land

MDPI

Article

Spatiotemporal Heterogeneity and Zoning Strategies of Multifunctional Trade-Offs and Synergies in Cultivated Land in the Hexi Corridor

Kaichun Zhou [1,2], Zixiang Sun [1], Tingting Ma [1], Yulin Li [1] and Binggeng Xie [1,2,*]

[1] College of Geographic Science, Hunan Normal University, Changsha 410081, China; zhoukaichun@hunnu.edu.cn (K.Z.); szx@hunnu.edu.cn (Z.S.); 202330163036@hunnu.edu.cn (T.M.)
[2] Hunan Key Laboratory of Geospatial Big Data Mining and Application, Hunan Normal University, Changsha 410081, China
* Correspondence: xbgyb1961@163.com

Abstract: As the indispensable basic resource of agricultural production, cultivated land has always carried the important mission of maintaining food stability, promoting rural economic development, and maintaining ecological balance. However, in application, there is often a conflict between the multiple functions of cultivated land and the limited ability of cultivated land to perform multiple functions. Therefore, this paper uses hot spot analysis, the IUEMS model, the InVEST model, Pearson correlation coefficients and self-organizing feature maps (SOFMs) to explore the multifunctional trade-offs and synergistic relationships of cultivated land in the Hexi Corridor at the grid scale and the zoning optimization scheme. The results revealed that from 2000 to 2020, the cultivated land production functions and social security functions in the Hexi Corridor maintained a high level and continued to rise, and the hot spots exhibited a stable pattern of "central and southeast concentration". The ecological function performance is relatively weak, and the hot spots are concentrated mainly in the southeast, whereas the landscape view recreational functions as a whole show a trend of gradual recovery after weakening. In terms of mutual relationships, there are significant synergies between cultivated land production and social security functions, whereas the trade-offs and synergies between other functions are complex and changeable. Production and social security show a coordinated spatial distribution pattern. Production, social security, and ecological functions are dominated by spatial trade-offs. The production and landscape recreation functions, social security and ecological functions, social security and landscape recreation functions, and ecological and landscape recreation functions are mainly synergistic in space. Through self-organizing feature map analysis, the cultivated land in the Hexi Corridor is divided into four functional areas: agricultural production-dominant areas, agricultural social security areas, ecological agriculture areas, and balanced development areas, and management objectives are proposed. This study can provide useful lessons and references for land use planning and management in other similar areas.

Keywords: Hexi Corridor; multiple functions of cultivated land; trade-offs/synergies; multifunctional zoning

check for updates

Academic Editor: Dingde Xu

Received: 7 January 2025
Revised: 30 January 2025
Accepted: 5 February 2025
Published: 7 February 2025

Citation: Zhou, K.; Sun, Z.; Ma, T.; Li, Y.; Xie, B. Spatiotemporal Heterogeneity and Zoning Strategies of Multifunctional Trade-Offs and Synergies in Cultivated Land in the Hexi Corridor. *Land* **2025**, *14*, 335. https://doi.org/10.3390/land14020335

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Cultivated land is the core of the rural ecological landscape and a valuable carrier of the inheritance of farming civilization [1,2]. However, with the acceleration of urbanization, farmland has been continuously encroached upon, and several problems, such as the loss

of cultivated landscapes, the deterioration of the ecological environment, a reduction in characteristic agricultural products, and a decline in biodiversity, have emerged frequently, which makes the study of the multifunctionality of cultivated land a focus of attention in the academic community and is the key to optimizing cultivated land resource allocation, guaranteeing food security, safeguarding ecological security, and promoting sustainable development [3,4].

From the "rice culture" in Japan to the concept of "multifunctional agriculture" in Europe, research on the multifunctionality of arable land has become an essential issue in global research on sustainable agricultural development [5]. In September 1999, the FAO of the United Nations further reinforced the essence of agricultural multifunctionality in boosting global agricultural and rural development. Currently, some scholars interpret the function of arable land as the role played by cultivated land in the process of interacting with human beings in terms of products and services to satisfy the needs of human survival and development [6–9]. China's research on the aspect began relatively late, in 2007, when the Chinese government first advocated for the development of diversified functions of agriculture to improve and develop the industrial system of modern agriculture, thus expanding the functions of agriculture from a single food supply to multiple levels, such as employment promotion, ecological protection, and cultural inheritance. In 2022, the Chinese government mentioned the development of smart agriculture and agricultural multifunctionality in relevant policies. Clearly, scientific and technological innovation and industrial integration promote the transformation of agriculture towards high-quality, multifunctional, and sustainable development. Although different countries' experts and scholars choose different entry points when exploring the multifunctionality of agriculture, its core connotation is centered on economic, social, ecological, and other perspectives and presents a unified characterization [10–12].

At present, scholars' discussions on the multifunctionality of cropland have focused mostly on the connotation and classification of the multifunctionality of cropland [13], evaluation and value measurement [10,14], spatial and temporal evolution trends [15], the analysis of drivers [16,17], trade-offs and synergistic relationships [18,19], and zoning optimization strategies [20–22]. In terms of research scale, the functional evolution and characteristics of cultivated land were mostly based on administrative districts [23–26]. There have been relatively minor studies on the evaluation and evolution features of the multifunctionality of cultivated land using grids or cultivated land patches as basic units, making it hard to analyze the spatial differentiation of cultivated land functions at a smaller scale and subsequently propose proposals for optimizing cultivated land management and protection. In terms of research objects, most studies have focused on traditional grain-producing areas, economically developed areas, or rapidly urbanizing areas. There has been a lack of research under different geographical conditions and from different geographical locations. In addition, the existing studies lack uniqueness in the construction of the evaluation index system, which make it difficult to highlight regional differences and conform to the actual situation of the region.

The Hexi Corridor, as a significant agricultural area and one of the commodity grain bases in the northwestern region of China, includes arid and semiarid regions. The ecological environment is relatively sensitive and vulnerable to disturbances caused by human activities, and with the increasing severity of ecological problems, such as the desertification and salinization of the land, it has limited the development of agricultural production. In addition, in 2000, arable land, forest land, and construction land increased in the region, while water, grassland, and unused land showed a decreasing trend, reflecting the acceleration of regional urbanization and changes in the ecological environment. Moreover, the state has introduced relevant policies to promote the development of agriculture and the

protection of cultivated land. In 2010, the cultivated land protection policy was strengthened, and the implementation of the system of "balance of occupation and compensation" of cultivated land, the adjustment of agricultural structure, and the construction of ecological environment had a certain impact on the multifunctionality of cultivated land. By 2020, the government had put forward a requirement for a "balance in and out" of cultivated land. Moreover, with the advancement of science and technology and the acceleration of agricultural modernization, the agricultural production mode in the Hexi Corridor region may have undergone significant changes. In addition, the government's increasing support for agriculture has promoted the industrial upgrading and transformation of the Hexi Corridor region, which has put forward new requirements and challenges for the multifunctionality of cultivated land. Therefore, this paper takes the Hexi Corridor as the research area and takes 2000, 2010, and 2020 as the research nodes. This paper (1) develops an evaluation index system tailored to the specific conditions of the region, (2) explores the spatial and temporal evolution features of multifunctional cultivated land and the spatial law of the synergistic relationship of the trade-offs between the functions at the grid scale, and (3) performs functional zoning of the cropland based on the analysis mentioned above. It fills the gap in the relevant research of the Hexi Corridor area. In addition, by selecting relevant indicators in line with regional characteristics to evaluate the multifunctionality of cultivated land, this paper provides a scientific basis and reference for the formulation of cultivated land protection and utilization policies in the Hexi Corridor and even for the whole country and is helpful to promote the rational allocation and efficient utilization of cultivated land resources.

2. Materials and Methods

2.1. Study Area

The Hexi Corridor is located in the northwestern part of Gansu Province in China. It is located between 37°17′ and 42°48′ north latitude and 92°12′103°48′ east longitude (Figure 1). In terms of terrain, the characteristics of the south, north and lows are presented. The type of climate is temperate continental. It is characterized by the scarcity of annual precipitation, a drought environment, frequent wind and sandy weather, and a significant temperature difference between day and night. One is China's important commodity grain base, along with concentrated economic crops, and the oasis agriculture is developed. In terms of socioeconomic, by the end of 2020, five cities in the Hexi Corridor reached 229.14 billion yuan.

2.2. Data Sources

The data used in this study include socioeconomic data, land use data, spatial distribution data of China's population and GDP, vegetation net primary productivity data, spatial distribution data of rapeseed planting in China, China's soil conservation capacity dataset, township street points, and digital elevation model (DEM) data (Table 1).

2.3. Research Methodology

2.3.1. Selection of Evaluation Units

Relying on the ArcGIS 10.8 software platform and after repeated tests, a 5 km × 5 km grid is selected as the multifunctional evaluation unit of cultivated land in the Hexi Corridor area. Following the land use data of the study area, the cultivated land maps from 2000, 2010, and 2020 were extracted, of which the cropland evaluation units in the study area for the three periods were 1990, 2120, and 2120 grids, respectively.

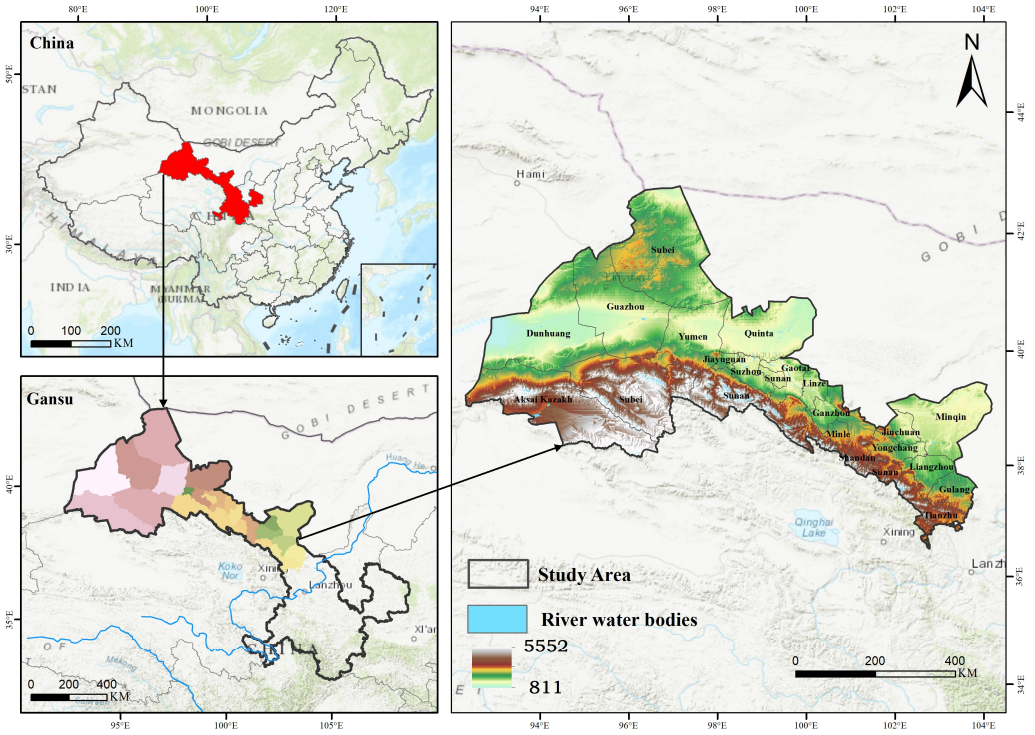


Figure 1. Hexi Corridor region.

Table 1. Data sources.

Data	Origin and Description
Land use data of Gansu Province China GDP spatial distribution kilometer grid dataset China's population spatial distribution kilometer grid dataset Administrative region	From RESDC (https://www.resdc.cn/) accessed on 5 June 2024.
Vegetation net primary productivity dataset	From NASA (http://ladsweb.modaps.eosdis.nasa.gov/) accessed on 5 June 2024.
Spatial distribution dataset of rapeseed planting in China	From the Yangtze River Survey Technology Research Institute of the Ministry of Water Resources (https://data.mendeley.com/datasets/hxhkphgmtt/1) accessed on 5 June 2024.
China soil conservation capacity dataset	From ScienceDB (http://www.scidb.cn)
Township street point data	The source is the administrative divisions of various levels on the official website of the National Bureau of Statistics, and then the coordinates are obtained using the POI reverse query tool
DEM data	From GSCloud (http://www.gscloud.cn) accessed on 5 June 2024.

2.3.2. Index System Construction

The multifunctionality of cultivated land forms as a result of the interaction of three major subsystems, namely, natural ecology, society, and the economy, covering multiple functions, from basic food production to climate regulation, as well as the agricultural leisure experience and landscape ecological protection. Considering the relevant research

findings and taking into account the distinctive circumstances of the Hexi Corridor area, this paper constructs a multifunctional comprehensive evaluation index system of cultivated land in the Hexi Corridor in terms of the production functions, ecological functions, social security functions, and landscape recreation functions, considering the accessibility and quantitative value of the data (Table 2).

Table 2. Evaluation indicator system and weights.

Standardized Layer	Indicator Layer	Causality	Computation Method	Weights in 2000	Weights in 2010	Weights in 2020
Production function	Cultivation rate of arable land	+	Cultivated area/total land area	0.0392	0.0336	0.0253
	Index of replanting	+	Cultivated area/sown area of crops	0.0489	0.0400	0.0295
	Average land value of arable land	+	Agricultural output value/arable land area	0.0598	0.0478	0.0322
	Food self-sufficiency rate	+	Grain production/ population × 420 kg	0.0609	0.0669	0.1944
Social security function	Agricultural output as a percentage of GDP	+	Agricultural output value/GDP	0.0521	0.0476	0.0335
	level of agricultural mechanization	+	Total power of agricultural machinery/ cultivated area	0.0518	0.0420	0.0308
	Number of agricultural employees	+	Statistical yearbook data	0.0529	0.0441	0.0341
	Cultivated land area per capita	+	Cultivated area/number of people	0.0689	0.0616	0.1628
Ecological function	Carbon sequestration and oxygen release	+	Calculated based on the IUEMS model	0.2315	0.1925	0.1539
	Habitat quality	+	Calculated based on the InVEST model	0.0791	0.0696	0.0612
	Soil conservation capacity	+	Calculated based on the InVEST model	0.1075	0.0952	0.0722
	Cropland fragmentation	-	Fragstats 4.2 calculations	0.0017	0.0012	0.0010
Landscape recreation function	Cropland shape index	-	Fragstats 4.2 calculations	0.0039	0.0027	0.0022
	Tillage aroma uniformity	+	Fragstats 4.2 calculations	0.0199	0.0170	0.0129
	Oilseed rape acreage	+	ArcGIS partition statistics	0.1214	0.2553	0.1537
	Distance from township governmental quarters	-	ArcGIS proximity analysis	0.0006	0.0005	0.0004

Note 1: the weight values of each indicator can be calculated by referring to the formula in Section 2.3.8. Note 2: oilseed rape acreage was selected as one of the indicators to evaluate the multifunctionality of cultivated land in the Hexi Corridor because there was a large area of rape flowers blooming in some areas in summer, forming a unique cultivated land landscape in the region, which can reflect the value of cultivated land landscape in this area.

(1) Production function

The production functions of cultivated land are its most basic and core function, which can fully satisfy the needs of human food consumption, have the ability to provide the necessary raw materials for agriculture-related industries, and are highly important for ensuring national food security and promoting agricultural economic development. Therefore, this paper from the perspective of agricultural production and food security selects four indicators: the cultivation rate of arable land, the index of replanting, the average land value of arable land, and the food self-sufficiency rate.

(2) Social security function

Cultivated land serves as the bedrock for agricultural production and becomes a solid pillar for rural economic development, profoundly affecting rural economic prosperity and social stability. From meeting basic living needs to providing farmers with a safety net for retirement and unemployment, arable land plays a vital role. Moreover, its stable

output provides indispensable material support for the lives of urban residents and thus plays an essential role in guaranteeing the stability and harmony throughout the entire society. From the three perspectives of economic support, employment security, and the agricultural production base, four indicators, namely agricultural output as a percentage of GDP, the state of agricultural mechanization, the quantity of agricultural employees, and the cultivated land area per capita, were selected.

(3) Ecological function

The ecological functions of arable land refer to the ecosystem benefits provided by arable land resources for human beings that are not direct material outputs, These functions play a crucial role in maintaining ecosystem balance by ensuring water security, protecting biodiversity, and maintaining soil health. In this study, four indicators were selected to quantify the ecological functions of croplands: carbon sequestration and oxygen release, habitat quality, soil conservation capacity, and cropland fragmentation.

(4) Landscape recreation function

The cultivated landscape is an important carrier of farming culture, a unique landform shaped by human agricultural practices, covering a vast area of cultivated land, fields, and farmland. Cultivated landscapes themselves have a unique esthetic value as a comprehensive landscape of nature and humanity. These landscapes can beautify the rural environment and enhance people's esthetic experience and quality of life. Therefore, according to the accessibility of the data, four indicators are selected to quantify the landscape recreation functions of arable land: the cropland shape index, tillage aroma uniformity, oilseed rape acreage, and distance from township governmental quarters.

2.3.3. Gridded Socioeconomic Data

The evaluation unit of this study is grid; thus, the socioeconomic data need to be regridded. Therefore, with reference to existing studies, county and district statistics were spatialized to the cultivated land within the grid [27,28]; the formula is as follows:

$$P_j = \frac{P_i}{A_i} \times M \quad (1)$$

where P_j is a particular socioeconomic indicator for the i-th grid, P_i is a particular socioeconomic indicator for the j-th county district, A_i is the cultivated land area in the county, and M is the cropland area in the grid.

2.3.4. Calculation Method of Carbon Fixation and the Oxygen Release Capacity

IUEMS is the urban ecological intelligent management system. It is an online ecological assessment tool developed by the Research Center for Eco-Environmental Sciences (RCEES) of the Chinese Academy of Sciences, aimed at conveniently and efficiently assessing ecosystem services and promoting sustainable urban ecological development. By combining the NPP algorithm and GIS technology, the IUEMS provides an effective tool for estimating and analyzing regional carbon sequestration and oxygen release capacity [29,30]. In this study, the NPP algorithm module in the IUEMS was used to input the collected data to calculate the NPP of the cultivated land in the Hexi Corridor, and then the carbon sequestration and oxygen release capacity was calculated on the basis of the NPP.

2.3.5. Habitat Quality Calculation Methodology

The InVEST model, a methodology for calculating habitat quality, is a tool designed to quantify ecosystem service functions and their economic value and is intended to assist in ecosystem management and policy decision-making processes. In this work, the InVEST

model was utilized as a tool to comprehensively evaluate the habitat maintenance status of croplands [31]. The formula is as follows:

$$Q_{xj} = H_j\left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + K^Z}\right)\right) \quad (2)$$

where Q_{xj} is the habitat quality index of grid x in the j-th arable land; H_j is the habitat suitability score in the j-th arable land; D_{xj}^z is the degree of habitat degradation; z is the normalization index, which was set to 2.5 in the model; and k is the half-saturation constant.

2.3.6. Calculation of the Soil Conservation Capacity

The InVEST soil conservation module operates on the basis of the universal soil loss equation (USLE), which comprehensively incorporates several variables, such as precipitation, soil properties, geomorphology, vegetation cover, and management practices. With the input of relevant data parameters, the model is able to calculate the amount of potential and actual soil erosion, as well as the total amount of soil conservation [32]. The specific formulas are as follows:

$$SEDRET = PKLS_x - USLE_x + SEDR_x \quad (3)$$

$$PKLS_x = R_x \times K_x \times LS_x \quad (4)$$

$$USLE_x = R_x \times K_x \times LS_x \times C_x \times P_x \quad (5)$$

$$SEDR_x = SE_x \sum_{y=1}^{x-1} USLE_y \prod_{z=y+1}^{x-1} SE_x \quad (6)$$

where $SEDRET$ represents the soil retention; $SEDR_x$ represents the sediment retention of grid x; SE_x represents the sediment retention rate; $PKLS_x$ represents the soil loss; $USLE_x$ and $USLE_y$ represent the actual erosion; and R_x, K_x, LS_x, C_x, and P_x represent the rainfall erosivity factor, soil erodibility factor, topography factor, vegetation cover factor, and soil and water conservation measure factor, respectively.

2.3.7. Standardization of Indicators for Multifunctional Evaluation of Arable Land

Given the significant differences in the attributes and units of measurement of the indicators, the direct use of these raw data can lead to imprecise evaluation results [16,17]. For this reason, this study adopts the technique of extreme difference standardization, aiming at the dimensionless processing of the indicators to ensure that different indicators can be compared and analyzed in a fair manner. The specific formulas are as follows:

Positive indicators:

$$X_{ij'} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \quad (7)$$

Negative indicators:

$$X_{ij'} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \quad (8)$$

where $X_{ij'}$ denotes the value of the i-th evaluation unit indicator j; X_{max} denotes the maximum value of the j-th indicator; X_{min} denotes the minimum value of the j-th indicator; and $X_{ij'}$ denotes the processed i-th evaluation unit indicator j standard value, with an interval from 0 to 1.

2.3.8. Determination of Evaluation Indicator Weights

The entropy weight method can assess the weights of indicators by evaluating the dispersion between indicators. In this study, it is used to calculate indicator weights [19]. The specific formula is as follows:

Calculate the entropy value e_j of indicator j :

$$e_j = -\frac{1}{ln_m}\sum T_{IJ} ln T_{ij} \tag{9}$$

Calculate the coefficient of variation d_j of indicator j :

$$d_j = 1 - e_j \tag{10}$$

Calculate the weight w_j of indicator j :

$$w_j = \frac{d_j}{\sum d_j} \tag{11}$$

where e_j is the entropy value of the j-th indicator and m is the number of samples.

2.3.9. Evaluation of a Multifunctional Index for Cultivated Land

To evaluate the strength of each function, this paper refers to relevant research and constructs a comprehensive evaluation model of cultivated land multifunctionality [19]. By calculating the standardized value of each function and multiplying it by its corresponding weight, the function index can be obtained. The formula is as follows:

$$U = \sum_{j=1}^{\mu} (x_{ij} \times w_{ij}) \tag{12}$$

where U is the multifunctional index of cultivated land, j is the evaluation index, and μ is the number of units for this function. x_{ij} is the normalized value of the j-th indicator. w_{ij} is the weight value of the j-th indicator.

2.3.10. Getis-Ord Gi* Statistics

Getis-Ord Gi* statistical technology calculates the z-score for each study unit to identify locations with statistically significant high (hot spots) and low (cold spots) values where spatial clustering occurs. Specifically, if the z-score of a region is significantly positive, it indicates that the values around the region are relatively high and belong to the hotspot area; Conversely, if the z-score is significantly negative, it indicates that the area is in the cold spot area. Its core purpose is to reveal geographical areas with statistically significant aggregation characteristics and then gain insights into the possible spatial effects of these areas, the role of process factors, and their spatial correlation. This study uses the hot and cold spot analysis tool of the ArcGIS platform to identify the spatial distribution pattern of multifunctional farmland in the Hexi Corridor [33]. The formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j}{\sum_{j=1}^{n} w_{ij}} \tag{13}$$

$$Z = \frac{\left(G_i^* - E\left(G_i^*\right)\right)}{\sqrt{V\left(G_i^*\right)}} \tag{14}$$

where G_i^* is the spatial agglomeration index of grid i, Z is the significance of agglomeration, w_{ij} is the spatial weight, x_j is the attribute value of grid i, $E\left(G_i^*\right)$ is the mathematical expectation of G_i^*, and $V\left(G_i^*\right)$ is the variance of G_i^*.

2.3.11. Trade-Offs and Synergy Analysis

The Pearson correlation coefficient serves primarily as a measure to assess the intensity of linear relationships between two variables. In this research, it is employed to analyze

temporal variations in the trade-offs and synergies among diverse cultivated land functions in the Hexi Corridor [33]. The formula is as follows:

$$R = \frac{\sum(xi - \overline{x})}{\sqrt{(xi - \overline{x})^2 - \sum(yi - \overline{y})^2}} \quad (15)$$

where R indicates the nature of the relationship between two functions; a positive R signifies a synergistic link between them, whereas a negative R implies a trade-off relationship. If R is 0, it indicates the absence of any correlation.

2.3.12. Bivariate Local Spatial Autocorrelation

On the basis of univariate autocorrelation analysis, Anselin proposed a bivariate local spatial autocorrelation model, an innovation that solved the previous limitation of spatial autocorrelation analysis that was limited to a single variable, enabling us to reveal the spatial correlation among multiple variables. In this study, bivariate spatial autocorrelation is applied to analyze the spatial changes in the trade-off synergistic relationships between the functions of arable land in the Hexi Corridor [34]. The specific calculation formula is as follows:

$$I_i^{ki} = \frac{x_i^k - \overline{x}_k}{\sigma^k} \sum_{j=1}^{n} \left[w_{ij} \frac{x_j^i - \overline{x}_i}{\sigma^i} \right] \quad (16)$$

where I_i^{ki} is the bivariate local spatial autocorrelation coefficient of grid i, x_i^k is the value of the k-th cropland function of grid i, x_j^i is the value of the i-th cropland function of grid j, $\overline{x}_k$ and $\overline{x}_k$ are the mean values of the two, and σ^k and σ^i are the variances of the two, respectively. This study uses spatial autocorrelation analysis, especially the bivariate local spatial autocorrelation model, to explore the spatial aggregation of the "four-dimensional" functions of cropland in depth.

2.3.13. Self-Organizing Mapping Feature Networks

The SOFM network is a network model capable of mapping high-dimensional datasets to low-dimensional spaces, thus revealing similar relationships among data. The SOFM model shows its strong advantages of self-organization and self-learning when dealing with complex scenarios with many influencing factors, which is especially effective for solving decision-making problems. This method realizes the unsupervised network training process by simulating the SOFM function of the brain nervous system and has been widely used in cluster analysis research in the fields of geography and ecology and has been proven to be an efficient unsupervised classification method. The algorithm is as follows:

(1) Initialize the weight coefficient w_{ij}, i.e., a random value given to the interval [0, 1], and then choose the neighborhood radius r and the learning rate $\eta(t)$;

(2) Enter the sample PK and normalize the weight vectors;

(3) Calculate the Euclidean distance between wij and Pk to find the smallest distance d to determine the winning neuron g;

$$d_g = min\left[d_j\right],\ j = 1,\ 2,\ \ldots,\ m \quad (17)$$

(4) Adjust all neurons within the winning neuron's neighborhood;

(5) Update learning rate $\eta(t)$ and topological neighborhood $ng(t)$;

$$\eta(t) = \eta(0)\left[1 - \frac{t}{T}\right] \quad (18)$$

where $\eta(t)$ is the initial learning rate, t is the number of sessions, and T is the total number of learning sessions.

$$N_g(t)int\left[N_g(0)\right]\left[1-\frac{t}{T}\right] \tag{19}$$

where $Ng(0)$ is the initial value of $ng(t)$.

(6) Repeat (3)~(5) above until the stop condition is met.

After training, the dominant neurons and their neighboring weight vectors in the final output layer will gradually approach the input vectors so as to achieve pattern classification.

In this study, the "Kohonen" package of R language 4.0 was used to perform self-organizing mapping (SOM) cluster analysis [35,36], and the performance of SOM networks under different cluster numbers was compared through multiple trainings, and the clustering results were finally obtained.

3. Results

3.1. Spatial and Temporal Analysis of the Multifunctional Evolution of Arable Land

Based on the results of the multifunctional assessment of arable land in the Hexi Corridor, we used cold and hot spot analysis to calculate the area of cold and hot spot regions for each function (Figure 2),and analyzed the temporal and spatial evolution characteristics of each function (Figure 3).

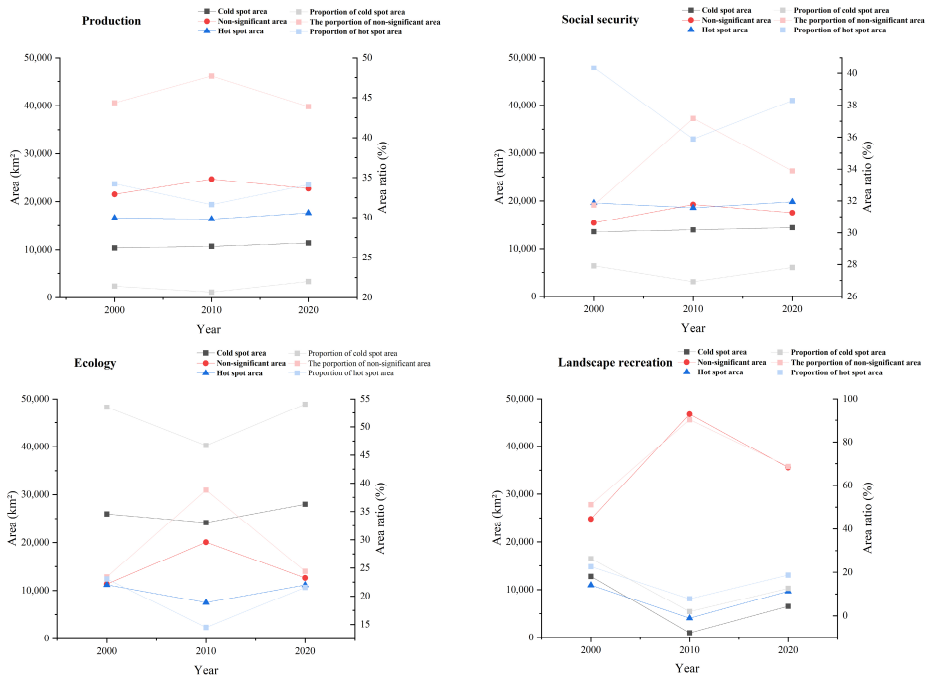


Figure 2. Changes in the areas of hot and cold spots.

3.1.1. Spatial and Temporal Analysis of the Evolution of the Production Functions of Arable Land

Between 2000 and 2020, the production functions maintained a high level and continued to rise. The area of hot spots experienced a slight decrease and then a significant increase, from 16,603.45 km^2 to 16,374.73 km^2, and then increased to 17,655.43 km^2, and its proportion was greater than 30% throughout the entire study period. Moreover, the area of cold spots also exhibited a slow growth trend, increasing from 10,397.05 km^2 to 11,392.98 km^2.

Spatially, the production functions of arable land showed a stable pattern of "low in the northwest and high in the southeast". The hot spots were concentrated mainly in the

central and southeastern parts of the region, including Linze, Ganzhou, Minle, Shandan, Yongchang, Liangzhou, Gulang, and Tianzhu Tibetan Autonomous. Cold spot regions, on the other hand, were more sporadically distributed in the northwestern part of the city of Dunhuang, Guazhou, Yumen, Jinta, and Sunan Yugu Autonomous, as well as in the southeastern part of the country, in parts of Minqin and Tianzhu Tibetan Autonomous.

3.1.2. Spatial and Temporal Analysis of the Evolution of the Social Security Functions of Arable Land

Between 2000 and 2020, the social security functions were maintained at a high level, and the development trend was similar to that of the cultivated land production functions. The hot spot area stabilized at approximately 20,000 km^2, accounting for nearly 40% of the area, indicating a strong social security support capacity. The area of cold spots increased slightly from 13,545.15 km^2 to 14,393.78 km^2, but the proportion remained stable.

Spatially, the hot spot regions of the social security functions of arable land were similar to those of the production functions, mainly concentrated in Linze, Minle, and Liangzhou. Spatially, the hot spot regions of the social security functions of arable land were similar to those of the production functions, mainly concentrated in Linze, Minle, and Liangzhou that are located in the central and southeast, and their coverage was wider, such as Minqin, which changed from a cold spot to a hot spot. Cold spots were scattered in the northwestern regions where arable land is scarce, and in some regions in the southeast, their coverage expanded compared with that of the production functions.

3.1.3. Spatial and Temporal Analysis of the Evolution of the Ecological Functions of Arable Land

Between 2000 and 2020, the ecological functions were relatively weak, which first decreased and then increased. In 2010, the area of hot spots was significantly reduced to less than 10,000 km^2, and its proportion fell below 20%, showing an overall shrinking trend. In contrast, the area of cold spots expanded, and the proportion of cold spots was maintained at more than 50%, occupying a dominant position.

Spatially, the hot spots of the ecological functions of arable land were focused mainly in southeastern Sunan Yugu Autonomous, Gulang, and Tianzhu Tibetan Autonomous, and the clustering effect was obvious. The cold spots were widely distributed in the northwestern and central regions and extended in a strip-like pattern, partially covering Minqin and Jinchuan. Notably, the spatial distribution pattern of the ecological functions of cultivated land in the Hexi Corridor remained relatively stable between 2000 and 2020, without significant changes.

3.1.4. Spatial and Temporal Analysis of the Evolution of Recreational Functions in Arable Landscapes

Between 2000 and 2020, the recreational functions of cultivated landscapes in the Hexi Corridor region as a whole tended to gradually recover after weakening. The area of hot spots experienced a decrease and then an increase and eventually reached a low point in 2010, which was only 4049.73 km^2, whereas the area of cold spots also showed the same trend of decreasing, increasing, and then shrinking to 1000 km^2 in 2010, and both accounted for a small proportion.

Spatially, the hot spot pattern of the recreational functions of arable landscapes has changed. In 2000, hot spots were primarily concentrated in Minle, Shandan, and Yongchang Counties in the central part of the Hexi Corridor and Minqin in the northeast, and a small number of hot spots were also distributed in Dunhuang and Guazhou in the northwestern part of the Hexi Corridor, but they were more sporadic. By 2010, the hot spots in the northwest and northeast regions had disappeared, and the hot spots were concentrated in

the three central counties. By 2020, Tianzhu Tibetan Autonomous had become a new hot spot area. The cold spots, on the other hand, were primarily concentrated in Tianzhu Tibetan Autonomous in 2000, but their spatial distributions were relatively sporadic throughout the study period.

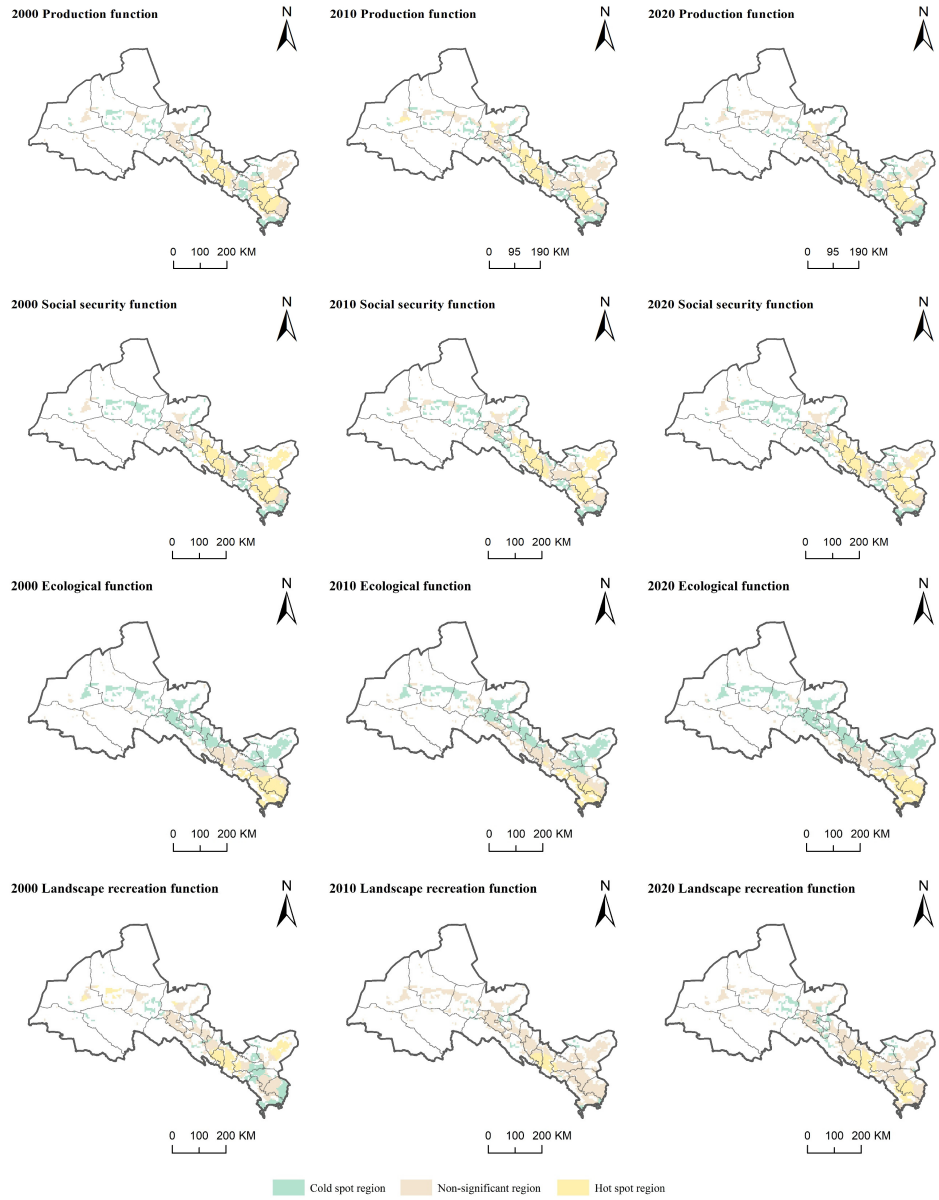


Figure 3. Spatial and temporal variations in cold/hot spot regions.

3.2. Multifunctional Trade-Offs and Synergistic Analysis of Arable Land

The trade-off relationship describes an antagonistic relationship between two functions, while the synergistic relationship reflects the positive relationship between the two functions. The outcomes from the multifunctional assessment of cultivated land were utilized to derive the coefficients, indicating the relationship between the different functions of the land, by employing Spearman's rank correlation analysis. (Figure 4). In addition, the bivariate local spatial autocorrelation analysis of GeoDa 1.22 software was used to determine the area share of the trade-off area and the synergistic area among each function (Figure 5), and the spatial pattern of the trade-off and synergy between the cultivated land functions in the Hexi Corridor was obtained (Figure 6). The specific results are discussed below. * and ** represent significance levels of 5% and 10%, respectively

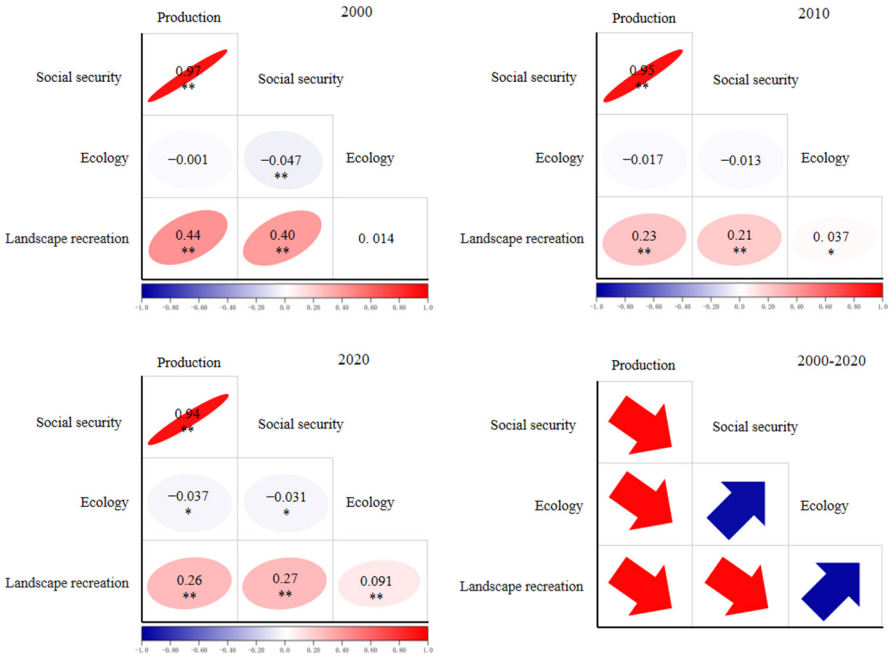


Figure 4. Multifunctional correlation coefficients of cultivated land. * and **represent significance levels of 5% and 10%, respectively.

3.2.1. Multifunctional Trade-Offs and Synergistic Temporal Changes in Croplands

The trade-off and synergistic relationships between the functions of arable land in the Hexi Corridor region were stable and have not been transformed. The synergy between arable land production and social security functions was significant. It further shows that the production capacity of cultivated land for grain and other agricultural products and the ability to provide basic livelihood security for farmers are mutually reinforcing. The trade-off between cultivated land production and ecological function has increased; this shows that the conflict between the two is intensifying, indicating that while arable land is increasing food production and meeting human food needs, the negative impact on the ecological environment is also quietly accumulating. The synergy between arable land production and landscape recreation functions decreased but then increased, which reflects the increase in agricultural production intensity or the change in land use mode; the landscape recreation value of cultivated land has been squeezed to a certain extent. The relationship between the social security functions of arable land and the ecological functions of the trade-off decreased and then increased. In the early stage, it may be due to the intensification of agricultural production activities which led to the increase in pressure on the ecological environment, which in turn affected the stable performance of the social security function of cultivated land. Later, the trade-off relationship gradually eased, indicating that the cultivated land use pattern may have been adjusted to a certain extent, or the implementation of ecological protection measures effectively alleviated the degradation of ecological functions, thereby reducing the direct conflict between social security functions and ecological functions. The synergy between the social security functions of cropland and the landscape recreation functions weakened, showing that this process is also accompanied by the increase in the pressure on cultivated land resources, the decline of the quality of the ecological environment, and the conflict of land use patterns. The synergistic enhancement of the ecological and landscape recreational functions of cropland gradually increased in significance, showing that arable land is not only the cornerstone of food production but also an indispensable green barrier and leisure space in the urban ecosystem. Overall, the systematic relationship between a variety of functions of cultivated land in the Hexi Corridor is dominated by a synergistic relationship, in which the production of cultivated

land and the social security functions are closely synergized, and the relationships between the other functions are complex and variable, but all of them maintain a certain degree of significance.

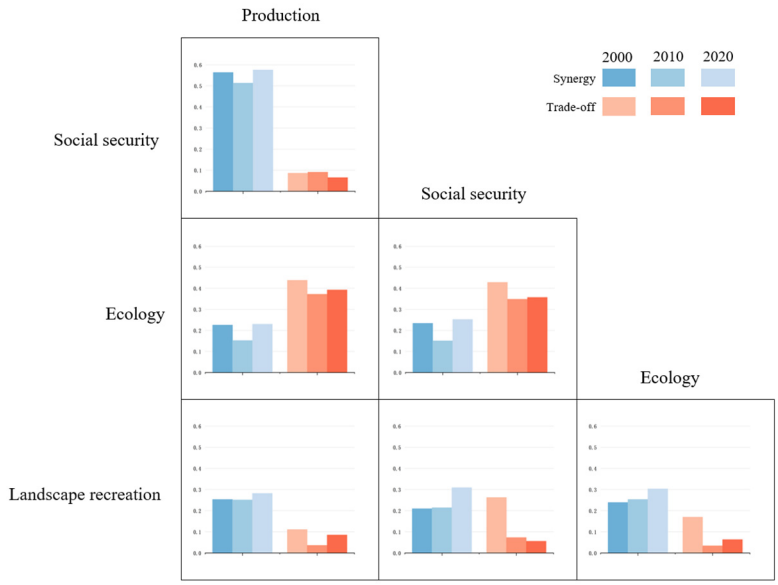


Figure 5. Percentage of area in the trade-off zone versus the synergy zone.

3.2.2. Multifunctional Trade-Offs and Synergistic Spatial Changes in Croplands

The overall spatial pattern of the synergistic relationship of production–social security function trade-offs in the Hexi Corridor region from 2000 to 2020 exhibited a synergistic distribution pattern with a stable spatial distribution, and the area share of synergistic zones first decreased but then increased. The H-H synergistic zone covered several counties and districts in the central part of the Hexi Corridor, such as Linze County and Ganzhou District, whereas the L-L synergistic zone was more sporadically located in Sunan Yugu Autonomous, Tianzhu Tibetan Autonomous, and some districts and counties in Jiuquan.

The production–ecological function trade-offs and synergistic relationships in the Hexi Corridor region from 2000 to 2020 were spatially dominated by the role of trade-offs, with the area share of the trade-off zone decreasing and then increasing but declining overall. The H-L trade-off areas were concentrated mainly in Dunhuang, Guazhou, Yumen, Jinta, Jiayuguan, Suzhou, Linze, Ganzhou, and Minqin in the southeastern and northwestern parts of the Hexi Corridor, whereas the L-H trade-off areas were distributed mainly in Tianzhu Tibetan Autonomous and Gulang in the southeast. The H-H synergistic areas were relatively small in number and distributed mainly in Liangzhou and Gulang.

The spatial pattern of production–landscape recreation functional trade-offs and synergistic relationships in the Hexi Corridor region from 2000 to 2020 was dominated by synergistic effects, and the proportion of synergistic zones gradually increased. H-H synergistic zones were spatially distributed as a slice and were located mainly in Minle and Shandan in 2000, and their spatial distribution expanded and increased in 2020. L-L synergistic zones were located mainly in Yumen, Jinta, Jiayuguan, Jinchuan, Gulang, and Tianzhu Tibetan Autonomous, and their spatial distribution was relatively decentralized.

The social security–ecological trade-offs in the Hexi Corridor from 2000 to 2020 were also significant, with a gradual increase in the proportion of the area of the trade-off zone, in which the H-L trade-off zone was distributed in Dunhuang, Guazhou, Yumen, Jinta, Jiayuguan, Suzhou, Linze, Ganzhou, and Minqin in the southeastern part of the Hexi Corridor and in the northwestern part of the Hexi Corridor, and the L-H trade-off zone was distributed in Tianzhu Tibetan Autonomous, Tianzhu, and Gulang in the southeastern part,

as well as Gulang in the southeast. Moreover, the H-H synergy zone was distributed mainly in Gulang and Tianzhu Tibetan Autonomous in the southeast, with a smaller coverage area, showing a spatial trend of shrinking and then increasing over time.

The social security–landscape recreation functions from 2000 to 2020 were based mainly on synergies, and the spatial layout and production were similar to those of the landscape recreation functions. The proportion of synergistic areas gradually increased, especially between 2010 and 2020. Among them, the H-H synergistic area expanded over time as a whole, and parts of Gulang and Liangzhou transformed from being nonsignificant to H-H synergistic areas in 2020, whereas the L-L synergistic area was distributed mainly in Yumen, Jiayuguan, Jinchuan, and Minqin, and parts of Gulang and Tianzhu Tibetan Autonomous gradually transformed from being L-L synergistic areas to nonsignificant areas.

From 2000 to 2020, the ecological and landscape recreation functions were primarily spatially synergistic, and the proportion of synergistic areas gradually increased, with the L-L synergistic areas primarily distributed in Yumen and Jinta in the northwest of the Hexi Corridor, Jiayuguan and Jinchuan in the southeast, and the H-H synergistic areas concentrated in the central Hexi Corridor, Minle, Shandan, Liangzhou, and Gulang in the southeast. The coverage gradually expanded during this period.

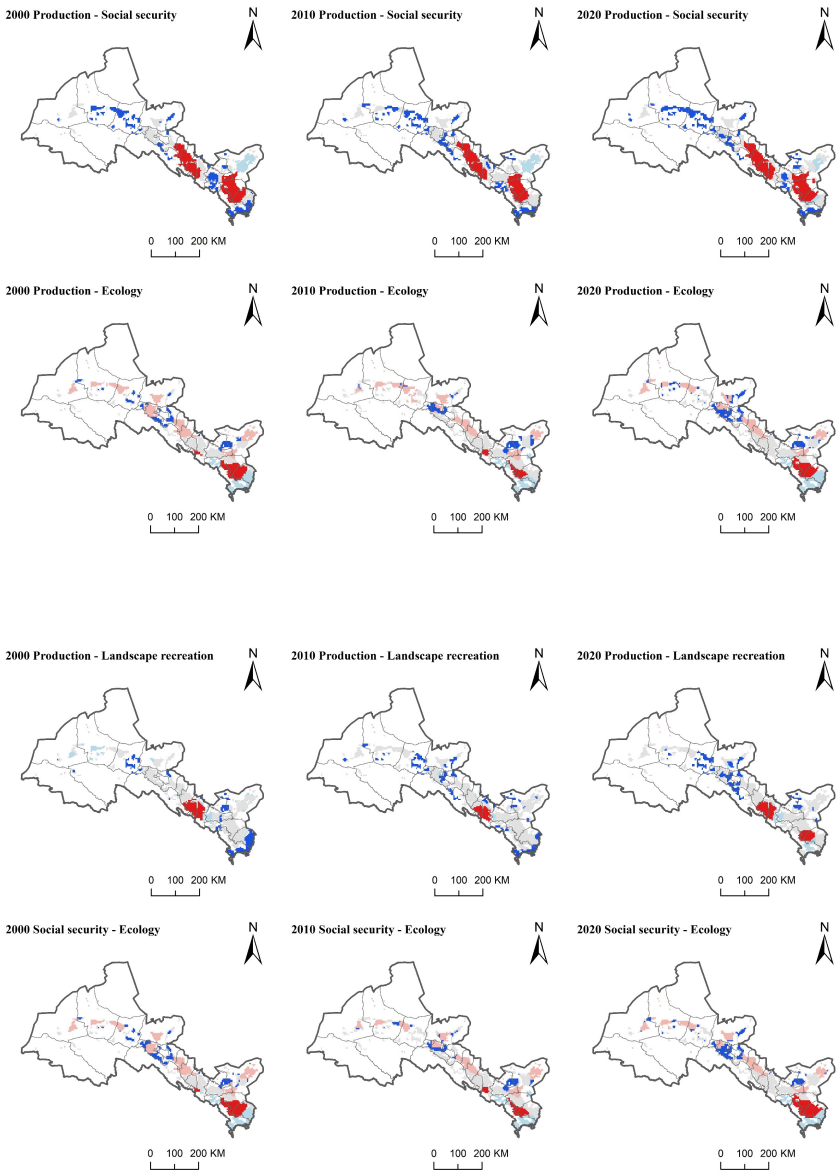


Figure 6. *Cont.*

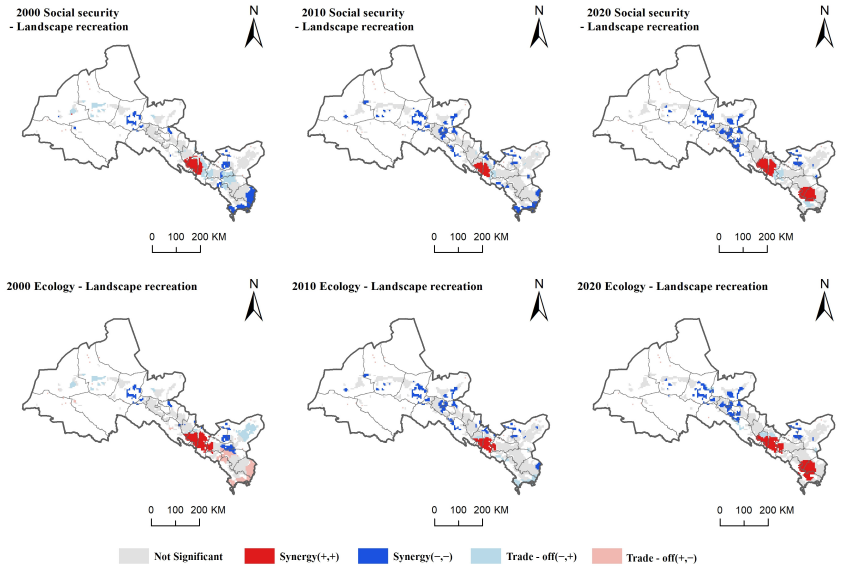


Figure 6. Weights of the spatial patterns of the synergistic relationships.

3.3. Optimization of Multifunctional Zoning of Cultivated Land in the Hexi Corridor

In this study, based on the results of the cold and hot spot analysis of cultivated land multifunction in 2020, the self-organizing mapping (SOM) cluster analysis was performed using the "Kohonen" package of R version 4.0 with each 5 km grid as a sample, and the performance of the SOM network under different cluster numbers was compared. A detailed comparison shows that when the number of clusters is set to four, there is good consistency within each cluster, and the spatial differences between clusters are significantly larger. The clustering results are shown in the figure below (Figure 7).

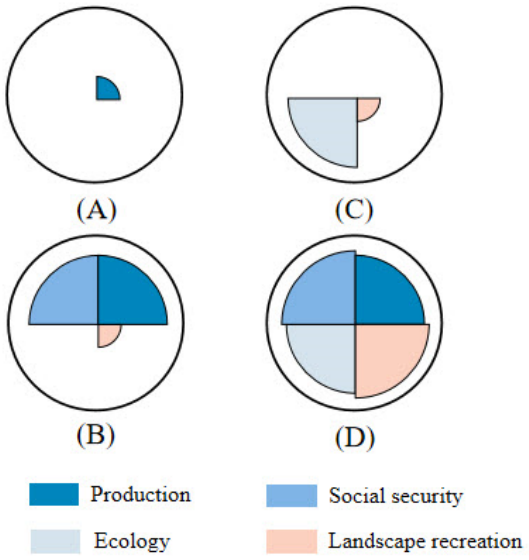


Figure 7. Clustering results of cultivated land multifunctionality. (**A**) shows that only the cultivated land production function is prominent. (**B**) shows that the production functions of arable land and social security functions were prominent. (**C**) shows that the ecological functions of cultivated land were outstanding. (**D**) shows that each function of the cultivated land was more prominent. Note: Figure 7 is a direct output from the R language.

As can be seen from Figure 7, Figure (A) shows that only the cultivated land production function is prominent. Figure (B) shows that the production functions of arable land and social security functions were prominent. Figure (C) shows that the ecological functions of

cultivated land were outstanding. Figure (D) shows that each function of the cultivated land was more prominent. Then, using the ArcGIS platform, the clustering table space output by the "kohonen" package of R 4.0 was connected to the cultivated land grid in the Hexi Corridor area in 2020 to obtain the spatial distribution characteristics of multifunctional zoning of cultivated land (Figure 8). Finally, according to the dominant cultivated land function and spatial distribution characteristics in each cluster, the cultivated land in the Hexi Corridor area was divided into the agricultural production-led zone, agricultural–social security zone, ecological–agricultural zone, and balanced development zone.

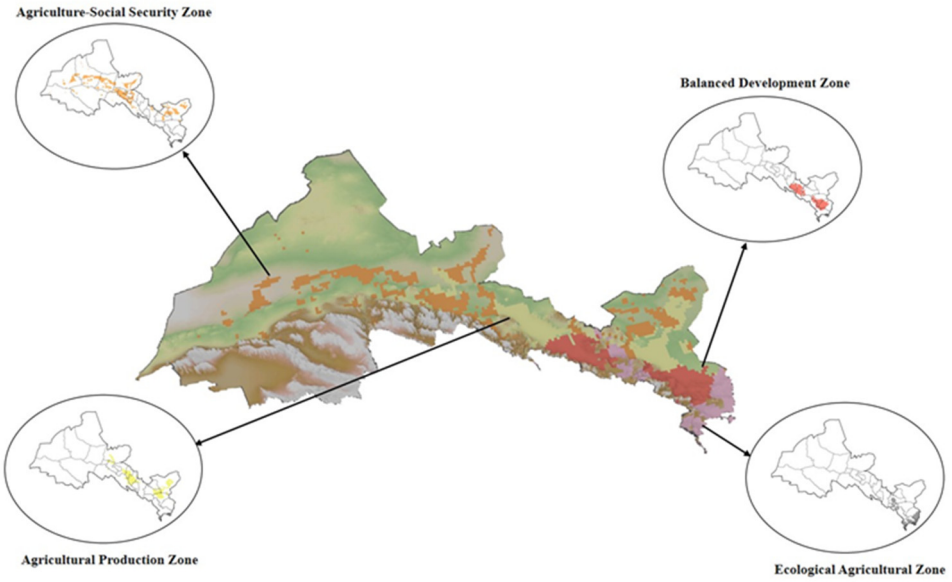


Figure 8. Results of multifunctional zoning of cultivated land.

3.3.1. Agricultural Production-Led Zone

The agricultural production zone was mainly distributed in Jinta, Suzhou, Gaotai, Linze, Ganzhou, Shandan, Yongchang, Liangzhou, and Minqin, accounting for 23.54% of the total area of arable land, and exhibited large and contiguous cropland areas, and its cropland food production capacity was more prominent. The most important commodity grain base and centralized production area of cash crops in northwestern China as well as the positioning of the region are needed to guarantee national food security. The region is positioned as an important area for guaranteeing national food security, developing characteristic agriculture, and promoting agricultural modernization, and management should focus on stabilizing food production, developing characteristic agriculture, promoting agricultural modernization, and facilitating industrial upgrading.

3.3.2. Agricultural–Social Security Zone

The agricultural–social security zone was distributed in the northwestern part of Dunhuang, Guazhou, Yumen, Jiayuguan, and Jinta as well as in the southeastern part of Shandan, Yongchang, Jinchuan, Liangzhou, and Minqin, accounting for 42.59% of the total area of cultivated land, and exhibited the characteristics of both food production and social functions, demonstrating the importance of the area in the production of agricultural products and in the society of mankind. This region provides social security services on the basis of agricultural development to guarantee food security and the production of specialty agricultural products, and its management objectives are to enhance production efficiency and the quality of food production, boost the level of agricultural technology and management, and establish a sound agricultural social security system.

3.3.3. Ecological–Agricultural Zone

The eco–agricultural zone was located mainly in Yongchang, Sunan Yugu Autonomous, Gulang, and Tianzhu Tibetan Autonomous, accounting for 12.91% of the total cultivated area. The region is located in the national key ecological function area of "Gansu Province Land Space Planning (2021–2035)"; its ecological value is remarkable, and its position is an important area for developing characteristic ecological agriculture, leading to the development of modern agriculture and boosting the construction of an ecological civilization. Its management objectives are to improve the productivity and quality of agricultural production; promote the ecological development of agriculture and the transformation of agriculture in the direction of ecology; and realize the greening, recycling, and sustainability of agricultural production.

3.3.4. Balanced Development Zone

The balanced development zone was mainly distributed in Minle, Shandan, Yongchang, Liangzhou, Gulang, and Tianzhu Tibetan Autonomous, accounting for 20.96% of the total area of arable land, which was massed and continuous, with a better agricultural foundation and greater productivity of arable land. The ice and snow meltwater of Qilian Mountain ensures the water demand of crops, forming a unique oasis landscape, and all the functions in the area exhibited higher levels; therefore, the region is positioned as an area to ensure the balanced utilization of cropland resources, promote the progress of modern agriculture, achieve ecological security, and meet the needs of agro-tourism. The management objectives are to improve resource deployment of arable land resources, promote the green development of agriculture, and enhance the landscape value and recreational functions of arable land.

4. Discussion

4.1. In-Depth Exploration of the Spatiotemporal Evolution Characteristics of Cultivated Land Multifunctionality

Since 2000, the productive land and social security functions of the Hexi Corridor have maintained a high level and have been enhanced. This trend is closely related to the government's continuous investment and policy support in the agricultural sector. In particular, since 2004, the government has successively issued a document focusing on the "three rural" issues and has implemented a series of agricultural support policies, such as direct grain subsidies and subsidies for improved seeds, which have effectively stimulated farmers' enthusiasm for production and improved agricultural production efficiency. The implementation of these policies has not only promoted the development of agricultural production but also ensured the basic livelihood of the farmers and enhanced the social security function of cultivated land. In contrast, the ecological function of cultivated land is relatively weak. In the past, the pursuit of high efficiency of agricultural production while ignoring the protection of the ecological environment led to the damage of the ecological function of cultivated land. In recent years, with the government's emphasis on the construction of ecological civilization, the Hexi Corridor has strengthened the protection and governance of the ecological environment, and the ecological function of cultivated land has been gradually restored. In the future, we should continue to adhere to the concept of green development and promote the harmonious coexistence of agriculture and the ecological environment. The evolution of the recreation function of cultivated land landscape reflects the change in people's lifestyle and consumption concept. With the increase in demand for leisure tourism, cultivated land is no longer only a provider of means of production but also an important place for people's leisure tourism. In recent years, with the rise in rural tourism and the promotion of the integrated development

of agriculture and tourism, the recreation function of cultivated land landscape has been gradually restored and improved.

4.2. Discussion of the Trade-Offs and Synergies of Multifunctional Cultivated Land

The stable coordination of cultivated land production and social security functions demonstrates the state's firm support for agriculture and the effective protection of farmers' rights and interests. However, the trade-off between cultivated land production and ecological function has intensified, which warns us that we must strengthen ecological protection and promote green and sustainable agricultural development while pursuing agricultural production benefits. In addition, although the synergy between cultivated land production and landscape recreation function is weakening, it is still significant, indicating that the development of agricultural multifunctionality is becoming a new driver of the local economy. In the future, the deep integration of agriculture and tourism will be the key to tapping agricultural tourism resources and promoting local economic transformation and upgrading.

In the spatial dimension, there are significant regional differences in the trade-off and synergy of cultivated land in the Hexi Corridor, which is not only restricted by natural conditions and the economic level but also affected by local policy guidance and regional development strategies. The central region has a strong agricultural foundation and significant synergy of social security functions. However, the marginal areas are limited by conditions, and the efficiency of agricultural production is low. The ecological environment in the northwest region is fragile, and agricultural production puts great pressure on the ecology of the environment. However, the synergies in areas with better ecological environment are significant, suggesting that we need to formulate ecological protection measures according to local conditions. In areas rich in tourism resources, such as Minle, Shandan, and other counties, agriculture and tourism are deeply integrated, realizing the effective play of agricultural multifunctionality; Resource-poor areas need to explore development paths suitable for their own characteristics.

4.3. Reflections on Zoning Management Strategies

The process of urbanization poses a challenge to the dominant zone of agricultural production, resulting in a large amount of cultivated land being occupied and difficult to effectively replenish, and the imbalance of cultivated land occupation and the compensation and abandonment of cultivated land aggravate the degradation of cultivated land. In order to cope with this problem, it is necessary to establish and improve the cultivated land protection system, strengthen supervision and approval, and ensure the balance of cultivated land occupation and quality. The government should increase agricultural input and introduce incentives to encourage land transfer and large-scale operations to ensure food production.

Agricultural–social security zones face problems such as drought, water shortage, and lagging infrastructure, which restrict agricultural production and social security functions. Therefore, it is necessary to strengthen the management of water resources, promote water-saving irrigation technology, and improve the utilization rate. At the same time, through land consolidation and soil improvement, high-standard farmland will be built to improve the output and quality of farmland and strengthen the management of food production risk to ensure security and stability. In addition, we will strengthen employment and entrepreneurship services for farmers, as well as provide skills training, entrepreneurship guidance, and policy support to help agricultural development.

The ecological function of the ecological agriculture area is significant, but the ecosystem is sensitive and susceptible to human activities and natural disasters, and the problems

of soil quality and land degradation are prominent. The management of cultivated land resources should be strengthened; the disorderly expansion of cities should be prevented from occupying cultivated land, and ecological buffer zones should be established around cultivated land to reduce soil erosion and environmental pollution. In addition, it is necessary to establish and improve the ecological monitoring network, to monitor and evaluate the ecological environment in real time, and to provide a basis for formulating scientific agricultural policies.

The balanced development zone is affected by the destruction of the ecological environment and the backward level of technical management, and the sustainability and esthetics of cultivated land use are impaired. It is necessary to scientifically plan the layout of cultivated land and make rational use of resources by introducing advanced agricultural technology and equipment to improve disaster resistance and stability. Moreover, it is necessary to develop ecological agriculture, improve the agricultural ecological environment, and enhance the ornamental and ecological value of the landscape, as well as combine natural scenery and cultural landscape, create a characteristic agricultural landscape belt, and promote the integrated development of agriculture and tourism.

4.4. Deficiencies and Future Prospects

In addition, in the formulation of zoning optimization strategies, although four zoning schemes are proposed in this paper, the specific management measures and implementation plans in each zoning may need to be further refined and improved, and future research should further broaden the channels of data acquisition, explore advanced analysis methods, and propose more forward-looking and operable zoning strategies. It provides strong support for the sustainable use of cultivated land in the Hexi Corridor.

5. Conclusions

The cultivated land functions in the Hexi Corridor area show diversified characteristics, among which the production and social security functions continue to be enhanced, and the hot spots continue to expand, demonstrating the prosperity of agricultural production and the stability of farmers' lives. However, the ecological function is relatively weak, and the overall trend is declining, highlighting the contradiction and challenge between ecological protection and agricultural development. The recreation function of cultivated land landscape has gradually recovered after fluctuations, showing new opportunities for rural tourism and leisure tourism, which can be further explored and utilized in the future. In terms of spatial layout, the hot spots of production and social security functions are highly overlapped and mainly concentrated in the central and southeast, while the northwest has become the cold spot area. In contrast, the hot spots of ecological functions are confined to the southeast, while the cold spots are widely scattered in the northwest and central regions. Although the hotspot areas of landscape recreation function have undergone changes, they generally show a trend of alternating dispersion and concentration, which provides a new perspective for the in-depth excavation and coordinated development of cultivated land multifunctionality in the Hexi Corridor.

In the time dimension, the synergistic relationship between cultivated land production and social security functions is stable and continuously enhanced, highlighting the stability of agricultural production and the guarantee of farmers' livelihood. However, the trade-off between cultivated land production and ecological functions is becoming increasingly tense, revealing the potential threat of agricultural production expansion to the ecological environment. At the same time, although the synergistic relationship between cultivated land and landscape recreation, social security and landscape recreation, and ecology and landscape recreation functions has its own characteristics, they all show a certain trend of

enhancement, indicating the expansion and improvement of agricultural multifunctionality. In terms of spatial layout, the regional characteristics of each functional synergy and trade-off area are distinct, and the continuous expansion of the area of the synergy area indicates that the mutual promotion effect between multiple functions in cultivated land use is becoming more and more significant, which provides strong support for the sustainable development of agriculture in the Hexi Corridor.

Based on the above analysis, this study further divides the cultivated land in the Hexi Corridor into four sub-zones: agricultural production-dominant area, agricultural–social security zone, ecological–agriculture zone, and balanced development zone and proposes management measures based on the characteristics of each sub-region, which can provide a useful reference for formulating cultivated land protection policies and optimizing land use structure in the Hexi Corridor area.

Author Contributions: Conceptualization, K.Z. and B.X.; methodology, K.Z. and Z.S.; software, K.Z. and Z.S.; validation, K.Z., Z.S. and B.X.; investigation, Z.S. and T.M.; data curation, Z.S.; writing—original draft preparation, K.Z. and Z.S.; writing—review and editing K.Z. and B.X.; visualization, Z.S., T.M. and Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key Research and Development Program of China (2022YFF1300705).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors are grateful to the editor and reviewers for their valuable comments and suggestions.

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

References

1. Lai, Z.; Chen, M.; Liu, T. Changes in and prospects for cultivated land use since the reform and opening up in China. *Land Use Policy* **2020**, *97*, 104781. [CrossRef]
2. Bao, J.; Mao, L.; Liu, Y.; Fan, S. Investigation of Spatiotemporal Changes and Impact Factors of Trade-Off Intensity in Cultivated Land Multifunctionality in the Min River Basin. *Agriculture* **2024**, *14*, 1666. [CrossRef]
3. Li, S.; Shao, Y.; Hong, M.; Zhu, C.; Dong, B.; Li, Y.; Lin, Y.; Wang, K.; Gan, M.; Zhu, J.; et al. Impact mechanisms of urbanization processes on supply-demand matches of cultivated land multifunction in rapid urbanization areas. *Habitat Int.* **2023**, *131*, 102726. [CrossRef]
4. Song, X.-Q.; Ouyang, Z. Route of multifunctional cultivated land management in China. *J. Nat. Resour.* **2012**, *27*, 540–551.
5. Long, H.L.; Ma, L.; Zhang, Y.N.; Qu, L. Multifunctional rural development in China: Pattern, process and mechanism. *Habitat Int.* **2022**, *121*, 102530. [CrossRef]
6. Fielke, S.J.; Wilson, G.A. Multifunctional intervention and market rationality in agricultural governance: A comparative study of England and South Australia. *Geo J.* **2017**, *82*, 1067–1083. [CrossRef]
7. Lerouge, F.; Sannen, K.; Gulinck, H.; Vranken, L. Revisiting production and ecosystem services on the farm scale for evaluating land use alternatives. *Environ. Sci. Policy* **2016**, *57*, 50–59. [CrossRef]
8. Manson, S.M.; Jordan, N.R.; Nelson, K.C.; Brummel, R.F. Modeling the effect of social networks on adoption of multifunctional agriculture. *Environ. Model. Softw.* **2016**, *75*, 388–401. [CrossRef]
9. Fagioli, F.F.; Rocch, L.; Paolotti, L.; Słowiński, R.; Boggia, A. From the farm to the agri-food system: A multiple criteria framework to evaluate extended multifunctional value. *Ecol. Indic.* **2017**, *79*, 91–102. [CrossRef]
10. Jang, G.; Wang, M.; Qu, Y.; Zhou, D.; Ma, W. Towards cultivated land multifunction assessment in China: Applying the "influencing factors-functions-products-demands" integrated framework. *Land Use Policy* **2020**, *99*, 104982. [CrossRef]
11. Liu, W.; Zhan, J.; Zhao, F.; Wang, C.; Zhang, F.; Teng, Y.; Chu, X.; Kumi, M.A. Spatiotemporal variations of ecosystem services and their drivers in the Pearl River Delta, China. *J. Clean. Prod.* **2022**, *337*, 130466. [CrossRef]

12. Tao, J.; Lu, Y.; Ge, D.; Dong, P.; Gong, X.; Ma, X. The spatial pattern of agricultural ecosystem services from the production-living-ecology perspective: A case study of the Huaihai Economic Zone, China. *Land Use Policy* **2022**, *122*, 106355. [CrossRef]
13. Zhu, Y.; Luo, P.; Zhang, S.; Sun, B. Spatiotemporal analysis of hydrological variations and their impacts on vegetation in semiarid areas from multiple satellite data. *Remote Sens.* **2020**, *12*, 4177. [CrossRef]
14. Liang, X.; Li, Y. Identification of spatial coupling between cultivated land functional transformation and settlements in Three Gorges Reservoir area, China. *Habitat Int.* **2020**, *104*, 102236. [CrossRef]
15. Wu, B.; Liu, M.; Wan, Y.; Song, Z. Evolution and coordination of cultivated land multifunctionality in Poyang lake ecological economic zone. *Sustainability* **2023**, *15*, 5307. [CrossRef]
16. Liu, Y.; Wan, C.; Xu, G.; Chen, L.; Yang, C. Exploring the relationship and influencing factors of cultivated land multifunction in China from the perspective of trade-off/synergy. *Ecol. Indic.* **2023**, *149*, 110171. [CrossRef]
17. Liu, J.; Jin, X.; Xu, W.; Sun, R.; Han, B.; Yang, X.; Gu, Z.; Xu, C.; Sui, X.; Zhou, Y. Influential factors and classification of cultivated land fragmentation, and implications for future land consolidation: A case study of Jiangsu Province in eastern China. *Land Use Policy* **2019**, *88*, 104185. [CrossRef]
18. Li, B.; Wang, W. Trade-offs and synergies in ecosystem services for the Yinchuan Basin in China. *Ecol. Indic.* **2018**, *84*, 837. [CrossRef]
19. Wang, Z.; Yang, H.; Hu, Y.; Peng, Y.; Liu, L.; Su, S.; Wang, W.; Wu, J. Multifunctional trade-off/synergy relationship of cultivated land in Guangdong: A long time series analysis from 2010 to 2030. *Ecol. Indic.* **2023**, *154*, 110700. [CrossRef]
20. Li, X.; Xiao, P.; Zhou, Y.; Xu, J.; Wu, Q. The Spatiotemporal Evolution Characteristics of Cultivated Land Multifunction and Its Trade-Off/Synergy Relationship in the Two Lake Plains. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15040. [CrossRef]
21. Qian, F.; Chi, Y.; Lal, R. Spatiotemporal characteristics analysis of multifunctional cultivated land: A case of Shenyang, Northeast China. *Land Degrad. Dev.* **2020**, *31*, 1812–1822. [CrossRef]
22. Yang, H.; Zou, R.; Hu, Y.; Wang, L.; Xie, Y.; Tan, Z.; Zhu, Z.; Zhu, A.X.; Gong, J.; Mao, X. Sustainable utilization of cultivated land resources based on "element coupling-function synergy" analytical framework: A case study of Guangdong, China. *Land Use Policy* **2024**, *146*, 107316. [CrossRef]
23. Zhang, S.; Hu, W.; Li, M.; Guo, Z.; Wang, L.; Wu, L. Multiscale research on spatial supply-demand mismatches and synergic strategies of multifunctional cultivated land. *J. Environ. Manag.* **2021**, *299*, 113605. [CrossRef] [PubMed]
24. Liu, C.; Xu, Y.; Huang, A.; Liu, Y.; Wang, H.; Lu, L.; Sun, P.; Zheng, W. Spatial identification of land use multifunctionality at grid scale in farming-pastoral area: A case study of Zhangjiakou City, China. *Habitat Int.* **2018**, *76*, 48–61. [CrossRef]
25. Chen, X.J.; Wang, J. Quantitatively determining the priorities of regional ecological compensation for cultivated land in different main functional areas: A case study of Hubei Province, China. *Land* **2021**, *10*, 247. [CrossRef]
26. Xiang, J.W.; Han, P.; Chen, W.X. Coordinated development efficiency between cultivated land spatial morphology and agricultural economy in underdeveloped areas in China: Evidence from western Hubei Province. *J. Geogr. Sci.* **2023**, *33*, 801–822. [CrossRef]
27. Yin, C.; Nie, Y.; Li, Y.; Zhou, Y.; Yu, L.; Qin, H.; Yu, J. Multifunctional trade-off and compensation mechanism of arable land under the background of rural revitalization: A case study in the West Mountain Regions of Hubei Province. *Environ. Sci. Pollut. Res.* **2023**, *30*, 96329–96349. [CrossRef] [PubMed]
28. Zhang, Y.; Long, H.; Tu, S.; Ge, D.; Ma, L.; Wang, L. Spatial identification of land use functions and their tradeoffs/synergies in China: Implications for sustainable land management. *Ecol. Indic.* **2019**, *107*, 105550.1–105550.14. [CrossRef]
29. Yang, W.; Pan, J. The role of vegetation carbon sequestration in offsetting energy carbon emissions in the Yangtze River Basin, China. *Environ. Dev. Sustain.* **2024**, *26*, 22689–22714. [CrossRef]
30. Ran, Y.J.; Zhao, X.Q.; Ye, X.M.; Wang, X.; Pu, J.; Huang, P.; Zhou, Y.; Tao, J.; Wu, B.; Dong, W.; et al. A framework for territorial spatial ecological restoration zoning integrating "Carbon neutrality" and "Human-geology-ecology": Theory and application. *Sustain. Cities Soc.* **2024**, *115*, 105824. [CrossRef]
31. Li, Y.; Luo, H. Trade-off/synergistic changes in ecosystem services and geographical detection of its driving factors in typical karst areas in southern China. *Ecol. Indic.* **2023**, *154*, 110811. [CrossRef]
32. Zeng, S.; Jiang, C.; Bai, Y.; Wang, H.; Liu, E.; Guo, L.; Chen, S.; Zhang, J. Understanding scale effects and differentiation mechanisms of ecosystem services tradeoffs and synergies relationship: A case study of the Lishui River Basin, China. *Ecol. Indic.* **2024**, *167*, 112648. [CrossRef]
33. Jia, Z.; Wang, X.; Feng, X.; Ma, J.; Wang, X.; Zhang, X.; Zhou, J.; Sun, Z.; Yao, W.; Tu, Y. Exploring the spatial heterogeneity of ecosystem services and influencing factors on the Qinghai Tibet Plateau. *Ecol. Indic.* **2023**, *154*, 110521. [CrossRef]
34. He, J.; Shi, Y.; Xu, L.; Lu, Z.; Feng, M. An investigation on the impact of blue and green spatial pattern alterations on the urban thermal environment: A case study of Shanghai. *Ecol. Indic.* **2024**, *158*, 111244. [CrossRef]

35. Xia, H.; Yuan, S.; Prishchepov, A.V. Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: Implications for spatial planning and management. *Resour. Conserv. Recycl.* **2023**, *189*, 106767. [CrossRef]
36. Gao, Y.; Wang, Z.; Li, C. Assessing spatiotemporal heterogeneity and drivers of ecosystem services to support zonal management in mountainous cities. *Sci. Total Environ.* **2024**, *954*, 176328. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.