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Optimizing land-use zonation in coastal areas: revealing the spatio-temporal patterns and trade-off/synergy relationships among farmland functions

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Under the interaction between natural ecosystems and human interferences, farmland extends to multi-functions such as production, ecological, social, and cultural functions. Despite the exponential increase in research on the multi-functional evaluation of farmland in recent years, little study has been conducted at fine spatial and long-time scales. Furthermore, the existing quantitative analyses of multifunctional synergies and trade-offs in farmland mainly consider static spatial patterns and neglect dynamic information. Selecting the Chinese coastal province of Zhejiang as the study area, this study thus evaluated the spatio-temporal patterns of farmland functions from 2000 to 2020 at the county scale and introduced the trade-off/synergy degree (TSD) model to quantify the intensity of the relationships among functions. The results showed that farmland functional values and their relationships were significantly heterogeneous in spatial and temporal distribution. In addition to social function, the other functions all exhibited an increasing trend. Furthermore, strong correlations were mainly observed between production, ecological and cultural functions. Ultimately, five farmland zones were determined by the k-means clustering algorithm and considering both functional values and their relationships, and targeted suggestions applicable to each zone were put forward in this study. This study contributes to the utilization and planning of farmland and its surrounding land, especially to the improvement of the policy of returning farmland to forests.

KEYWORDS
multi-functions, spatio-temporal patterns, trade-off/synergy, zonation, farmland

1 Introduction

In the past decades, the area of farmland increases partly by damaging forests, causing a series of issues, such as ecological stability damage (Yao et al., 2022). In order to effectively improve the quality of ecological environment construction, the Chinese government has proposed the construction of the project of returning farmland to forest. In the other side, due to the food scarcity issues, there is also a need to increase the area of farmland for food production. Therefore, it is crucial to balance the use of farmland and forests in a coordinated manner.

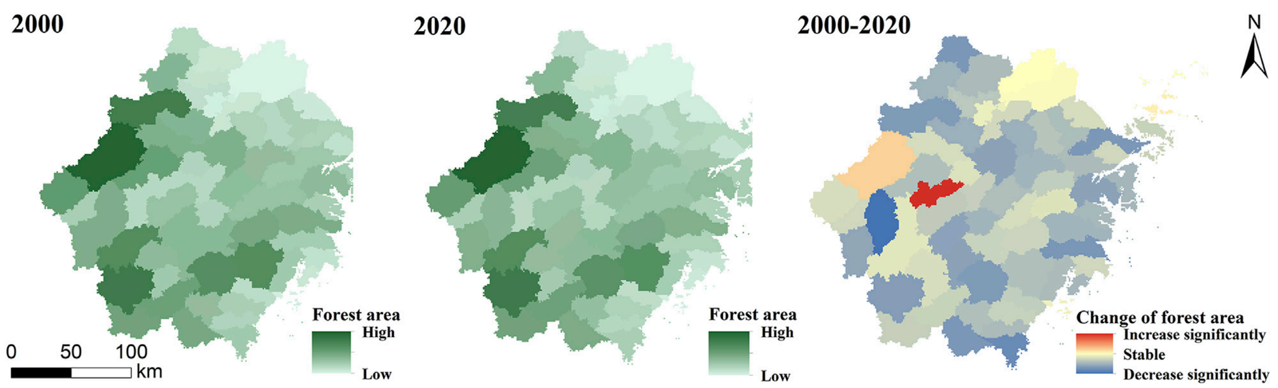

FIGURE 1
Spatiotemporal variations of forest area in Zhejiang Province during 2000 and 2020.

Farmland is the material basis for human survival (Heyang et al., 2022). However, rapid socioeconomic development has put increasing pressure on farmland conservation in some developing countries (Deng et al., 2015). For example, China's urbanization rate is up to 60.6% by 2020. Correspondingly, due to urbanization, agricultural restructuring, ecological retreat, etc., the farmland area of China has decreased by 2 million hectares from 2000 to 2020. It is evident that farmland requires to be protected urgently in order to maintain its sustainable utilization.

Nowadays, with changing lifestyles and consumer attitudes, the diverse demand of residents for farmland is becoming increasingly evident (Jia et al., 2022). As a result, farmland has evolved from having only one production function to having production, ecological, social, and cultural functions coexist (Sinan et al., 2023). In 2020, Chinese farmland provided 664 million tons of food, ensuring the livelihood of 564 million rural residents, and contributed 6% of the ecosystem service value, which reflects the significant multifunctionality of farmland. Within this context, the problems of farmland conservation, such as uncontrolled competition for demand, marginalization, and degradation of farmland ecosystems, are also becoming increasingly severe (Zhu et al., 2021). To solve the ecological destruction of farmland, environmental pollution and other problems caused by irrational use of farmland, the Chinese government has attached great importance to the farmland issue, put forward the concept of "green development," resolutely halted the "non-grain" production of farmland, and suggested that farmland be moderately returned to forests or forests be returned to farmland, etc. (Ziyue et al., 2022). Thus, multimodal management of farmland conservation is vitally needed. For areas where ecological damage has been caused by irrational and extensive farmland use, there is an urgent need to carry out environmental protection projects, like returning farmland to forest.

In terms of the concept of farmland's multifunctionality, its classification has become increasingly abundant as people have gained an in-depth awareness of the farmland's functions (OCDE, 2001). For instance, the OECD (Organization for Economic Co-operation and Development) provides a definition of agricultural multifunctionality, stating that farmland systems possess various capacities and fulfill functions such as food production, landscape maintenance, ecological conservation, and rural employment security (Winfried and Warkentin, 2006). Chinese scholars have also defined farmland's multifunctionality as meeting multiple human needs, encompassing crop production, ecological environment, urban spatial barrier, cultural leisure, and social security functions, among others (Katharina Helming, 2020). Generally, scholars recognize four main categories to summarize the multifunctionality of farmland: production, ecological, social, and cultural functions, influenced by the growing spiritual needs, evolving consumption concepts of residents, and emerging ecological issues (Andreas et al., 2019). Of particular note, in 2018, the "Opinions on the Implementation of the Rural Revitalization Strategy", a document of the "Central Government No. 1″, pointed out that the countryside should be tapped into multi-functions and value of the countryside, building a number of leisure and tourism parks with diverse functions, focusing on the synergy and relevance, and support the comprehensive revitalization of the countryside (Zhu et al., 2021). The cultural function has garnered increased attention due to the thriving development of rural tourism in China (Yu et al., 2023).

Presently, research on the multifunctionality of farmland primarily focuses on conceptual classification, value evaluation, conservation policies, and management strategies (Bostian and Herlihy, 2014; Chen et al., 2016). The multifunctions of farmland are the outcome of intricate interactions between the natural environment and human society, resulting in explicit spatial and temporal heterogeneity in its functions (Pu et al., 2022). Conducting spatiotemporal analysis can facilitate a more comprehensive understanding of changes in farmland's multifunctionality, thereby providing suitable management recommendations to stakeholders. However, studies exploring the dynamics of spatial and temporal patterns based on long-term data series are scarce. Additionally, the majority of recent studies have employed administrative districts as the evaluation unit for their research scope (Zhang et al., 2018; Junna et al., 2022). Multifunctional studies of farmland at the provincial level typically select municipalities as the smallest study unit, neglecting detailed information at the county scale (Fan et al., 2018). This limitation hinders the comprehensive exploration of functional variations in farmland and the

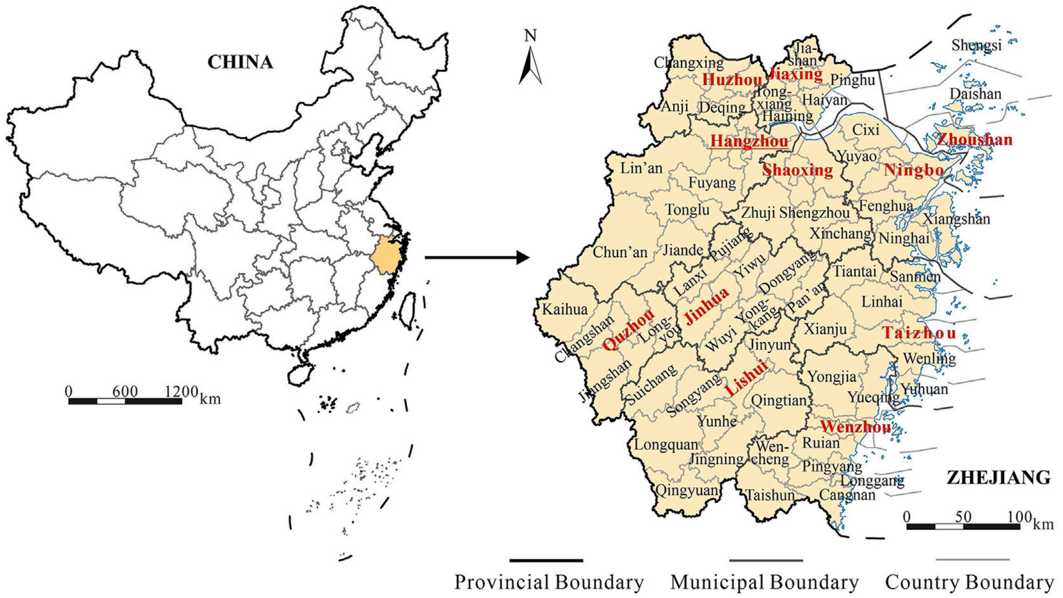

FIGURE 2
Location of Zhejiang province in China.

development of targeted conservation management strategies at the local level.

Besides spatiotemporal variability, the diverse functions of farmland often interact in complex ways due to the uneven spatial distribution and selectivity of human activities (Yang and Hu, 2022). These interactions can manifest as mutually beneficial synergies, where an increase in one function promotes an increase in another, or as antagonistic trade-offs, where an increase in one function results in a decrease in another. For instance, agricultural machinery and equipment inputs can enhance agricultural output, contributing to economic development and social functions (Xigui et al., 2022). However, excessive application of pesticides and fertilizers, while improving farmland yield, may have detrimental effects on the ecological function (Su et al., 2014). Hence, integrating these interconnections is crucial in the multifunctional assessment of farmland to minimize unfavorable trade-offs and maximize its compound advantages. However, most studies on multifunctional synergies and trade-offs in farmland have primarily relied on qualitative analysis (Qiao et al., 2019). Existing quantitative analyses mainly focus on spatial information, neglecting temporal dynamics (Leh et al., 2013). To comprehend the impact of dynamic natural and socioeconomic factors on the multifunctionality of farmland within a specific timeframe and quantify spatiotemporal variations in the strength of synergies and trade-offs, this study aims to employ trade-off/synergy degree (TSD) analysis (Zhao and Li, 2022).

The rapid development of urbanization and the need for large-scale construction land is usually at the expense of forest and farmland area. Zhejiang Province is one of the typical cities with rapid urbanization, has experienced a significant reduction in forest land area in most of its regions from 2000 to 2020 (Figure 1). Moreover, Zhejiang Province has also faced a sharp contradiction between urban development and farmland protection. Thus, it urgently needs to adapt its farmland management into multifunctional management, which can satisfy residents' diverse demands and ensure deep and targeted conservation and utilization of farmland and forests resources. According to the challenges mentioned above, this study thus takes Zhejiang Province as the research area to evaluate farmland's multi-functions (production, ecological, social, and cultural functions) from 2000 to 2020 at county scale: 1) assessing the spatial and temporal patterns of diverse functions; 2) further analyzing the spatial patterns of synergistic or trade-off relationships (qualitative and quantitative) between these functions; 3) through a spatial clustering analysis of multifunctional values and synergistic or trade-off intensity among various functions of farmland, finally proposing referenced suggestions for the sustainable management, planning, and decision making of farmland and its surrounding land (especially forest land) resources.

2 Materials and methods

2.1 Study area

Zhejiang Province (Figure 2) is located in the Yangtze River Delta on China's southeast coast (118°01′–123°10′E and 27°02′–31°11′N). It covers 105,500 square kilometers in total. Among them, it covers a predominantly mountainous area with fewer plains. Forests comprise 61% of the total area, while farmland accounts for only 11.92%. One of the most developed provinces in China, Zhejiang Province has 11 prefectural-level administrative regions, an urbanization rate of 72.7%, and a *per capita* GDP of 100,700 yuan. Under the context of the rural revitalization strategy in China, rural tourism in Zhejiang Province has grown rapidly with an operational revenue of 46.94 billion yuan, its rural visitors made up 65% of all visitors to the province in 2020.

TABLE 1 Evaluation index system of farmland's multi-functions.

Functions	Indicators	Calculation methods	Units	Weights	Indicator direction
Production function	The unit output of grain crops	Grain yield/sown area of grain crops	kg/hm^2	0.2513	+
	The unit yield of cash crops	Output of cash crops (vegetables and oil plants)/sown area of cash crops	kg/hm^2	0.7487	+
Ecological Function	Use intensity of agricultural chemicals	[pesticide application amount + chemical fertilizer application amount (converted into pure) + agricultural film application amount]/farmland area	kg/hm^2	0.0458	−
	Road Network Density	(highway mileage + railway mileage)/total land area	-	0.0709	−
	Farmland ecosystem diversity	-Σbi× Lnbi (bi is the ratio of the sown area of various crops); Among them, crops are divided into food crops, oil crops, vegetables, fruits, and other crops	-	0.0586	+
	Ecological dominance of farmland type	Paddy field area/total farmland area	%	0.8247	+
Social Function	Food Self-Sufficiency Ratio	Grain output/(resident populationx400 kg)	%	0.2501	+
	Agricultural employment rate	Agricultural population/total agricultural population	%	0.1220	+
	Agricultural contribution rate	Agricultural output value/GDP	%	0.4889	+
	Income equity	Per capita disposable income of rural residents/*per capita* disposable income of urban residents	-	0.1390	+
Cultural Function	The average number of rural tourists	Number of rural tourists/farmland area	$people/hm^2$	0.7771	+
	Urbanization level	Non-agricultural population/permanent resident population	%	0.2229	+

Over the past two decades, ecological damage has been caused by the behavior of increasing the area of farmland through the destruction of forests. At the same time, with the growth of metropolitan areas, the conflict between farmland conservation and urban development has grown more obvious. The production and ecological function of farmland are under extreme pressure due to the rising popularity of rural tourism and the unwarranted promotion of urbanization. Moreover, the management and use of farmland are severely hampered by the demand for land from rural tourism. In context with this, it is vital to evaluate farmland's multifunctionality and investigate appropriate management and utilization methods to ensure its sustainable development in Zhejiang Province.

2.2 Data collection and pre-processing

Multi-sourced natural geographic and statistical data for 2000 and 2020 were used in the present study. Among them, the natural geographic data (farmland area, district area, etc.) were obtained from the Resource and Environmental Science Data Center (RESDC) (http://www.resdc.cn) The statistical datasets include economic data (GDP, *per capita* disposable income, etc.), demographic data (agricultural population and resident population, etc.), and agricultural data (grain production and fertilizer application, etc.). The Zhejiang Statistical Yearbook was used to compile the aforementioned information for each county in Zhejiang Province. (2000 and 2020).

All the aforementioned datasets were vectorized, normalized, and further analyzed in ArcGIS software (ESRI Inc., Redlands, CA, United States of America). The maximum-minimum difference normalization approach was used to normalize the raw data in order to eliminate the variations in scale between each indicator. which was shown as follows:

$$Positive\ indicator:\ x_{i,j}^{t'} = \frac{X_{i,j}^{t} - min(x_j)}{max(x_j) - min\ (x_j)} \quad (1)$$

$$Negative\ indicator:\ x_{i,j}^{t'} = \frac{max(x_j) - X_{i,j}^{t}}{max(x_j) - min\ (x_j)} \quad (2)$$

Where: $X_{i,j}^{t}$ indicates is the j-th indicator of the i-th county in the t-th year, $x_{i,j}^{t'}$ is the standardized value of $X_{i,j}^{t}$, max (x_j) and min (x_j) are the maximum and minimum values of the j-th indicator in all of the counties and years.

2.2.1 Analysis of the spatial and temporal patterns of farmland's multi-functions

1. Establishing the evaluation index system

The present study established an integrated evaluation index system to reveal the spatiotemporal patterns of the multifunctionality of farmland. (Table 1). Within the index system, four types of functions, including productive, social, ecological, and cultural functions, were determined by respective indicators.

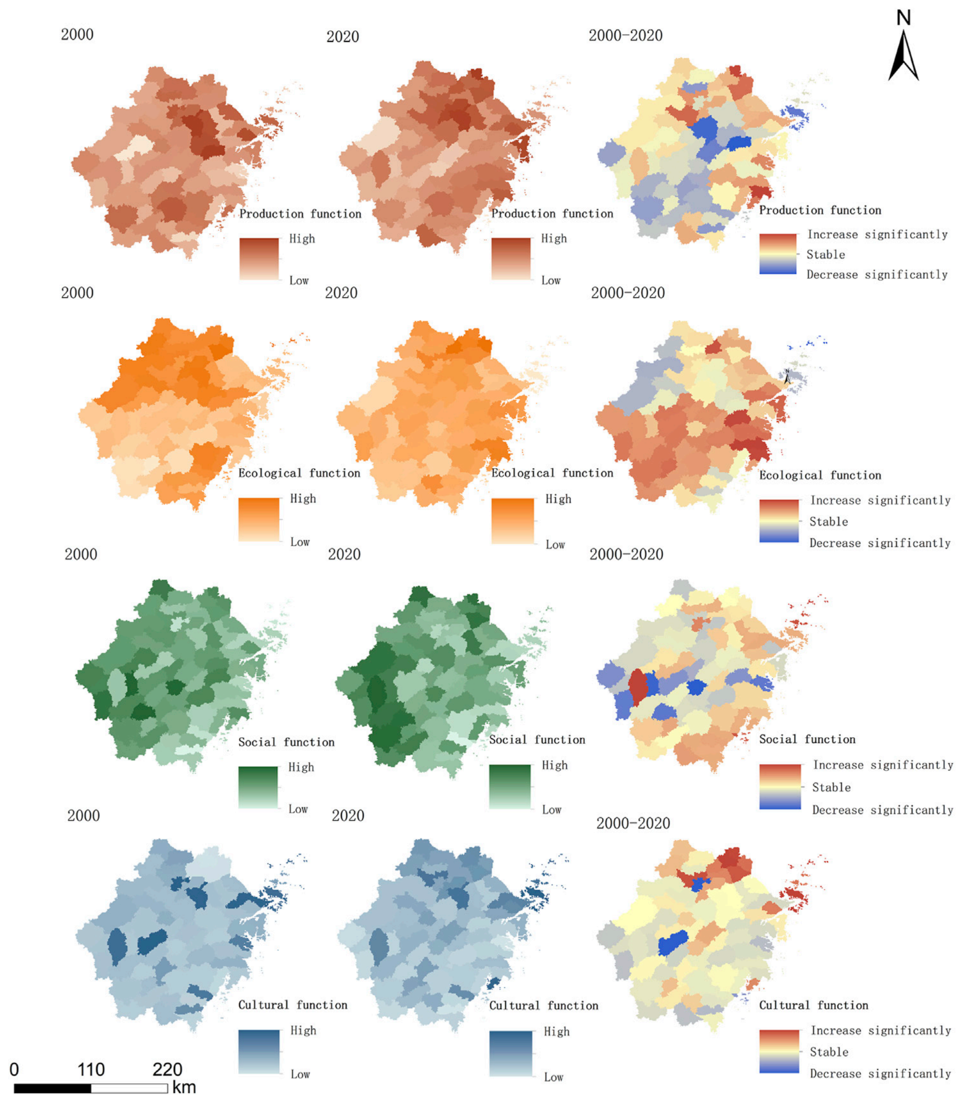

FIGURE 3
Spatiotemporal variations of multi-functions of farmland in Zhejiang Province during 2000 and 2020.

Production is the basic function of farmland (Qianwen et al., 2017). This study refers to the capacity that farmland can produce commercially productive food crops, oilseeds, vegetables, and other economic crops. Both the unit output of grain crops and the unit yield of cash crops (Xuelin et al., 2021) indicators were used to evaluate the production function of farmland due to the large percentage of cash crops grown in the metropolitan region.

Farmland's capacity to maintain water and soil, enhance the ecosystem, and sustain biodiversity is reflected in its ecological function (Su et al., 2017). Previous research has revealed that paddy fields demonstrate greater biodiversity and stronger ecological benefits compared to other types of farmland use (David et al., 2002). Furthermore, human interference of high intensity can somewhat impact the stability of agricultural ecosystems. Consequently, this study chose indicators such as the dominance of paddy fields (represented by the percentage of paddy fields), ecosystem diversity, environmental safety (measured by the intensity of pesticide, fertilizer, and agricultural film use), and road network density to assess the ecological function of farmland. Among these indicators, the international safe fertilizer application standard of 225 kg/hm^2 was adopted as a reference for safe fertilizer usage.

Farmland's social function includes providing livelihood and employment security for farmers (Song and Ouyang, 2012). The food self-sufficiency ratio, among the four related metrics, reflects how effectively regional farmland can guarantee food security for the regional population. The income equity of urban and rural residents indicates the income gap between urban and rural residents. It guarantees an economic income for farmers by using farmland. The agricultural employment ratio and agricultural contribution ratio reflect the level of social stability guaranteed by farmland in terms of both output and income respectively. Farmland plays a significant role in ensuring livelihood and employment security for farmers (Song and Ouyang, 2012). The food self-sufficiency ratio, one of the four relevant metrics, is an indicator of how effectively regional farmland can ensure food security for the local population. The

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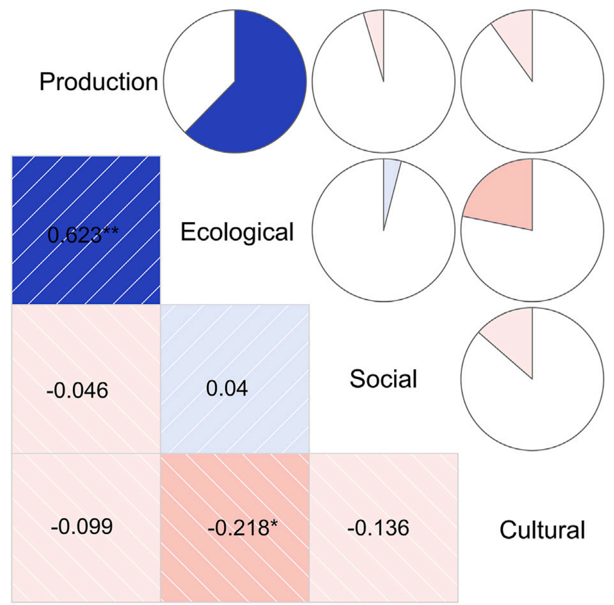

FIGURE 4
Correlations between functions of farmland calculated by Spearman's rank correlation analysis. Note: * and ** respectively denote p < 10% and p < 1%; blue indicates positive correlation and red indicates negative correlation; the darker the color, the stronger the correlation.

income equity between urban and rural residents serves as a measure of the income disparity between these two groups. It aims to ensure a sustainable economic income for farmers through the utilization of farmland. The agricultural employment ratio and agricultural contribution ratio are indicators that reflect the level of social stability provided by farmland in terms of both output and income (Jia et al., 2022).

Cultural function refers to the ability of farmland to meet human spiritual needs as a site for aesthetics and recreation (Jiang et al., 2020). People's pursuit of a spiritual and civilized existence has increased as urbanization has progressed. Also taking into account that rural tourism and cultural function are extremely associated, this study selected the average number of tourists from rural areas and the level of urbanization to illustrate the cultural function of farmland (Yue et al., 2022).

2. Determining the weights of indicators

We used the entropy approach to calculate the weights of indicators in order to reduce the impact of subjective elements during the evaluation procedure. To evaluate and standardize the metrics, all 71 counties in Zhejiang Province were chosen. The equation reads as follows:

$$ri = xi \Big/ \sum_{i=1}^{n} xi \tag{3}$$

$$ei = \frac{1}{lnm} \sum_{i=1}^{n} ri * lnri \tag{4}$$

$$gi = 1 - ei \tag{5}$$

$$wi = gi \Big/ \sum_{i=1}^{n} gi \tag{6}$$

Where wi is the entropy weight of the indicator i; gi is the dispersion coefficient of the ith indicator; ei is the entropy value of the ith indicator; n is the total number of evaluation units; m is the number of secondary indicators.

3. Calculating of multi-functions of farmland

According to the following formula, the multi-functions of farmland in 71 counties in Zhejiang Province were assessed in 2000 and 2020, respectively, using standard values and weights of the indicator data:

$$F_i = \sum_{j=1}^{m} w_j * x_{i,j}^{t'} \tag{7}$$

Where F_i is the evaluation value of the function i; w_j is the weight of indicator j; $x_{i,j}^{t'}$ is the standard value of indicator j.

Finally, to visualize the geographical patterns of each function across landscapes, values of each function of farmland were classified into five classes, ranging from low to high, using the natural breaks classification method. Additionally, we calculated the change value (β) of each function between 2000 and 2020 and divided them into five cases (decrease significantly, $\beta \le -0.3$; decrease, $-0.3 < \beta \le -0.1$; stable, $-0.1 < \beta \le 0.1$; increase, $0.1 < \beta \le 0.3$; increase significantly, $\beta \ge 0.3$) to further explore the spatio-temporal variations of various functions of farmland.

2.2.2 Evaluation of synergistic or trade-off relationships between multi-functions of farmland

Firstly, the relationships between the multi-functions of farmland were characterized using Spearman's rank correlation analysis. A positive or negative correlation coefficient indicates a synergistic or trade-off relationship, respectively, between the two functions of farmland. This correlation analysis was conducted in SPSS 22.0 and visualized in R (Jia et al., 2022).

Secondly, the value of trade-off/synergy degree (TSD) (Zhao and Li, 2022) was employed to qualitatively and quantitatively examine the interactions in this study in order to better investigate the geographical distribution characteristics of synergy and trade-offs between functions. The principle of this index is to determine whether the relationship between functions changes in a specific period, and if the product of the changes in two functions is >0, it indicates a synergistic relationship. Otherwise, the two functions show a trade-off relationship. Moreover, its absolute value reflects the strength of the synergistic or trade-off relationships (Eqs 8, 9).

$$TSDi - j = \begin{cases} 0 \quad \left(\Delta F_{i,t2-t1} * \Delta F_{j,t2-t1} = 0\right) (\text{no relationship}) \\ \sqrt{\left(\left(\Delta F_{i,t2-t1}\right)^2 + \left(\Delta F_{j,t2-t1}\right)^2/2\right.} \left(\Delta F_{i,t2-t1} * \Delta F_{j,t2-t1} > 0\right) (\text{synergies}) \\ -\sqrt{\left(\left(\Delta F_{i,t2-t1}\right)^2 + \left(\Delta F_{j,t2-t1}\right)^2/2\right.} \left(\Delta F_{i,t2-t1} * \Delta F_{j,t2-t1} < 0\right) (\text{trade} - \text{off}) \end{cases} \tag{8}$$

$$\begin{cases} \Delta F_{i,t2-t1} = \left(F_{i,t2} - F_{i,t1}\right)/F_{i,t1} \\ \Delta F_{j,t2-t1} = \left(F_{j,t2} - F_{j,t1}\right)\Big/F_{j,t1} \end{cases} \tag{9}$$

Where $\Delta F_{i,t2-t1}$ and $\Delta F_{j,t2-t1}$ are the relative changes in F_i and F_j between the time point t1 and t2 respectively; $F_{i,t1}$ and $F_{i,t2}$ represent the value of Fi at time point t1 and t2 respectively; $F_{j,t1}$ and $F_{j,t2}$ represent the value of Fj at time point t1 and t2 respectively.

2.2.3 Comprehensive clustering analysis of functional and relationships values

This study conducted a spatial clustering analysis to incorporate the multi-functional values and the relationships between diverse functions into a farmland zoning program, which could offer new insights into differentiated farmland protection. The aims of this study were to achieve differentially optimized management of farmland, eliminate or weaken the undesirable trade-off relationship, and promote the coordinated development of diverse functions. Firstly, we assigned values from 1 (six pairs of trade-off relationships) to 7 (six pairs of synergistic relationships) to conduct a relationship indicator (RI), representing the relationships between diverse functions (six pairs of functions in total). Secondly, the k-means clustering algorithm (He et al., 2021) was conducted based on the four types of functional values (Production, ecological, social and cultural productions) and their relationships value (RI). The optimal k value was selected by the elbow method. Ultimately, farmland zones were determined and differential suggestions for each farmland zone served as references provided for the managers and decision-makers.

3 Results

3.1 Spatiotemporal patterns of multi-functions of farmland

The spatial and temporal variations of the multi-functions of farmland were shown in Figure 3. In 2020, farmlands with high production values were concentrated in the northern and eastern plains. High ecological values were mainly located in the northern and southern regions, and farmlands with low ecological effects were predominately located in the southwest. In terms of social function, the eastern regions show low values and the western regions exhibited relatively high social capacity. Regarding cultural function, high values were concentrated in the northern farmlands, and the southern mountainous counties displayed low cultural values. In general, the spatial distributed variability of functional values in 2020 was more apparent than that in 2000.

During the study period, the values of production, ecological and cultural functions showed upward trends, and the social values decreased significantly. Among them, the functional values of farmlands in the northern and central regions changed significantly. This may be due to the fact that production support policies such as direct food subsidies, agricultural tax exemptions and tax reductions have contributed to a significant increase in farmland yields, and the production function of farmland has continued to improve. At the same time, the ecological function of farmland has been enhanced with the continuous implementation and development of the policy of returning farmland to forests to promote the improvement of the ecological environment. In addition, the cultural function of farmland has become increasingly prominent as a result of the implementation of the Rural Revitalization Plan and the booming development of rural tourism. However, while food production has been increasing over the past 20 years, the reduction of farmland has also forced more and more farmers to lose their land to non-agricultural activities, which might lead to a decline in food self-sufficiency and agricultural employment, and contribute to a decrease in social function.

3.2 Synergistic and trade-off relationships between multi-functions of farmland

Figure 4 presented the results of Spearman's rank correlation analysis. From the perspective of correlation types, among the 6 sets of correlations between the four functions of farmland, 2 sets were positive (between production, social and ecological functions), and four sets were negative (mainly between cultural and other functions). Regarding correlation strength, four sets were weak correlations, and two sets were strong correlations. The strong correlations were mainly observed between the production and ecological and cultural functions.

Figure 5 demonstrated the distribution patterns of the synergistic and trade-off relationships between six pairs of functions of farmland. Combining Figure 6, it was evident that 15.5% of the counties have trade-offs between production and ecological functions, mainly in central and southwestern study areas, and the other counties showed a synergistic relationship between the two functions. Production and social functions had a trade-off relationship for 81.7% of the counties. While the remainder mainly located in the central and southwestern regions showed a synergistic relationship between the two functions. Additionally, there was a synergistic relationship between production and cultural functions for 83.1% of the counties, primarily concentrated in the northern, eastern and southern regions. 80.3% of the counties had a trade-off relationship between ecological and social functions, and the other counties showed a synergistic relationship between the two functions, scattered in southwest and central regions. Overall, 90.1% of the counties had a synergistic relationship between ecological and cultural functions. In contrast, a synergistic relationship between social and cultural functions was observed in 7% of counties, mainly distributed in the central regions of the study area.

As displayed in Figure 7, the number of synergy and trade-offs between diverse functions for each county was also calculated by this study. Four counties had more trade-offs between six pairs of functions of farmland, demonstrating the intense human influences it received. In contrast, more synergistic relationships were found in 3 counties, meaning higher environmental quality in these regions. Additionally, 90.14% of the total counties had the same amount of synergy and trade-offs.

The present study further calculated the TSD indicator to reveal the spatial patterns of strength values of the synergy or trade-offs among various functions. As shown in Figure 8, in terms of production and ecological functions, the TSD values were higher in the south and lower in the north. The northwest and southeast areas were observed higher TSD values between production and social functions. Between the production and cultural functions, as well as the ecological and cultural functions, both northern and southern regions exhibited higher TSD values. Regarding the ecological and social functions, the high TSD values mainly

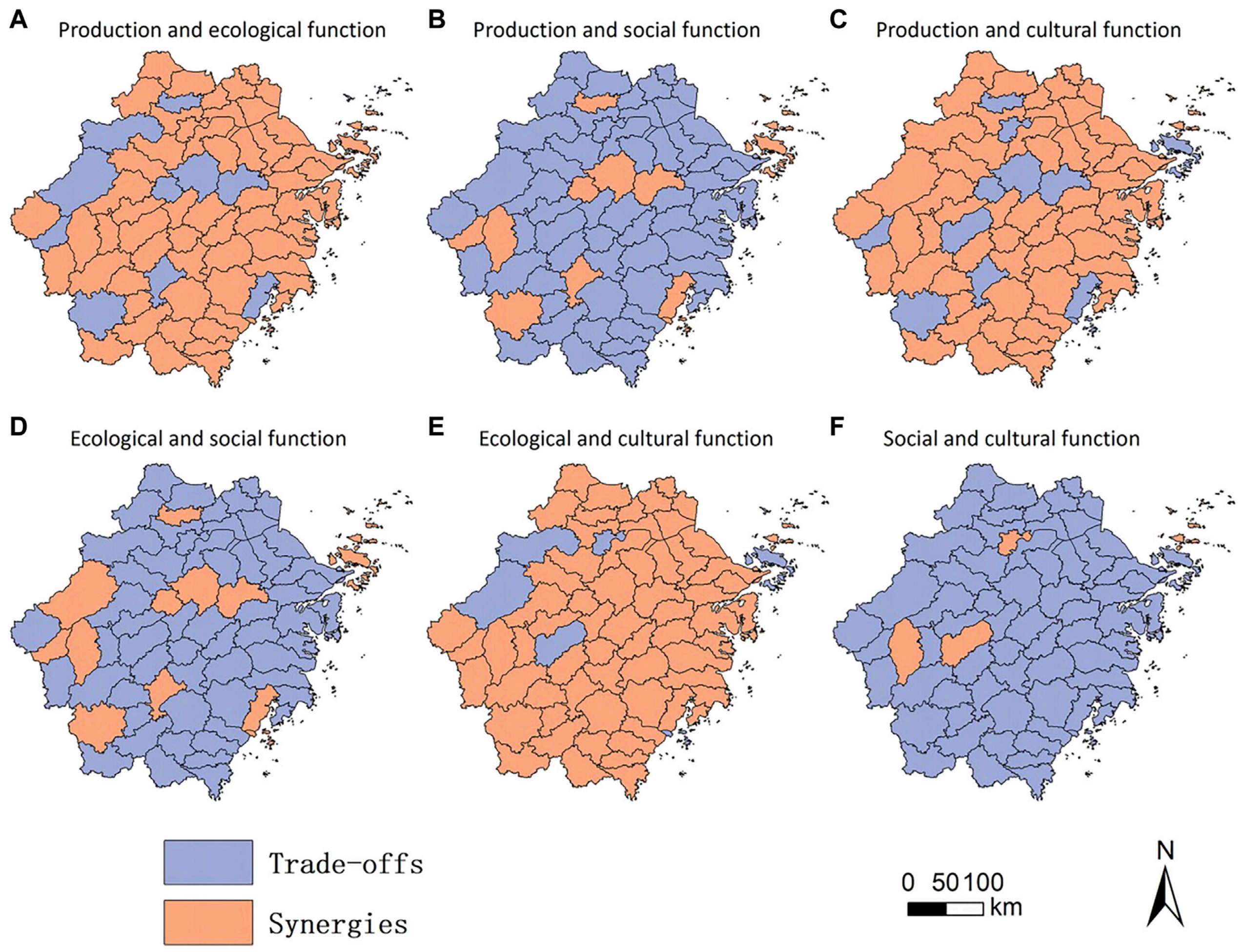

FIGURE 5
Spatial distribution of trade-offs and synergies between six pairs of functions.

concentrated in the southern areas. In contrast, the southern areas were found relatively low TSD values between social and cultural functions.

The reason for the above phenomenon may be due to the fact that with the continuous progress of science and technology, pesticides and chemical fertilizers, agricultural machinery, plastic film, etc. are widely used in agricultural production, and the material output, economic efficiency and production efficiency of farmland are greatly improved, and the value of production function is strengthened. However, the excessive use of pesticides and chemical fertilizers will have a negative influence on the farmland and affect the ecological function of the environment; and the large amount of agricultural machinery will reduce the number of jobs per unit of farmland and reduce the function of social security. However, the excessive use of pesticides and fertilizer will cause a negative influence on the farmland, affecting the ecological function. Also, the large input of agricultural machinery will reduce the number of jobs per unit of farmland, reducing the value of social function. The production function of farmland lays a material foundation for the play of cultural function, and the number of tourists received by rural tourism has gradually increased, which has led to the consumption of tourists, such as picking and purchasing agricultural products and converting agricultural products into food and beverage revenues, etc. which has led to an increase in the proportion of *per capita* net agricultural income of rural households, and attracted part of the farmers to return to engage in agricultural cultivation or related services, which slows down the decline of the social function.

3.3 Clustering analysis based on characteristics of multi-functions and their relationships

As indicated in Figure 9, after clustering analysis, the study area was divided into five regions (C1 to C5). Among them, C1 accounted for 63.38% of the total counties and was characterized by high social values, low cultural values and middle RI values. It was located in the central and southern regions. C2 constituted 21.13% of the total counties. This region was characterized by high production, ecological, social, cultural values and middle RI values. The northern plains were observed by most of this region. C3 (7.04% of the total counties) exhibited relatively low social values and

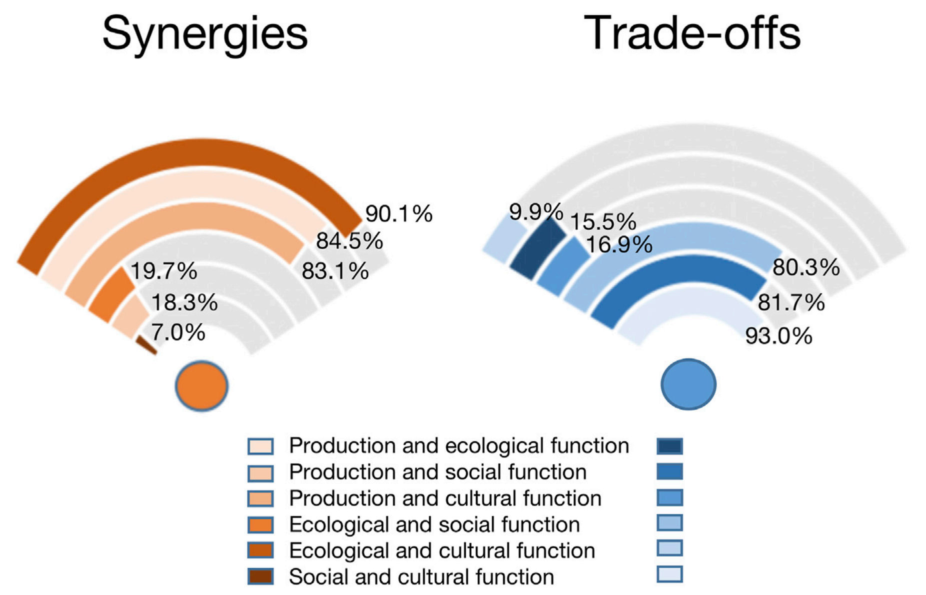

FIGURE 6
Proportion of county with trade-offs and synergies for the farmland functions pairs.

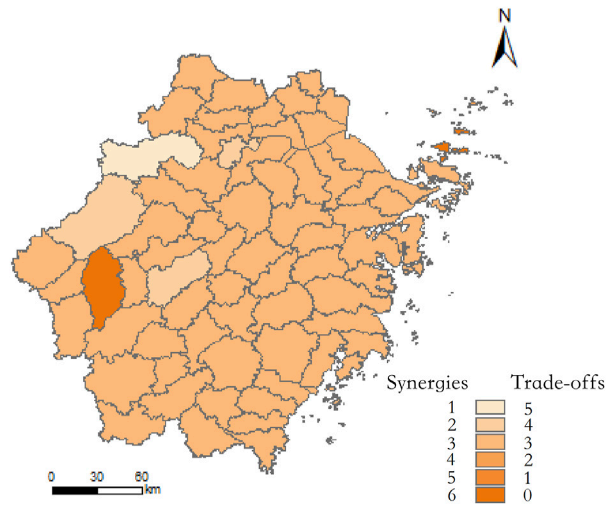

FIGURE 7
Number of synergy or trade-offs between functions in counties.

middle RI values. These counties were scattered in the North-East and South-East plains. C4 (5.63% of the total counties) was concentrated in the northwest mountains with low production and low RI values. On contrary, C5 (Taizhou county and Zhoushan county) showed relatively high RI values. Additionally, this region was characterized by high cultural and low social values.

4 Discussion

The multifunctionality of farmland has been considered the essential strategy for maintaining sustainable agricultural and rural development around the world (Yang and Hu, 2022). Due to the scarcity and importance of farmland resources, it is necessary and urgent to incorporate the multifunctional characteristics of farmland into its use, management and planning programs (Zhu et al., 2020). At present, the evaluation of the multifunctionality of farmland remains challenging due to the diversity of functional types, the heterogeneity of spatial and temporal distribution, and the selectivity of human use. On one hand, with respect to the research scale, studies on farmland multifunctionality have rarely been reported at both fine spatial scale and long-timescale, which might ignore the detailed information to support the formulation of targeted conservation management advice in local areas. On the other hand, by understanding the spatial patterns of the complex interactions among diverse functions, decision-makers can regulate relevant factors to improve the synergy intensity and reduce undesirable trade-offs. However, the existing quantitative analyses of multifunctional synergies and trade-offs in farmland mainly consider spatial information and neglect the information on temporal dynamics (Leh et al., 2013).

According to the challenges mentioned above, in this study, we constructed comprehensive evaluation index systems to assess the levels of multi-function of farmland at the county level, deeply revealing the spatiotemporal evolution characteristics of these functions. Compared with other studies, at a more refined county-level scale, we focused more on the interaction, and explored the synergistic or trade-off relationships between different functions, making the study scientific and accurate. And used TSD indicators to calculate the intensity of synergistic and trade-offs, rather than conducting a rough assessment. The inclusion of TSD indicators in the decision-making process related to land-use planning and agricultural policy can

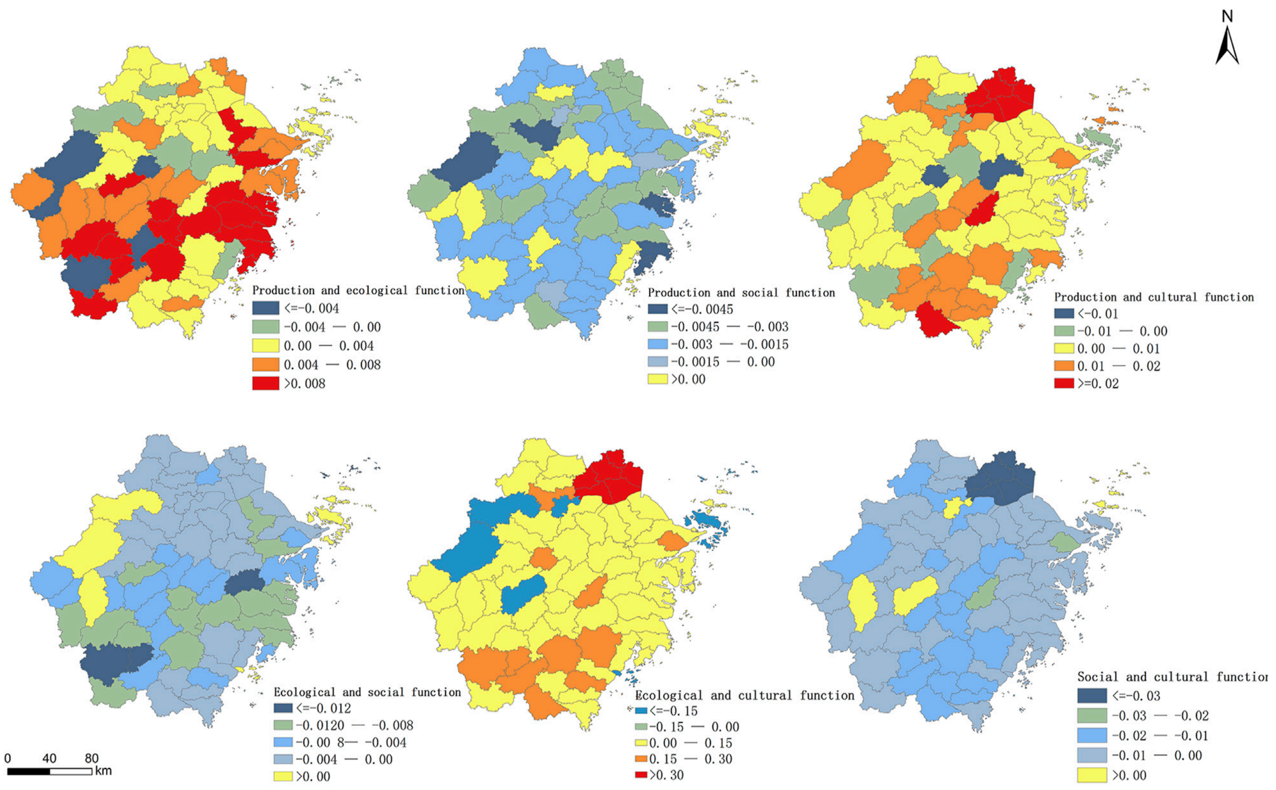

FIGURE 8
Spatial patterns of the synergies and trade-offs (measured by TSD) between farmland functions on the county scale.

effectively identify the types of relationships that exist between the different functions of farmland and quantify the strength of trade-offs or synergies, thus making decisions more scientific and convincing. Also, the TSD indicator is an extension of the traditional correlation analysis because it can detect local rather than global relationships between farmland. So, it could be adapted for broader regional assessments at county level. On this basis, we divide the study area into zones, and for the development characteristics of different regions, we can make targeted reference suggestions for sustainable management of farmland resources, planning and decision-making, as well as make relevant suggestions for improving the policy of returning farmland to forests, to promoting the coordinated development of various functions of farmland.

4.1 Spatiotemporal changes in multi-functions of farmland at the county levels

The assessment results support the argument that the multi-functions of farmland show various spatial and temporal patterns due to natural and socio-economic factors. In accordance with the findings of previous studies, plains with superior natural conditions and convenient management showed high production capacity (Yue et al., 2022). Usually, the remote mountainous farmlands exhibited relatively high ecological effects. Because these farmlands were far from downtown, and there was little human disturbance. In contrast, this study found that high ecological farmlands were mainly located in the northern plains (Shaoxing county and Jiaxing county), while the southwestern mountainous regions (Quzhou county and Lishui county) showed the low values of ecological function. This may be due to Jiaxing city and Shaoxing urban area are located between two regions with high economic development, Hangzhou and Shanghai, and it is difficult to gather production factors such as capital, labor and technology in the counties under their jurisdiction, but because of this, the threat of farmland occupation and agricultural degradation is mitigated to some extent, the value of ecological function is high. However, Quzhou county and Lishui county are lagging in terms of development, and in the context of rapid urbanization, large-scale development and utilization of land have led to low values of ecological functions. We also discovered that the lower level of economic development, the higher social values and the lower cultural capacity of farmland (Quzhou county and Lishui county). Farmlands within deprived areas were mostly used for subsistence and due to poor condition of infrastructure and low spiritual needs, rural tourism was hardly developed in these areas.

Furthermore, the results also showed a great increase in the production, ecological and cultural functions of farmland, but social function experienced an obvious decrease between 2000 and 2020. Support policies of production, such as direct grain subsidies, agricultural tax breaks, and tax exemptions, contributed to a significant increase in the production of farmland. At the same time, with the continuous development of the policy of returning farmland to forests, the ecological environment has been improved, and the ecological function of farmland has been enhanced.

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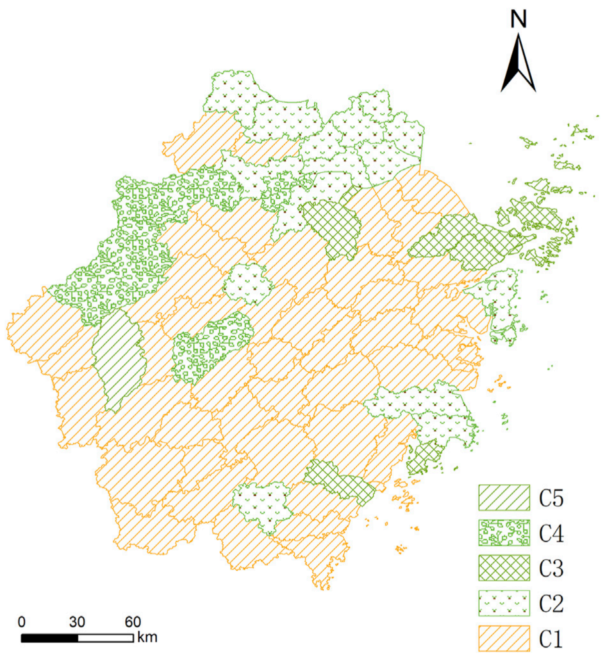

FIGURE 9
Multifunctional clustering regional distribution of farmland.

4.2 Synergistic and trade-off relationships analysis

In addition to the spatial and temporal patterns of multi-functions of farmland, the spatial characteristics of multifunctional relationships are crucial factors for decision-makers to consider when developing sustainable management options for farmland (Yu et al., 2023). Previous researches primarily used static spatial correlation coefficients to quantify the synergies and trade-offs among functions of farmland (Xigui et al., 2022). However, the processes of agricultural history have been ignored by this method and the present situation is the consequence of long-term synergies and trade-offs between functions. Therefore, it is difficult to fully and accurately reveal the impact mechanisms of the relationships. Meanwhile, few studies have quantified the intensity of relationships among functions at spatial scale. For example, Zhang et al. (2020) measured the relationships by using binary values (0, 1), but the magnitude of the relationships was not measured (Zhang et al., 2020). This study used the TSD indicator to evaluate the intensity of the relationships between functions by considering both spatial and temporal patterns of multi-functions of farmland within the study area.

Also, our results exhibited that the trade-offs and synergistic relationships were inconsistent in space. This result can provide a clear indication of the areas where synergies and trade-offs occur. Moreover, we find that, although food production has been increasing over the past two decades, the reduction of farmland due to the farmland return program has also forced more and more farmers to lose their land to non-agricultural activities and migrate from the countryside to the cities, leading to a decrease in food self-sufficiency and agricultural employment and a decrease in the value of the social function (Xigui et al., 2022). Moreover, in recent years, the number of sightseeing gardens for agricultural products has been increasing, and fruits, vegetables and other cultivated agricultural products are offered to the outside world for picking in greenhouses, and the number of visits to the countryside has been increasing, and the number of visits to the countryside and the annual business income have been increasing abruptly. The production function of farmland lays the material foundation for the performance of the cultural function, while the further enhancement of the cultural function of farmland provides a new opportunity and economic guarantee for the development of the production function of farmland (Chongzhen et al., 2022), and they will gradually move towards the direction of "high synergy" through long-term integration and benign mutual feedback. Thus, differentiated strategies for farmland utilization and conservation can also be developed based on the results.

4.3 Suggestions for the utilization, management and planning of farmland and forest land

With the increasing contradiction between urbanization and farmland conservation (Deng et al., 2015). In the 19th National Congress of the Communist Party of China, rural revitalization was put on the agenda as a national strategy (Zhu et al., 2020). In this context, there is an urgent requirement to advocate the diversified cognition and multi-level utilization of the functions of farmland, to explore the optimization of the functional layout, and to give full play to the cultural and spatial advantages of farmland, so as to better integrate it into the layout of urban development. It is necessary to ensure the rational and sustainable use of farmland resources through farmland zoning (He et al., 2021). As stated above, two aspects, the spatial patterns of multifunctional values and synergistic or trade-off intensity should be included in a scientific farmland-zoning program. However, current research tends to approach farmland zoning based only on multifunctional values, which might limit the coordinated development of diverse functions of farmland (Xigui et al., 2022).

Thus, this study integrated spatial information of multifunctional values and relationships between functions into a farmland-zoning program. In the context of sustainable agricultural development in the Zhejiang Province, governments should formulate relevant policies based on the local conditions within each farmland zone, develop local natural resources rationally, and strive to create synergetic outcomes that maximize multifunctional benefits. Specifically, we proposed the synergetic development of functions of farmland for zones with a lower trade-off intensity. And in the farmland zone with a high trade-off intensity, it is suggested that develop the dominant function with relatively high functional values and simultaneously reduce the trade-offs among these functions, promote their synergetic effects, and improve the capacity for their sustainable development. For the C1 region, it should accelerate the implementation of the rural revitalization strategy, vigorously develop rural tourism and promote the development of cultural functions due to its characteristics of high social value and low cultural value, should continue to promote the existing policy of returning farmland to forests. For good quality farmland planted with economic forests by farmers

(C2), which is mainly located in the northern part of Zhejiang, has high production, ecological, social, and cultural values, but has a small area of forest land, so it's necessary to appropriately strengthen the implementation of the policy of returning farmland to forests, and protect the ecological environment while synergistically developing the region. The C3 and C5 regions, both of which exhibit low social function values and have sufficient forest land areas, can appropriately increase arable land through the development of forested land, so as to increase the number of people employed in agriculture and the value of agricultural production and so on, thus increasing the number of people employed in agriculture and the value of agricultural output. Area C4 has a low value of production function, but has sufficient forest area, so it can appropriately carry out the behavior of returning forests to fields to increase the area of farmland and increase the value of production function. This study contributes to an in-depth understanding of the synergistic and trade-off relationships between functions of farmland, offers new insights into differentiated farmland protection, and serves as a reference for related research in other regions.

4.4 Limitations

There are also some limitations in the current study that need to be improved in the future. Regarding the indicators used to evaluate the farmland functions can be further filtered and employed in accordance with the actual situation in the study area using principal component analysis. Furthermore, although the synergistic and trade-off relationships between functions of farmland were quantified and mapped at county scale, exploring the influencing factors for trade-offs will provide more valuable information to enhance the coordination development among various functions of farmland in future research.

5 Conclusion

According to the challenges in evaluating the multi-functions of farmland mentioned above, this study evaluated the spatial and temporal patterns of multi-functions (production, ecological, social, and cultural functions) of farmland from 2000 to 2020 at county scale and quantified the intensity of the synergistic and trade-off relationships among functions by the TSD analysis at spatial scale. Finally, using the k-means clustering algorithm, this study integrated the above spatial results of the multifunctional evaluation and TSD analysis into a farmland-zoning program to provide a reference for differentiated farmland protection. The results showed that the functions of farmland were significantly heterogeneous in their spatial and temporal distribution. The production, ecological and cultural functions of farmland increased considerably, but social function experienced an obvious decrease in Zhejiang Province during the study period. Moreover, the synergistic and trade-off relationships and intensity were also inconsistent in space. Ultimately, five farmland zones were determined, and targeted suggestions applicable to each zone were put forward in this study, as well as suggestions for improving the policy of returning farmland to forests in the zones. In each zone, the multifunctional values indicated the current situation and the future usage of the farmland, and the TSD values assisted in judging the potential of the multi-functional compound development of the farmland within the zone. This study contributes to the utilization and planning of farmland and its surrounding land, especially to the improvement of the policy of returning farmland to forests.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JW: Conceptualization, Formal Analysis, Writing–original draft, Writing–review and editing. SH: Conceptualization, Supervision, Writing–review and editing. CH: Methodology, Writing–review and editing. RZ: Data curation, Writing–original draft. ChZ: Writing–review and editing. CoZ: Data curation, Formal Analysis, Writing–review and editing. YS: Investigation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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