1926 (0.3761)
PAL	−0.3066 ** (0.1482)	−0.2403 *** (0.0815)	−0.1716 ** (0.0796)	−0.1422 (0.1306)	0.2034 ** (0.1091)	0.2284 (0.2691)	0.1513 (0.1603)	0.1074 (0.1311)
AFE	0.4392 (0.9169)	0.4487 (0.6793)	1.1734 (1.4399)	1.1450 (1.6786)	−0.4076 * (0.2343)	−0.4266 ** (0.1924)	−1.0927 *** (0.2813)	−1.072 *** (0.2267)
EPFE	−2.3667 (2.4673)	−1.6259 (2.2444)	−1.1818 (1.5935)	−2.0335 (2.1941)	−0.9513 *** (0.2887)	−0.7314 *** (0.2376)	−1.8510 *** (0.1984)	−1.6598 *** (0.1250)

Note: the standard error of coefficient estimation is shown in brackets; '*', '**', and '***' represent the significance levels of 10%, 5% and 1%, respectively; "—" represents no data.

This study uses the estimation results of the impact of urbanization on CEISG in the study area for comparison. The decomposition of the effect is shown in Table 3. The estimates of the direct effect (−0.1221) and indirect effect (0.1169) of urbanization on the CEISG did not pass the significance test, indicating that the improvement of urbanization in the main potato-producing areas in this study has no significant impact on CEISG. In addition, in terms of the significance of the estimated values of each variable, the direct effect (−0.1102) and the total effect (−0.0863) of technical efficiency on CEISG are significantly negative, indicating that the improvement of technical efficiency can reduce CEISG. The direct effect of the proportion of disaster-affected areas on CEISG is significantly positive (0.0244), indicating that a larger affected area means higher CEISG. The direct effect (−0.1250) and total effect (−0.0690) of agricultural openness on the CEISG are significantly negative, reflecting that higher agricultural openness means more awareness of green production, which helps to lower CEISG. Urbanization has a more significant impact on CEIPP, compared with the decomposition of effect on CEIPP. Urbanization in poor areas has a greater impact on the sustainable development of specialty food in these areas and is of great significance for the achievement of SDG 1, SDG 2, and SDG 12 in these areas.

Table 3. Effect decomposition of factors influencing CEISG under emission matrix.

Variable	Direct Effect	Indirect Effect	Total Effect
CU	−0.1221 (1.5377)	0.1169 (1.3704)	−0.0051 (0.6802)
PTE	−0.1102 (0.0585) *	0.0239 (0.4806)	−0.0863 (0.0464) *
PCAO	0.0264 (0.5814)	−0.0410 (0.5286)	−0.0146 (0.4648)
PDA	0.0244 (0.0103) ***	−0.0152 (0.1449)	0.0111 (0.2332)
PIS	−0.1935 (0.8113)	0.1236 (0.9328)	−0.0699 (1.0954)
AO	−0.1250 (0.0294) ***	0.0560 (0.0417)	−0.0690 (0.0310) ***
PAL	0.0130 (0.7409)	0.0125 (0.6805)	0.0255 (0.4413)
AFE	−0.2414 (1.6306)	0.1367 (1.5129)	−0.1046 (0.8954)
EPFE	0.1103 (2.6425)	−0.2973 (2.5579)	−0.1869 (2.3567)

Note: the standard error of coefficient estimation is shown in brackets, '*' and '***' represent the significance levels of 10%, 5% and 1%, respectively.

4. Discussion

Based on the empirical analysis, the study found that urbanization can generally reduce the carbon emission of potato production and promote its sustainable development. Obviously, this is different from the traditional view that urbanization has a negative impact on food security and the ecological environment [20,62–64]. Scholars have gradually realized that urbanization has a positive impact on food security in middle-income or developing countries [21,65,66]. Urbanization has led to the release of rural land and a decrease in rural population, as well as a reduction in fragmentation of arable land, thereby promoting economies of scale and environmental protection [66,67]. Urbanization has promoted the development of agricultural mechanization and water-saving technology, solved the impact of labor shortage, reduced the water footprint, and promoted the sustainable development of food production. This is consistent with the conclusion of this study, which is that the rapid urbanization process in impoverished areas of China has led to a decrease in the carbon emission intensity of potato production and favored promoting green and sustainable development. We will further explore the impact of urbanization on carbon emissions from potatoes and staple crops based on China's actual situation and propose policy suggestions to promote sustainable development of the potato industry.

Firstly, analyses of the factors influencing CEIPP show that urbanization-related variables (CU, PU, LU and EU) have the largest coefficient and the most remarkable impact. The rapid development of urbanization leads to a decrease in agricultural population, so the large-scale operation of potatoes has become a trend [25,65], and mechanization, greening, informatization, and service socialization have become important choices. The modernization of potato production also means a reduction in CEIPP. Therefore, it can be concluded that urbanization is the key factor affecting CEIPP. Consequently, it is necessary to promote new urbanization to achieve emission reduction and efficiency increase in potato production. The main potato-producing areas in China are located in the Southwest and Northwest with poor agricultural resource endowment and fragile ecological environment. It is urgent to promote sustainable urban development and thereby drive emission reduction and efficiency increase in potato production. Meanwhile, advantageous production areas and leading enterprises are encouraged to jointly promote potato-characterized urbanization [68].

Secondly, according to the influencing factors of CEIPP and decomposition of the effects, CU, PU and EU have significant negative impacts on CEIPP, and the direct effects are also significantly negative, reflecting that the improvement of CU, PU, and EU can reduce CEIPP. Therefore, in order to reduce CEIPP and promote its sustainable development, it is necessary to improve PU and EU, and improve the quality and level of CU. On the one hand, the role of technology and financial development in the process of economic urbanization should be strengthened. It is necessary to improve the agricultural technology innovation service system and invest more in green technologies and financial capital in the modern production of potatoes. On the other hand, it is essential to fully leverage the spillover effect of population urbanization on agricultural carbon emissions reduction [69] and improve the supporting mechanism for urban and rural education. In potato advantageous production areas, it is necessary to increase the scale of human capital accumulation, improve the quality of human capital [70,71], and optimize the spatial layout of human capital to promote balanced regional development.

Thirdly, according to the influencing factors of CEIPP and the decomposition of the effect, LU has a significant positive impact on CEIPP, and the direct and indirect effects are both positive, indicating that the improvement of LU increases CEIPP. Therefore, it is necessary to enhance the efficiency of land use in the process of land urbanization and, to a certain extent, avoid disorderly expansion of land urbanization [72,73]. Based on the economic conditions of potato advantageous production areas, reasonable urbanization policies can be formulated to improve land use efficiency, manage agricultural land effectively, and improve the compensation mechanism for land acquisition [74]. It is important to leverage the comparative advantages of potato production regions based on their resource endowment, transform potato production methods through spillover effects of technology, improve land use efficiency [75], avoid excessive land occupation by agricultural production, and ultimately achieve quality and efficiency improvement in potato production.

Finally, the decomposition of the effect of urbanization on CEIPP and CEISG in poor areas shows that the improvement of CU helps to reduce CEIPP, but its impact on CEISG is not significant, indicating the different impact of urbanization on CEIPP and CEISG. Besides, existing studies show that potato planting has obvious advantages over the other three staple foods in terms of income and cost-profit ratio [76]. Therefore, the promotion of the potato industry in poor areas in the process of urbanization will not only help to improve farmers' income but also help to reduce the intensity of agricultural carbon emissions and promote the green and sustainable production of specialty food. It has become an important way to achieve SDG 1, SDG 2, and SDG 12 in these areas [77,78].

5. Conclusions and Limitations

5.1. Conclusions

The rapid urbanization process has gradually deepened its role in the sustainable development of agriculture, especially in the sustainable supply of food in poor areas. However, the impact mechanism of different dimensions of urbanization on food sustainability in poor areas has not yet been fully unpacked. Therefore, this study focuses on the specialty food potatoes mainly grown in poor areas of China, explores the impact mechanism of urbanization on the carbon emission intensity of potato production (CEIPP) with the spatial Durbin model, and compares with the carbon emission intensity of staple grain (CEISG) results. This study matched the distribution of main potato-producing areas with national-level poverty-stricken counties in China and contrasted with the main staple grain-producing areas to determine the research area. Then, an improved carbon emission model for potato production and a multi-dimensional urbanization framework of "economy-population-land" were used to calculate CEIPP and the urbanization levels, respectively. The mechanism of the impact of urbanization on CEIPP was explored with the spatial Durbin model (SDM), which was compared with CEISG results. The main conclusions are as follows:

Urbanization of main potato-producing areas developed rapidly from 2002 to 2020, which is in line with the decrease of CEIPP. The decrease in CEIPP has a significant impact on slowing down the growth of total carbon emissions and has greater potential for reduction, especially in Central and Western China, which has a large poverty-stricken population. This is of great significance in promoting the realization of SDG 1, SDG 2, and SDG 12. Compared with traditional staple grain, urbanization has become a key factor influencing CEIPP. The results indicate that different dimensions of urbanization can explain the impact of urbanization on the sustainable production of regional specialty food in China to varying degrees. The improvement of comprehensive urbanization, population urbanization, and economic urbanization reduces CEIPP, while land urbanization increases CEIPP. Therefore, to reduce CEIPP and promote its sustainable development, it is necessary to improve population urbanization and economic urbanization, properly avoid the disorderly expansion of land urbanization, and improve the quality and level of comprehensive urbanization. The study is also expected to provide empirical references for other middle-income or developing countries and ultimately contribute to achieving global food security and sustainable development.

5.2. Contributions and Limitations

This paper has made some contributions to the study of the relationship between urbanization and sustainable food production, especially in poor areas. Firstly, this paper constructs a theoretical analysis framework of the multi-dimensional urbanization (economy-population-land) impact mechanism on sustainable food development, deeply explores the relationship between urbanization and sustainable food production, inspires divergent thinking on the impact mechanism of various types of urbanization on sustainable food production, and enriched the understanding of factors affecting sustainable food security. Secondly, compared with existing research, this paper mainly focuses on the urbanization process and the sustainable production of regional specialty foods in poor areas. Taking potato production, the regional specialty food in poor areas of Central and Western China, as an example, this study explores the impact mechanism of multi-dimensional urbanization in poor areas on the carbon emission intensity of potato production. This study provides a new perspective on enhancing the ability of urban development in poor areas to cope with climate change and exploring low-carbon agricultural production and sustainable nutrition improvement.

It is undeniable that this paper may have some limitations. Firstly, this paper lacks the latest data support. Thus, future research interests should focus on collecting the latest data and substituting the new data into empirical models for analysis to verify the robustness of this study. Secondly, we only selected potatoes, the most representative specialty food in poor areas of Central and Western China, as the research object. However, there are also some other specialty foods in these poor areas, such as barley and millet, which are also important entities affecting regional food security and nutrition improvement and are also affected by rapid urbanization. In future research, the scope of study on regional specialty foods can be expanded to supplement the research on the impact of urbanization on sustainable food security in poor areas. Thirdly, Chinese-style urbanization integrates the synchronous development of industrialization and modernization, and the urbanization process in poor areas selected in this paper is closely related to the Western Development Strategy implemented by the Chinese government; meanwhile, the Chinese government has been promoting potatoes as the staple food since 2014, and currently, potatoes have become a star brand of industrial poverty alleviation projects in many poor areas. Therefore, the conclusions of this study might be less representative of other nations' agricultural efforts. In the future, research perspectives should be expanded to a global scale, and the impact of urbanization on sustainable food security in different regions or groups should be discussed.

Author Contributions: Conceptualization, Y.N. and J.L.; methodology, Y.N. and J.L.; software, J.L. and Y.J.; validation, Z.L. and J.L.; formal analysis, Y.N. and Z.L.; investigation, J.L. and Y.J.; resources, Y.N. and Z.L.; data curation, Z.L.; writing—original draft preparation, Y.N. and Z.L.; writing—review and editing, Y.N. and J.L.; visualization, J.L. and Y.J.; supervision, J.L.; project administration, Z.L.; funding acquisition, Z.L. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Priority Research Program of Chinese Academy of Sciences (Grant No. XDA20010102) and the National Social Science Foundation of China (Grant No. 20CJY054).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Descriptive statistics of variables.

Variable	Symbol	Units	Mean	Max	Min	Std. Dev.
Total carbon emissions from potato production	TCEPP	kt	74.2601	830.0787	0	109.5726
Carbon emission intensity of potato production	CEIPP	kg/t	151.1928	430.9275	46.7676	66.4279
Total carbon emissions of staple grain	TCESG	kt	227.0389	659.1663	4.8246	170.9339
Carbon emission intensity of staple grain	CEISG	kg/t	141.7795	288.8373	41.4387	44.3048
Per capita agricultural output value	PCAO	10^4 CNY/Person	1.5656	7.5170	0.1642	1.2313
Comprehensive urbanization	CU	—	0.4062	1.0000	0.0912	0.1998
Economy urbanization	EU	—	0.5033	0.9415	0.1308	0.1710
Population urbanization	PU	—	0.0174	0.1952	0.0001	0.0305
Land urbanization	LU	—	0.8851	0.9973	0.6533	0.0615
Production technical efficiency	PTE	—	0.8553	1.5090	0.0000	0.3068
Proportion of disaster areas	PDA	—	0.2601	0.6918	0.0212	0.1511
Potato industrial structure	PIS	—	0.5606	0.7400	0.3390	0.0906
Agricultural openness	AO	—	0.0742	0.5270	0.0000	0.1038
Production agglomeration levels	PAL	—	1.3922	4.2328	0.6070	0.6033
Proportion of agricultural fiscal expenditures	AFE	— —	0.1154	0.2038	0.0295	0.0333
Proportion of environmental protection fiscal expenditure	EPFE	—	0.0253	0.0673	0.0000	0.0176

Note: "—" represents no data.

Table A2. Global Moran index of CEIPP.

Year	Adjacency Matrix	Distance Matrix	Economic Matrix	Emission Matrix
2002	0.175 (0.174) *	0.932 (0.331) ***	0.909 (0.325) ***	0.821 (0.324) ***
2003	0.070 (0.175)	0.945 (0.334)***	0.905 (0.328) ***	0.845 (0.326) ***
2004	0.160 (0.159) *	0.893 (0.300) ***	0.831 (0.295) ***	0.796 (0.293) ***
2005	0.241 (0.169) **	0.968 (0.321) ***	0.951 (0.315) ***	0.935 (0.314) ***
2006	0.364 (0.182) ***	0.956 (0.348) ***	0.935 (0.342) ***	0.935 (0.341) ***
2007	0.121 (0.176)	0.969 (0.336) ***	0.964 (0.330) ***	0.934 (0.328) ***
2008	0.036 (0.157)	0.979 (0.296) ***	0.969 (0.291) ***	0.961 (0.289) ***
2009	0.016 (0.172)	0.967 (0.326) ***	0.942 (0.321) ***	0.941 (0.319) ***
2010	−0.004 (0.160)	0.903 (0.302) ***	0.848 (0.297) ***	0.875 (0.296) ***
2011	−0.149 (0.148)	0.980 (0.278) ***	0.965 (0.273) ***	0.963 (0.272) ***
2012	0.207 (0.167) **	0.969 (0.317) ***	0.954 (0.312) ***	0.947 (0.311) ***
2013	0.233 (0.176) **	0.969 (0.336) ***	0.946 (0.330) ***	0.947 (0.329) ***
2014	−0.102 (0.134)	0.989 (0.247) ***	0.983 (0.243) ***	0.980 (0.242) ***
2015	−0.164 (0.169)	0.959 (0.321) ***	0.945 (0.316) ***	0.932 (0.315) ***
2016	−0.070 (0.166)	0.947 (0.315) ***	0.940 (0.310) ***	0.921 (0.309) ***
2017	0.042 (0.169)	0.942 (0.321) ***	0.956 (0.315) ***	0.950 (0.314) ***
2018	0.150 (0.154) *	0.978 (0.290) ***	0.988 (0.285) ***	0.983 (0.284) ***
2019	0.149 (0.162) *	0.972 (0.306) ***	0.972 (0.301) ***	0.969 (0.299) ***
2020	0.099 (0.175)	0.953 (0.333) ***	0.961 (0.328) ***	0.966 (0.326) ***

Note: the standard error of coefficient estimation is shown in brackets; '*', '**', and '***' represent the significance levels of 10%, 5% and 1%, respectively; "—" represents no data.

Table A3. Wald, LR, and Hausman test results of model selection.

	Adjacency Matrix		Distance Matrix		Economic Matrix		Emission Matrix	
	Statistic	p	Statistic	p	Statistic	p	Statistic	p
Wald-SDM-SLM	252.224	0.000	240.983	0.000	322.596	0.000	368.452	0.000
Wald-SDM-SEM	293.709	0.000	280.079	0.000	390.363	0.000	435.649	0.000
LR-SDM-SLM	95.079	0.000	98.446	0.000	118.646	0.000	164.095	0.000
LR-SDM-SEM	122.284	0.000	125.162	0.000	150.031	0.000	200.041	0.000
Hausman	53.226	0.000	59.315	0.000	86.337	0.000	97.121	0.000

Table A4. Results of factors influencing CEIPP under adjacency matrix and distance matrix in SDM.

Variable	Adjacency Matrix				Distance Matrix			
CU	−0.3290 (0.8262)	—	—	—	−11.3582 * (6.1638)	—	—	—
PU	—	−1.1750 ** (0.4739)	—	—	—	−7.2467 (8.6210)	—	—
LU	—	—	−4.9682 (4.7371)	—	—	—	14.0057 (12.7668)	—
EU	—	—	—	0.8243 (1.0016)	—	—	—	15.3329 (45.6396)
PTE	−1.4298 *** (0.1920)	−1.3608 *** (0.2036)	−1.5201 *** (0.1705)	−1.4745 *** (0.1881)	−1.0710 (0.7859)	−1.0851 *** (0.4119)	−1.1611 ** (0.6683)	−1.5269 *** (0.4159)
PCAO	0.0178 (0.0577)	−0.0867 * (0.0481)	−0.0680 * (0.0398)	−0.1200 ** (0.0595)	0.0325 (0.0513)	0.0502 (0.0612)	0.0172 (0.0475)	0.1158 ** (0.0576)
PDA	0.0561 (0.2788)	−0.1333 (0.2104)	0.1416 (0.2554)	0.0795 (0.2501)	−0.1445 (0.2271)	−0.1622 (0.2389)	−0.1477 (1.2721)	0.3960 (1.1855)
PIS	0.4631 (0.7384)	0.7441 (0.6364)	0.2547 (0.5476)	0.1366 (0.7431)	0.8267 (0.9920)	0.7826 ** (0.3922)	0.8984 ** (0.4282)	−8.0887 (5.1992)
AO	−0.0523 (0.3766)	0.0868 (0.3337)	−0.2470 (0.3929)	−0.1578 (0.2717)	−0.0811 (0.3116)	−0.0502 (0.2792)	−4.1114 (5.2539)	−1.8751 * (1.0826)
PAL	0.0458 (0.1261)	0.1316 (0.1041)	0.2070 * (0.1176)	0.2631 ** (0.1239)	−0.0287 (0.1120)	0.9335 (0.8417)	0.0179 (0.0746)	3.6272 (4.6921)
AFE	−0.3456 (1.5895)	0.2441 (1.2199)	0.8377 (1.5512)	0.0625 (1.3506)	0.5004 (1.4122)	0.5016 (1.4370)	0.6734 (1.5680)	−2.6097 (9.5515)
EPFE	−1.5566 (2.1128)	−1.0224 (2.2679)	2.3035 (3.2289)	2.5033 (2.7901)	−1.6838 (2.2124)	−1.3391 (2.2168)	−1.7402 (2.5643)	3.0220 (5.0685)
W·CU	—	—	—	—	11.6368 * (6.2993)			
W·PU	—	—	—	—	—	7.1821 (6.4663)	—	—
W·LU	—	—	2.4569 *** (0.3821)	—	—	—	—	—
W·EU	—	—	—	—	—	—	—	−11.3238 (7.8992)
W·PCAO	—	0.2654 ** (0.1220)	—	—	—	—	—	—
W·PDA	−0.9169 ** (0.3908)	—	−0.7677 (0.4064)	−0.7739 * (0.4283)	—	—	−0.3063 **** (0.1392)	—
W·PIS	3.0743 ** (1.5041)	3.9243 * (2.1423)	—	3.2303 * (1.9399)	—	—	—	9.7015 *** (4.2911)
W·AO	−0.4033 ** (0.1969)	3.7553 ** (1.8099)	—	3.4167 ** (1.7217)	—	—	4.1666 (5.3817)	—
W·PAL	—	−0.4549 * (0.2992)	−0.3569 * (0.2083)	−0.5893 ** (0.2997)	—	−1.0038 (0.8649)	—	−3.6665 * (2.2663)
W·EPFE	—	—	−5.9141 * (3.2737)	−6.0740 ** (2.6441)	—	—	—	—
Spatial	−0.0270	−0.0223	−0.0261	−0.0213	0.2526	0.2407	0.2111	0.2037
R^2	0.4772	0.6162	0.7682	0.7008	0.3308	0.4081	0.4370	0.3883
Log-likelihood	−147.3083	−141.9783	−142.6348	−141.2104	−152.3276	−152.6529	−152.9239	−153.6696

Note: the standard error of coefficient estimation is shown in brackets; '*', '**', and '***' represent the significance levels of 10%, 5% and 1%, respectively; "—" represents no data.

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ISBN 978-3-7258-0578-5