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Investigation of Spatiotemporal Changes and Impact Factors of Trade-Off Intensity in Cultivated Land Multifunctionality in the Min River Basin

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Abstract: Exploring the interrelationships and influencing factors of the multifunctionality of cultivated land is crucial for achieving its multifunctional protection and sustainable use. In this paper, we take the Min River basin as a case study to construct a multifunctional evaluation system based on “agricultural production, social security, ecological service, and cultural landscape” using multi-source data. We analyze the spatial and temporal characteristics of the multifunctionality of cultivated land through kernel density estimation (KDE) and visual mapping. Subsequently, we assess the trade-off strength between the multifunctional aspects of cultivated land using the root mean square error (RMSD). Finally, we identify the drivers of the multifunctional trade-off intensity of cultivated land and analyze their influencing mechanisms using Geographic Detectors. The results show that (1) from 2010 to 2020, the multifunctional structure of cultivated land in the study area underwent significant changes: the levels of agricultural production, social security, and ecological service functions first increased and then decreased, while the levels of cultural landscape function and comprehensive function continued to increase. The spatial distribution is characterized, respectively, by “high in the east and low in the west”, “high in the west and low in the east”, “high in the north and low in the south”, “high in the whole and sporadically low in the northeast”, and “high in the middle and low in the surroundings”. (2) During the study period, the trade-off strengths related to social security functions increased, while the trade-off strengths of the remaining multifunctional pairs of cultivated land showed a weakening trend, with high values of trade-off strengths among functions particularly prominent in the Nanping Municipal District. (3) Both natural and human factors significantly affect the multifunctional trade-off strength of cultivated land. Among the specific factors, elevation, slope, average annual temperature, and per capita GDP are the key factors influencing the strength of the trade-offs between functions. The results of this study provide empirical support for enriching the understanding of the multifunctionality of cultivated land and offer a decision-making basis for promoting the differentiated management of cultivated land resources and the synergistic development of its multifunctionality.

Keywords: multifunctional cultivated land; Min River basin; trade-off intensity; spatiotemporal evolution

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1. Introduction

Cultivated land provides a fundamental guarantee for human survival and socio-economic development [1]. For a long time, the grain production and employment-carrying functions of cultivated land have played a vital role in maintaining social stability [2]. However, with rapid urbanization, industrialization, and improved economic conditions, the demands on cultivated land have become more diverse. Traditional management practices that focus solely on the production function of cultivated land are increasingly inadequate to meet the growing and varied needs of the population [3]. As a result, the cultural heritage, ecological preservation, tourism, and recreational functions of cultivated land are gaining attention, highlighting its multifunctional nature. The intensified human–land relationship makes the multifunctional use of cultivated land a viable strategy to balance the needs for land protection with socio-economic development [4].

The concept of cultivated land multifunctionality, which originated from the idea of agricultural multifunctionality, can be traced back to studies of "rice culture" in Japan [5]. Research on multifunctionality has since expanded to include land use, ecosystem services, and rural development, following the categorization logic of agricultural multifunctionality [6]. Although there is no unified definition of the multifunctional connotation of cultivated land, it is widely accepted that cultivated land should satisfy diverse human needs, encompassing both natural and socio-economic attributes [7–15]. Accordingly, this study divides the multifunctionality of cultivated land into four categories—agricultural production, social security, ecosystem services, and cultural landscape functions—to comprehensively reflect its multiple values.

Due to significant differences in cultivated land resources, economic development levels, and management practices across regions, trade-offs often exist between different functions of cultivated land, while synergies can occur when multiple functions increase or decrease simultaneously [16,17]. Promoting the coordinated development of these functions can enhance the production, ecological, and social benefits of cultivated land use, offering new approaches for its protection. Qualitative research on the relationships between multifunctional coordination and trade-offs typically uses graphical methods, such as radar charts, full-array polygon maps, and rose diagrams [18]. Quantitative research often employs models like correlation analysis, linear regression, gray relational analysis, and principal component analysis to identify relationships between multifunctional aspects of cultivated land [19–21]. Some scholars also use scatter plots, power functions, and Pareto curves to explore nonlinear relationships between these functions [22,23].

Existing studies on the factors influencing cultivated land multifunctionality can be divided into two categories. The first focuses on interactions within single subsystems of cultivated land multifunctionality, particularly through studies on trade-offs, coordination, and coupling [17,24,25]. The second explores the driving mechanisms of external factors on the multifunctionality of cultivated land [26–28]. Factors such as natural location, population, and industrial dynamics during urbanization are common drivers of changes in cultivated land functions [29]. Under varying natural, geographical, social, and economic conditions, each function of cultivated land shows distinct distribution patterns. While many factors contribute to regional differences in cultivated land multifunctionality, the analysis of the internal functional relationships within these regions requires further exploration. Few studies have addressed the spatial differences and dynamic changes in the intensity of trade-offs between multifunctional aspects of cultivated land, and the analysis of the natural and socio-economic drivers of these trade-offs is insufficient.

As the "granary" of Fujian Province, the Min River basin's cultivated area accounts for 42.8% of the province's total and produces about 600 million kilograms of commercial grain annually, making it a significant representative of the main grain-producing areas in Southern China. However, understanding the multifunctionality of cultivated land in the Min River basin has historically been limited to its production function, with few studies examining its broader multifunctional aspects [30]. Therefore, this paper selects the Min River basin as a case study, constructing a multidimensional evaluation system for cultivated land multifunctionality—including agricultural production, social security, ecological services, and cultural landscape functions. We conduct an empirical investigation using multi-source data, analyze temporal and spatial characteristics through kernel density estimation and ArcGIS, and assess multifunctionality at the county scale using root mean square error (RMSE). Additionally, we examine the temporal and spatial changes in multifunctional trade-off intensity at the county level and quantify the driving factors behind these changes using geographic detectors. This research aims to provide a scientific basis and policy recommendations for optimizing cultivated land and implementing differentiated management of these resources.

2. Materials and Method

2.1. Overview of the Study Area

The Min River basin is located between 116°23′ E to 119°43′ E and 25°23′ N to 28°19′ N in the subtropical zone, characterized by a mild climate and abundant rainfall. The main river of the Min River is 541 km long, with a total river length of 2872 km and a drainage area of 60,900 km^2. Of this area, 59,000 km^2 is within Fujian Province, making up 98.2% of the basin's drainage area and nearly half of the province's total area of 122,000 km² (Figure 1). The basin is approximately 300 km wide from east to west and 300 km long from north to south, encompassing all of Sanming City and Nanping City, as well as parts of Ningde, Fuzhou, Quanzhou, Putian, Longyan, and other cities (see Table 1 for details). By the end of 2020, the basin's per capita cultivated land area was 0.0764 hectares, which is 1.78 times higher than the per capita cultivated land area of 0.0275 hectares in Fujian Province. In 2020, the total grain output of the basin was 3,596,930 tons, accounting for 71.61% of the province's total output, underscoring its importance as a key base for commercial grain production in the province.

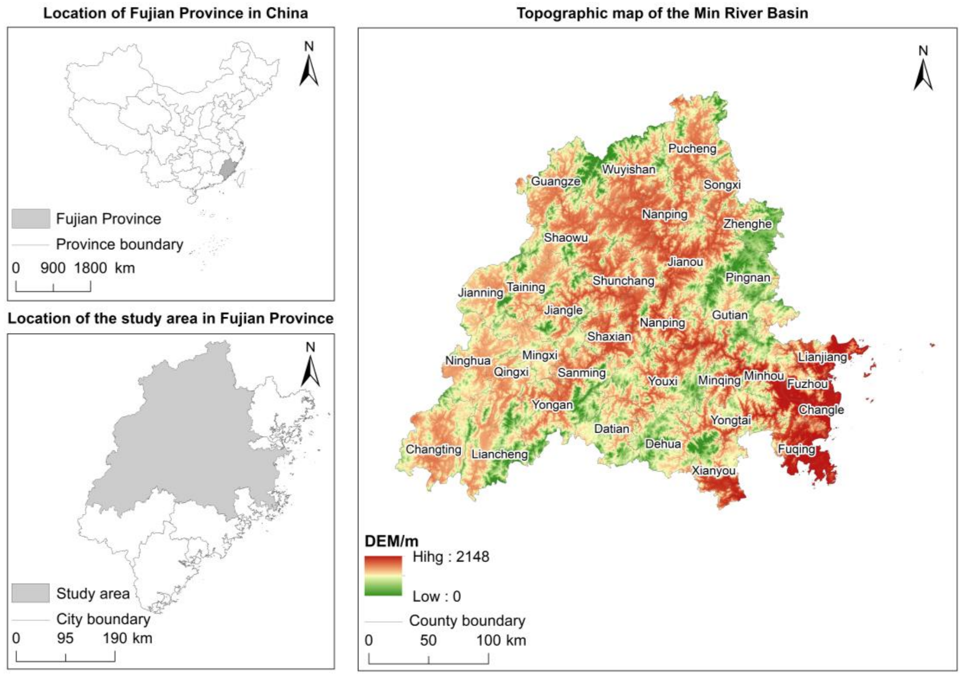

Figure 1. Geographical location of the study area.

Table 1. Distribution in the upper, middle, and lower reaches of the Min River basin.

Region	Number of Divisions/Units	Name of County Administrative Division
Upper Min River basin	20	Changting County, Pucheng County, Wuyishan City, Songxi County, Guangze County, Zhenghe County, Shaowu City, Shunchang County, Jian'ou City, Nanping City, Liancheng County, Jianning County, Taining County, will Le County, Sha County, Mingxi County, Sanming City, Ninghua County, Qingliu County, Yong'an City
The middle reaches of Min River basin	3	Datian, Gutian, Youxi counties
Lower Min River basin	10	Pingnan County, Dehua County, Minqing County, Minhou County, Yongtai County, Fuzhou City, Changle City, Fuqing City, Lianjiang County, Xianyou County
Total	33	

2.2. Data Resource

This paper selects 33 county-level administrative regions in the Min River basin as the research unit, including 26 counties, 3 municipal districts, and 4 county-level cities. The data used in this paper include land use data, meteorological data, and social and economic data. The land use data are from the Resources and Environmental Data Center, Chinese Academy of Sciences (http://www.resdc.cn (accessed on 29 June 2024)). Land use/cover is classified into six categories: cultivated land, forest land, grassland, water area, construction land, and unused land, according to the "Land Use/Land Cover Remote Sensing Monitoring Data Classification System" provided by the Resources and Environmental Data Center, Chinese Academy of Sciences. The precipitation and temperature data were generated based on spatial interpolation of the observational data of meteorological elements from the Data Center for Resources and Environment, Chinese Academy of Sciences (http://www.resdc.cn (accessed on 29 June 2024)). Elevation data are obtained from the geospatial data cloud (http://www.gscloud.cn (accessed on 29 June 2024)). All the statistical data are from the Fujian Provincial Statistical Yearbook and the Fujian Provincial Rural Statistical Yearbook from 2011 to 2021. Since the data of adjacent years of the above indicators are correlated and rarely have abnormal changes, the missing data of individual years are approximately obtained by trend extrapolation or the interpolation method. The data are from the Data Center for Resources and Environment, Chinese Academy of Sciences (http://www.resdc.cn (accessed on 29 June 2024).

2.3. Research Methods

2.3.1. Multi-Functional Index of Cultivated Land

Scholars have extensively researched the classification of cultivated land multifunction, but there is no unified standard in the academic community, leading to the formation of three primary classification systems [31]. The first system is based on the ecological functions of cultivated land, focusing on the ecosystem services it provides [32]. The second system classifies cultivated land functions according to human needs, emphasizing demand-driven aspects [33–35]. The third system is a comprehensive classification that divides the functions into economic, social, and ecological categories, considering the integrated supply and demand of cultivated land functions [36–38]. Despite differences in the definitions and classifications of cultivated land multifunction, the comprehensive classification system has gained widespread acceptance among scholars. Therefore, drawing on previous research, this study divides the multifunction of cultivated land into four categories: agricultural production, social security, ecosystem services, and cultural landscape functions.

The agricultural production function is the most basic function of cultivated land, ensuring a sufficient supply of agricultural products and promoting economic growth through development and utilization [39]. The economic value created by the production function is represented by the average agricultural output per unit of land, while the average grain yield per unit of land reflects the land's capacity to produce grain [40]. The cultivation rate and multiple cropping index indicate the degree of development and utilization of cultivated land and are positively correlated with its agricultural production function.

The social security function refers to cultivated land's capacity to support economic development, employment, and food security. Agriculture's contribution to GDP reflects the extent to which cultivated land use contributes to economic growth [41]. Higher per capita net income of farmers indicates greater revenue from cultivated land utilization. The proportion of employment in the primary industry measures the region's dependence on cultivated land for employment, reflecting its role in supporting rural livelihoods and providing social security. A higher index indicates a stronger social security function of cultivated land. The per capita grain possession reflects the ability of cultivated land to ensure food security in the Min River basin [42].

The ecosystem service functions describe the ability of the cropland system to deliver ecological goods or services. Crops contribute to carbon sequestration through photosynthesis, which mitigates the greenhouse effect by absorbing carbon dioxide and releasing oxygen. The carbon storage capacity of cropland is measured using the carbon storage module. Different habitat types affect biodiversity differently; habitat quality indicators can measure biodiversity support. Consequently, the habitat quality module is used to assess the impact of different land use types and quantify habitat quality, representing the ecological function of cropland. Research indicates that a higher proportion of paddy fields corresponds to increased biodiversity and a stronger function in maintaining ecological security [43]. Thus, the ecological advantage of cropland types is expressed by the proportion of paddy fields in the cropland area. To account for ecological pressure from population density, the number of people per unit of cropland area is used as an inverse indicator [44].

The cultural landscape function encompasses unique cultural resources characterized by regional attributes that are hard to replicate [45]. Urban residents seek leisure and recreation in suburban cultivated land, and the landscape's location and context influence the development of this function [46]. Due to the difficulty of obtaining precise data on the distance between cultivated land and transportation facilities such as airports and roads, rural road accessibility is used as a proxy to evaluate transportation support for cultural landscape functions. Well-developed transportation infrastructure is crucial for rural tourism development, allowing tourists to reach destinations efficiently. In terms of landscape attributes, contiguous and coherent cultivated land shapes are more conducive to landscape aesthetics. Thus, indicators such as the shape index of cultivated land, the degree of concentration [47], and the representational landscape conditions are selected, with classification criteria assigned based on relevant guidelines and data. Furthermore, leisure agriculture has emerged as a new form of industry and consumption, playing a significant role in promoting integrated rural development [48]. Therefore, the number of leisure agriculture demonstration sites established up to the current year is selected as an indicator of cultivated land's cultural development level (Table 2).

According to the cultivated land multifunctional evaluation index system, the range standardization method was used to standardize the original data, the entropy method was used to determine the index weight, and the linear weighting method was used to calculate the cultivated land multifunctional level in each province. The calculation method is as follows:

$$\mathrm{u_i} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{W_j Xij}' \tag{1}$$

In the formula, $\mathrm{X_{ij}}$ is the standardized value of the j-th evaluation indicator for the iii-th province; $\mathrm{W_j}$ is the weight of the jjj-th evaluation indicator; and $\mathrm{u_i}$ is the value of the cultivated land function for the iii-th province, ranging from [0, 1]. A higher value indicates a higher level of that specific cultivated land function.

2.3.2. Kernel Density Estimation

The primary advantage of kernel density estimation (KDE) is that it does not depend on prior knowledge of data distribution or require basic assumptions about parameter models. Instead, it uses continuous density functions to describe the spatial distribution characteristics and temporal evolution of variables directly from the data itself [49,50]. Consequently, this paper employs the kernel density estimation method, utilizing Eviews 8.0 software, to analyze the multifunctional stages and dynamic characteristics of cultivated land. The calculation method is as follows:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x_i - x}{h}\right) \tag{2}$$

where, n is the sample size; h is the bandwidth; x_i is the sample observation value; $K(\cdot)$ is the kernel function.

Table 2. Multifunctional index system of cultivated land.

Destination Layer	Criterion Layer	Index Level	Computing Method	Attribute
Multifunctional evaluation index system of cultivated land	Agricultural production function (AF)	Per capita grain output (X1)	Grain production/cultivated area	+
		Total agricultural output value per land (X2)	Total agricultural output value/cultivated area	+
		Land reclamation rate (X3)	Arable area/total land area	+
		Multiple cropping index (X4)	Total sown area of crops/total cultivated area	+
	Social security function (SS)	Contribution of primary industry to GDP (X5)	Output value of primary industry/Gross regional product	+
		Rural per capita net income (X6)	Per capita net income of farmers	+
		The carrying capacity of agricultural workers (X7)	Number of people employed in agriculture/rural population	+
		Per capita grain consumption (X8)	Total grain production/permanent population at the end of the year	+
	Ecological service function (ES)	Carbon storage (X9)	InVEST model	+
		Habitat Quality (X10)	InVEST model	+
		Ecological dominance (X11)	Paddy field area/arable area	+
		Population per unit of arable land (X12)	Population/arable area	−
	Cultural landscape function (CL)	Landscape Shape Index (X13)	Fragstats model	+
		Cultivated Land Aggregation Index (X14)	Fragstats model	+
		Road Accessibility (X15)	Rural road mileage/cultivated area	−
		Cultivated land cultural development level (X16)	Total number of leisure agriculture demonstration sites in the year	+

2.3.3. Root Mean Square Error

The concept of benefit equilibrium, as proposed by Bradfon [51], introduces the root mean square error (RMSE) as a measure to quantify the disparity between the value of a single function indicator and the average value of a multifunction indicator. This measure also represents the uneven rate of change in the multifunctionality of territorial space in the same direction. It intuitively expresses the spatial differences in the intensity of trade-offs between agricultural production, social security, ecological services, and cultural landscape functions. The *RMSE* value ranges from 0 to 1. A higher value indicates a stronger tradeoff intensity, whereas a lower value indicates a weaker trade-off intensity. RMSE is computed using the following formula:

$$RMSE = \sqrt{\frac{1}{n-1} \times \sum_{i=1}^{n} (CLF_i - CLF)^2} \tag{3}$$

where, CLF_i is the standard value of the i type of territorial spatial function, and cultural landscape F is the average value of territorial spatial function.

2.3.4. Geographic Detector

The geographic detector model is a statistical method used to detect the spatial stratification heterogeneity of dependent variables and reveal its driving mechanism. After revealing the spatial differentiation characteristics of cultivated land multifunctional trade-off, using the core factor detection of the geographic detector, the q statistic value was used to quantitatively reveal the interpretation degree of each variable X (influence factor) to the dependent variable Y (cultivated land multifunctional trade-off intensity) [36]. The following formula calculates q statistics:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \tag{4}$$

In the formula, h represents the layer of explanatory variables in the study area, N and N_h denote the number of observations for the entire study area and the h-th layer, respectively, while σ^2 and σ_h^2 represent the variance of the dependent variable Y for the entire study area and the h-th layer, respectively. The range of the q value is [0–1], with a q value closer to 1 indicating a higher degree of explanation of the dependent variable Y by the independent variable X.

3. Results and Discussion

3.1. Spatial and Temporal Pattern of Multi-Functional Evolution of Cultivated Land in the Min River Basin

According to the analysis of the proportion of each cultivated land function in the comprehensive functional species, as shown in Figure 2, the multifunctional structure of cultivated land in the Min River basin has significantly changed from 2010 to 2020. The cultural landscape function has consistently grown over this decade, with its proportion increasing markedly from 16.74% in 2010 to 30.45% in 2020. This growth reflects society's increasing recognition of the value of agricultural cultural heritage and natural landscapes, as well as a greater emphasis on the versatility of agriculture. Meanwhile, the proportion of agricultural production and ecological service functions has declined annually. The share of agricultural production functions decreased from 28.85% in 2010 to 26.13% in 2020, while the proportion of ecological service functions dropped from 20.78% in 2010 to 14.86% in 2020. These declines may be related to the reduction in cultivated land due to urbanization, the adjustment of agricultural structures, and the growing demand for ecological protection. The trend in the proportion of the social security function is more complex, showing a fluctuation of first decreasing and then rising, although the overall trend remains downward. In 2015, the proportion of social security functions reached its lowest point at 28.23%, while in 2010, it peaked at 33.63%. This change may be associated with socio-economic development, demographic shifts, and adjustments in social security policies. Among all functions, the social security and cultural landscape functions hold the largest proportions in comprehensive functions, suggesting that policymakers and land managers should prioritize these leading functions in regional development and thoroughly consider them in land use planning.

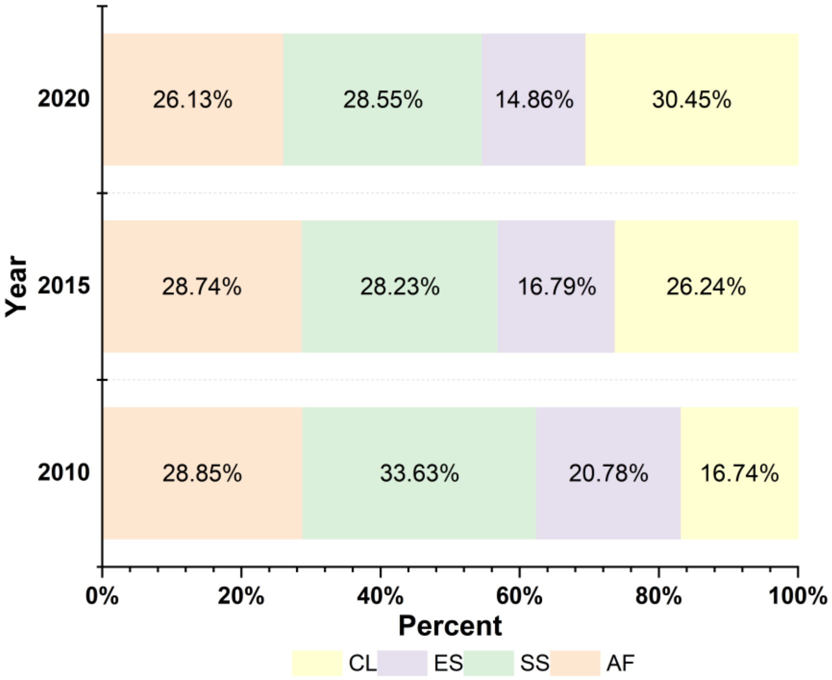

Figure 2. Multi-functional structure of cultivated land in the Min River basin from 2010 to 2020.

Based on the evaluation results of various functional levels of cultivated land, the kernel density curves of agricultural production, social security, ecological services, and cultural landscape functional levels of cultivated land in 2010, 2015, and 2020 were drawn (Figure 3). From the agricultural production function KDE curve, the center of gravity of the curve shifted first to the right and then to the left; the curve turned from a single peak to a multi-peak. The principal peak value increased, indicating that the agricultural production function level of cultivated land in the Min River basin increased first and then decreased during the study period. The agricultural production function of counties and cities showed a trend of multi-polarization, but the overall difference narrowed. From the social security functional kernel density curve, the center of gravity of the curve shifted first to the left and then to the right, constantly in a uni-peak state. The peak value continued to rise, indicating that the social security function level of cultivated land in the Min River basin declined and then increased. The gap between counties and cities narrowed during the study period. From the kernel density curve, the center of gravity of the curve did not shift significantly and remained a single peak. The peak height changed little, indicating that the level of cultivated land ecological service function in the Min River basin was stable during the study period. The ecological service function in the Min River basin converged to a unified equilibrium point. From the cultural landscape functional kernel density curve, the center of gravity of the curve gradually shifted to the right, the curve turned from an unimodal peak to a bimodal peak, and the height gradually decreased, indicating that the function level of the cultivated land cultural landscape in the Min River basin showed an overall upward trend during the study period. The cultural landscape functions of counties and cities gradually became multipolar, and the differences expanded.

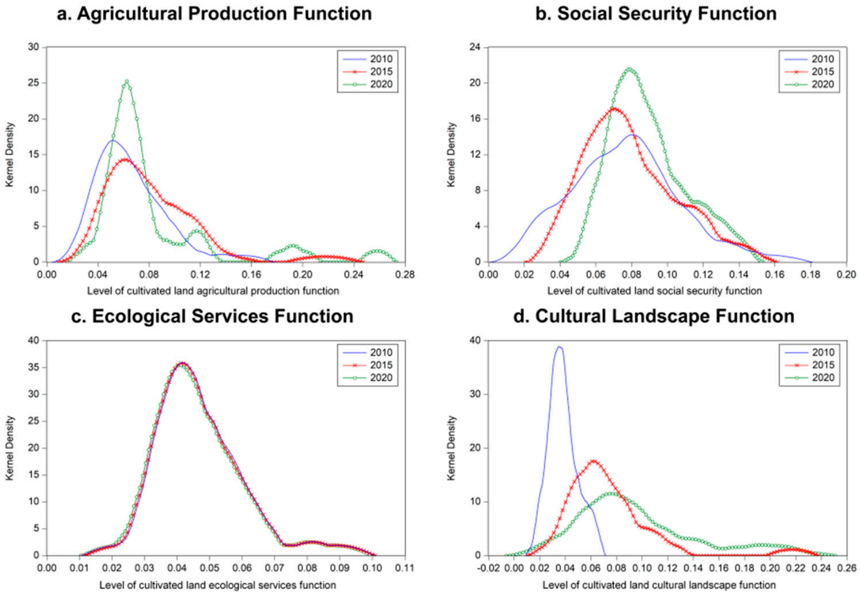

Figure 3. Temporal evolution characteristics of various functions of cultivated land in the Min River basin in 2010, 2015, and 2020.

In order to intuitively show the spatial distribution of each function, the ArgGIS natural break point method was used to divide the function into five levels, and the change rules of the comprehensive function of cultivated land, agricultural production function, social security function, ecological service function, and cultural landscape function of Min River basin in 2010, 2015, and 2020 were drawn, as shown in Figures 4 and 5. During the study period, the comprehensive function level continued to rise, and the number of high-level areas increased from 8 to 29, showing the distribution characteristics of "high in the middle and low around the periphery". The level of agricultural production function increased first. Then it decreased, but the overall level showed a slight increase. The middle-level regions increased from 7 to 13, showing a spatial disequilibrium pattern of "high in the east and low in the west". The social security function generally showed a fluctuating upward trend, with the number of low-level areas decreasing from 14 to 7 and the number of middle-level areas increasing from 10 to 14, with the characteristics of "high in the west and low in the east" as a whole. The ecological service function level change is relatively stable, and only one middle-level area in the east changes into a low-level area, showing the distribution characteristics of "high in the north and low in the south" on the whole. The functional level of the cultural landscape improved significantly, and the number of high-level areas increased from 12 to 31, showing the distribution characteristics of "overall high, scattered low in the northeast".

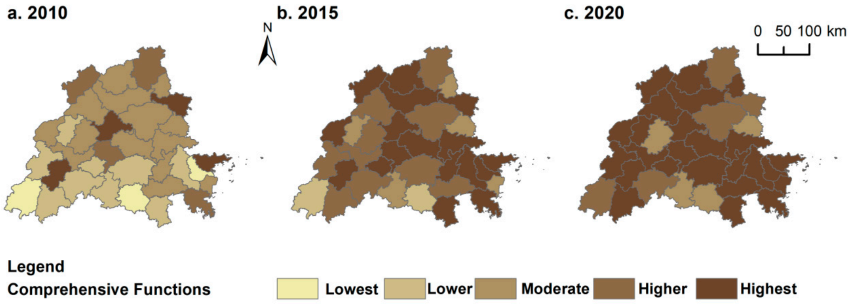

Figure 4. Spatial pattern of cultivated land comprehensive function in the Min River basin in 2010, 2015, and 2020.

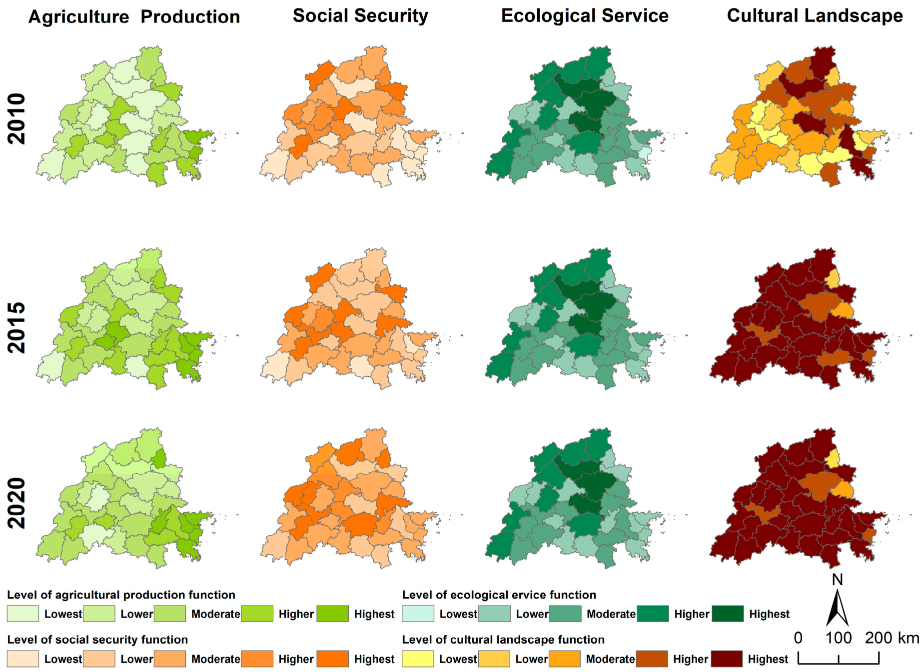

Figure 5. Spatial pattern of sub-functions of cultivated land in the Min River basin in 2010, 2015, and 2020.

3.2. *Analysis of Multifunctional Tradeoff Intensity of Cultivated Land in Minjiang River Basin*

Based on the RMSE model, the intensity of trade-offs between the multifunctionality of cultivated land in the Minjiang River basin for the years 2010, 2015, and 2020 was determined. From Figure 6, it is evident that the trade-off intensity related to social security functions has generally increased across all pairwise relationships, while the trade-off intensity for other cultivated land functions has shown a weakening trend. Notably, the trade-off intensity between agricultural production and cultural landscape has experienced the most significant decrease. Figure 7 illustrates the spatial distribution differences in trade-off intensity between the multifunctionality of cultivated land across the counties and cities in the Min River basin.

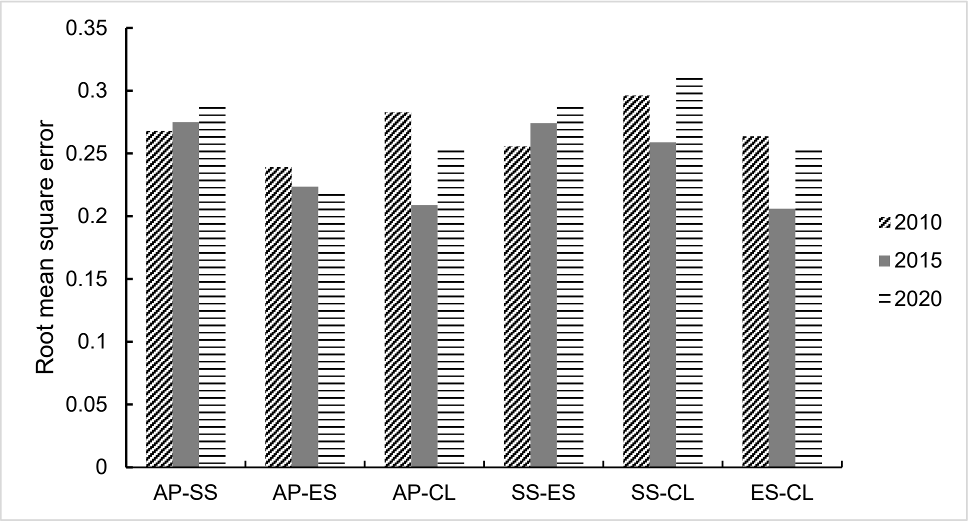

Figure 6. Average annual value of multifunctional trade-off intensity of cultivated land in 2010, 2015, and 2020.

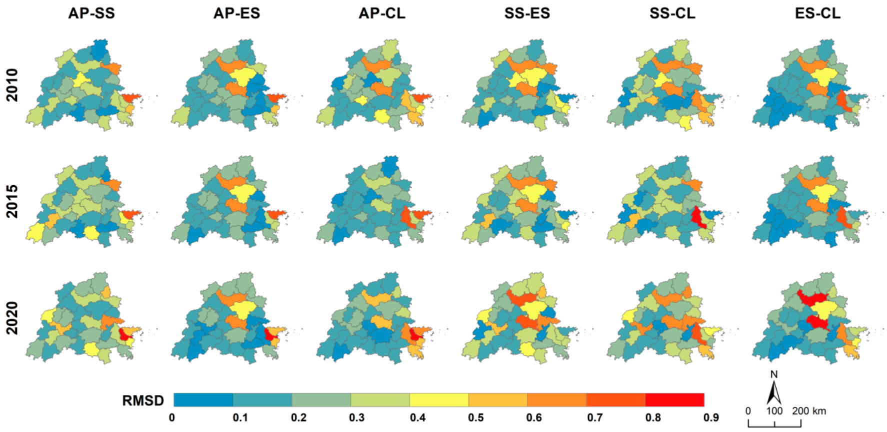

Figure 7. Spatial distribution of multifunctional tradeoff intensity of cultivated land in Minjiang River basin in 2010, 2015, and 2020.

Specifically, the trade-off intensity between agricultural production and social security, as well as between social security and ecological services, has increased year by year. This is primarily due to the rapid socioeconomic development of Fujian Province since 2010, following the approval and implementation of national strategies such as the "Opinions of the State Council on Supporting the Accelerated Construction of the Economic Zone on the West Coast of the Taiwan Strait" and the "Development Plan of the Economic Zone on the West Coast of the Taiwan Strait". The significant improvement in social security, coupled with the relatively slower growth in agricultural production and ecological services, has led to an imbalance in the development of these functions. The spatial distribution of these two trade-offs exhibits a "contraction of low-value areas and expansion of medium- to high-value areas", with the most pronounced effects seen in Sanming, Nanping, and Fuzhou.

The evolution of trade-off intensity related to the cultural landscape function follows a similar pattern, exhibiting a "U-shaped" trend. This can be attributed to the rapid economic development of Fujian Province after 2010, which spurred advancements in agricultural production technology and the enhancement of social security capabilities. Consequently, there has been a growing demand for cultural landscape functions, along with a greater emphasis on ecological awareness, which has contributed to the reduction in trade-off intensity related to cultural landscape functions. As residents' living standards continue to improve, there has been an increasing demand for leisure, tourism, and cultural experiences. This may prompt the government and various social sectors to re-evaluate the importance of cultural landscape functions and implement measures to further strengthen their development. Since the improvement in agricultural production, social security, and ecological services has been less pronounced than the improvement in cultural landscape functions, the trade-off intensity related to cultural landscape functions has increased after 2015. The spatial distribution of trade-off intensity associated with cultural landscape functions shows a clear polarization trend, with low-value areas concentrated in the southern and western regions, while high-value areas are concentrated in the central and eastern regions, particularly in the upstream Nanping area and downstream Fuzhou area. The trade-off intensity between agricultural production and ecological services shows a continuous decreasing trend.

This is likely due to the completion of regional infrastructure, shifts in agricultural development methods, and the implementation of ecological protection measures such as reforestation and wetland conservation during the "12th Five-Year Plan" and "13th Five-Year Plan" periods. These efforts have effectively promoted the coordinated development of agricultural production and ecological services, reducing the trade-off intensity between these functions. In terms of spatial distribution, a "higher in the north and lower in the south" pattern is observed.

3.3. Analysis of Influencing Factors of Multi-Functional Trade-Off Intensity of Cultivated Land in Min River Basin

Relevant studies have shown that multifunctional trade-offs result from the interaction between natural and human factors [36]. The spatial distribution of landscape and human activities is determined by natural factors such as elevation, slope, precipitation, and temperature. At the same time, economic development and urbanization levels lead to drastic changes in cultivated land use. The number of rural agricultural employees, expenditure on agriculture, forestry, and water affairs (X8), and cultivated land area (X9) are the most direct reflection of the interaction type and intensity of human activities in the process of cultivated land use, which directly affect the ecological processes such as material cycling, soil erosion, and biodiversity, resulting in the trade-off between the multiple functions of cultivated land. Therefore, in this paper, nine indexes, including elevation (X1), slope (X2), precipitation (X3), annual average temperature (X4), per capita GDP (X5), urbanization rate (X6), number of rural agricultural employees (X7), expenditure on agriculture, forestry, and water affairs (X8), and cultivated land area (X9), are selected as influencing variables from the aspects of natural factors and human factors. The spatial differentiation of functional trade-off intensity of agricultural production, social security, ecological services, and cultural landscape in the study area was investigated using the geographical detector model.

Different influencing factors affected the spatial differentiation of multifunctional trade-off intensity of cultivated land in different years (Figure 8). From the perspective of influencing factors, the spatial differentiation of agricultural production-social security, agricultural production-ecological services, agricultural production-cultural landscape, and ecological services-cultural landscape trade-off during the study period were most affected by natural factors, and the average q values were 0.4299, 0.4494, 0.3963, and 0.3769, respectively. The spatial differentiation of social security-cultural landscape and ecological services-cultural landscape trade-off was most affected by human factors, with average q values of 0.3392 and 0.3345, respectively.

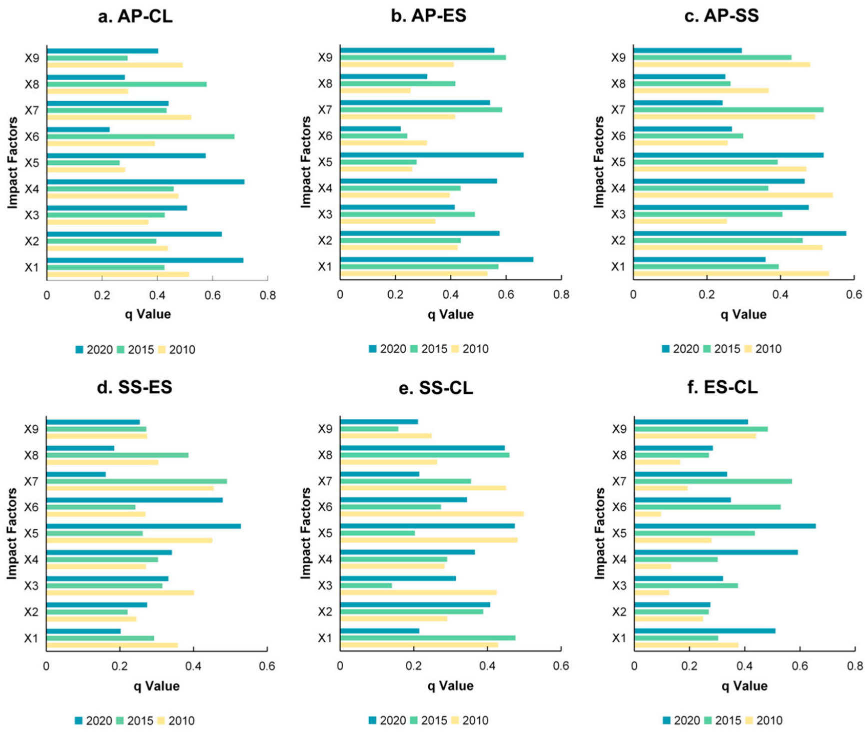

Figure 8. Detection results of factors affecting the intensity of multi-functional trade-off of cultivated land in the Min River basin in 2010, 2015, and 2020.

Specifically, precipitation and GDP per capita have a minor impact on the AP-CL trade-off, as they did not rank among the top three impact factors in 2010, 2015, and 2020. The dominant factors of this trade-off relationship were different in the three years. Namely, the number of rural agricultural employees, urbanization rate, and average annual temperature, and the corresponding q values were 0.5226, 0.6788, and 0.7153, respectively. For the AP-ES trade-off, the influencing factors include elevation, slope, per capita GDP, number of rural agricultural employees, and cultivated land area. In 2010, elevation was the dominant factor, while in 2015, the cultivated land area became dominant, and by 2020, the dominant factor changed again to elevation. The q values for these years were 0.5333, 0.5994, and 0.6989, respectively. Among the factors influencing the AP-SS trade-off, urbanization rate and expenditure on agriculture, forestry, and water affairs have little influence. In contrast, the leading factors in 2010, 2015, and 2020 are elevation, number of rural agricultural employees, and slope, whose q values are 0.531, 0.5173, and 0.5782, respectively. The dominant factor of the ES-CL trade-off relationship is cultivated land area in 2010, the number of rural agricultural employees in 2015, and per capita GDP in 2020, with q values of 0.4407, 0.5710, and 0.6575, respectively. The dominant factor of the SS-CL trade-off relationship is the urbanization rate in 2010, elevation in 2015, and per capita GDP in 2020, with q values of 0.4991, 0.4761, and 0.4746, respectively. The leading factor of the SS-ES trade-off relationship in 2010 and 2015 is the number of rural agricultural employees. In 2020, it turns into per capita GDP, with q values of 0.4546, 0.4911, and 0.5289, respectively. The influencing factors of cultivated land multifunctional trade-off are highly uncertain, and most of the leading factors change with time, which provides a new perspective for understanding the dynamics of cultivated land multifunctional trade-off.

3.4. Discussion

Cultivated land is a complex system resulting from the interaction between nature and humans, and its multifunctionality exhibits clear stage and regional differentiation. As a fundamental attribute of cultivated land, multifunctionality helps people understand the multidimensional impact of territorial space development on the sustainable development of regional social, economic, and ecological environments. For the well-being of human society and to balance the interests and needs of all stakeholders, it is essential to identify the multifunctions of regional cultivated land and explore the mechanisms and dynamic development of these functions to maximize the overall benefits of cultivated land. Therefore, this paper evaluates the multifunctional levels of cultivated land and their evolution over time and space. It further investigates the trade-off intensity between different cultivated land functions and explores the mechanisms behind the evolution of these trade-offs through the quantitative analysis of driving factors, enriching the understanding of cultivated land multifunctionality.

The research shows that the trade-offs between cultivated land functions in the Min River basin exhibit clear regional differentiation. The results indicate that interactions between different functions show spatial heterogeneity and dynamic changes over time due to the region’s unique social, economic, and natural ecological conditions. This finding aligns with the work of Xia H [52]. The average trade-off intensity between multifunctions of cultivated land in the Min River basin follows the pattern “SS-CL > AF-SS > SS-ES > AF-CL > ES-CL > AF-ES”, indicating a stronger trade-off between social and economic development and cultural landscape functions, particularly in highly urbanized districts. Over time, the trade-off intensity related to social security functions has increased, while the relationships among other cultivated land functions have weakened. This increase is mainly because Fujian Province, a region experiencing rapid social and economic development in Eastern China, has significantly improved its social security functions, whereas the development of other functions has lagged, similar to Shi T’s findings [53]. The weakening trend in the intensity of trade-offs among other functions is primarily attributed to the modernization of agriculture and the increase in ecological diversity. The “Action Plan for Scientific and Technological Innovation of Modern Agriculture with Characteristics of

Fujian Province (2015–2020)" has established a market-oriented system for scientific and technological innovation in modern agriculture that integrates industry, academia, and research. This plan provides scientific and technological support for the green transformation and upgrading of the agricultural sector in Fujian Province, promoting both the modernization of agriculture and ecological sustainability.

Regarding influencing factors, elevation, slope, and average annual temperature are key determinants of the agricultural production function. These factors constitute regional background conditions that fundamentally affect the agricultural production capacity of cultivated land. A suitable slope promotes soil moisture retention and ensures uniform distribution of light, while stable temperature conditions are beneficial for crop growth, thereby enhancing the primary production function. This finding is consistent with Han Z [54], further confirming the fundamental role of natural conditions in agricultural production. Additionally, per capita GDP is a significant influencing factor for the trade-offs between ecological service functions, cultural landscape functions, and social security functions, aligning with Liu Y's research results [36]. The increase in per capita GDP reflects not only the improvement of farmers' living standards and disposable income but also promotes the upgrading of the consumption structure of agricultural products, thereby stimulating farmers' enthusiasm for agricultural development. This helps increase investment in agricultural production, enhance the grain production capacity of cultivated land, and strengthen the social security function. However, as per capita GDP grows, some farmers may choose to settle in cities, leading to the transfer or abandonment of some cultivated land, potentially reducing the utilization level of cultivated land and restricting its overall functional development.

Based on the findings of this paper and the multifunctional realities of arable land across the basin and in each county and district, several strategic optimization suggestions for arable land use are proposed. The disparities in economic development levels, urbanization rates, and natural geographic conditions among counties and districts in the Min River basin have caused significant heterogeneity in the development and utilization of arable land. Therefore, a differentiated development strategy that emphasizes locally advantageous functions should be constructed according to local conditions. Scientific and reasonable arable land planning should be formulated to optimize the layout and structure of arable land in the Min River basin, fully leveraging the unique advantages of arable land resources in each region. This approach aims to promote diversified and coordinated agricultural development and achieve a strategic shift from quantity growth to quality enhancement. Additionally, improving soil quality, adjusting land slope suitability, and optimizing irrigation and drainage systems can reasonably enhance the natural conditions of arable land, increase utilization efficiency and output benefits, and refine arable land management. These measures enable more intelligent decision-making, thereby enhancing the economic and social value of arable land. Furthermore, the legal protection and regulatory mechanisms for arable land should be strengthened to strictly limit the encroachment of non-agricultural construction on arable land, thereby maintaining the total quantity and quality of arable land. At the same time, efforts should be made to strengthen the ecological restoration and environmental management of arable land to promote the synergistic development of its multifunctionality, providing solid support for sustainable agricultural development and the overall progress of the social economy.

4. Conclusions

In this paper, multi-source data—including socio-economic, land cover, and meteorological data—were integrated to evaluate the multifunctionality of cultivated land in 33 county-level administrative regions of the Min River basin from 2010 to 2020. The multifunctionality was assessed across four dimensions: agricultural production, social security, ecological services, and cultural landscape. Kernel density estimation and visual mapping were employed to describe the spatio-temporal changes in these functions. Additionally, the root mean square error (RMSE) model was used to analyze the evolution of the multifunctional trade-off intensity of cultivated land over time. Key driving factors behind these trade-offs were identified using a geographic probe model, providing empirical evidence for regional cultivated land management and supporting the integration of multifunctional trade-offs in national spatial planning. This study holds significant theoretical and practical value. The main conclusions are as follows:

(1) From 2010 to 2020, the multifunctional structure of arable land showed notable temporal changes, with the agricultural production function initially rising and then declining, the social security function decreasing before increasing, the ecological service function remaining stable, and both the cultural landscape function and overall multifunctionality continuing to rise. Spatially, the functions displayed distinct patterns: agricultural production was "high in the east and low in the west", social security was "high in the west and low in the east", ecological services were "high in the north and low in the south", cultural landscape was "overall high in the north and low in the south", and the comprehensive function was "overall high in the west and low in the south.

(2) From 2010 to 2020, the average trade-off intensity related to social security functions increased over time while trade-offs among other multifunctions weakened. The trade-offs between agricultural production and social security, as well as between social security and ecological services, intensified annually. The spatial distribution of these trade-offs showed a pattern of "low-value areas shrinking, middle and high-value areas expanding", especially in Sanming City, Nanping City, and Fuzhou City. Trade-off intensities related to cultural landscape functions exhibited a U-shaped trend, with a polarized spatial distribution: low-value areas concentrated in the south and west, and high-value areas in the middle and east, particularly in Nanping City and Fuzhou City. The trade-off intensity between agricultural production and ecological services showed a declining trend with a spatial pattern of being "high in the north and low in the south".

(3) The multifunctional trade-off intensity of cultivated land was significantly influenced by both natural and human factors, with different factors driving different spatial patterns of trade-offs. Natural factors most strongly affected the spatial differentiation of trade-offs between agricultural production and social security, agricultural production and ecological services, agricultural production and cultural landscape, and ecological services and cultural landscape. In contrast, socio-economic factors primarily influenced the trade-offs between social security and cultural landscape, as well as between ecological services and cultural landscape. Among the specific influencing factors, elevation, slope, and average annual temperature were critical for agricultural production functions, while per capita GDP was a key factor in the trade-offs among other functions.

This paper investigates the mechanisms driving the spatio-temporal evolution and trade-off intensity of cultivated land multifunctionality. However, it does not fully capture the coupling effects of cultivated land systems under the influence of complex internal and external factors. Future research should further explore the nuanced development needs and functional supply of cultivated land within multi-ecological societies. Additionally, due to data limitations, some evaluation indicators used in this study require refinement. For instance, using the number of leisure agriculture demonstration sites as a quantitative indicator may not accurately reflect the development level of the cultural landscape function in regional cultural landscape resources. Subsequent studies should leverage big data to deepen the exploration of cultivated land's cultural landscape functions.

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