TYPE Original Research
PUBLISHED 10 March 2025
DOI 10.3389/fenvs.2025.1542002

Check for updates

OPEN ACCESS

EDITED BY
Salvador García-Ayllón Veintimilla,
Polytechnic University of Cartagena, Spain

REVIEWED BY
Jinman Wang,
China University of Geosciences, China
Peidong Han,
Northwest A&F University, China

*CORRESPONDENCE
Aman Fang,
fangaman@henau.edu.cn

RECEIVED 09 December 2024
ACCEPTED 19 February 2025
PUBLISHED 10 March 2025

CITATION
Fang A, Shi Y, Chen W, Shi L, Wang J and Ma Y (2025) Trade-off and synergy relationships and regional regulation of multifunctional cultivated land in the Yellow River Basin.
Front. Environ. Sci. 13:1542002.
doi: 10.3389/fenvs.2025.1542002

Trade-off and synergy relationships and regional regulation of multifunctional cultivated land in the Yellow River Basin

Aman Fang[1]*, Yuanqing Shi[1], Weiqiang Chen[1], Lingfei Shi[1], Jinlong Wang[2] and Yuehong Ma[1]

[1]College of Resources and Environmental Sciences, Henan Agricultural University, Zhengzhou, China, [2]Henan Province Fifth Geological Brigade Co., Ltd., Zhengzhou, China

Exploring the multifunctional trade-off and synergy relationship of cultivated land is of great significance for protecting cultivated land resources, ensuring food security, maintaining ecological security, and promoting high-quality development in the Yellow River Basin. Based on the selection of 379 counties with concentrated distribution of cultivated land, this study comprehensively evaluates the three-dimensional functional level of "production-society-ecology" of cultivated land from 2010 to 2020. The coupling coordination degree model, land system function trade-off degree model, and K-means clustering analysis method are used to analyze the trade-off and synergy relationship between cultivated land functions and divide the functional zones in the Yellow River Basin. 1) In the last 10 years, the levels of cultivated land production, social, and ecological functions in the Yellow River Basin are in the range of 0.01–0.47, 0.04 to 0.23, and 0.03 to 0.23, respectively. The production function is at a stable level, while the overall level of social and ecological functions has slightly improved. 2) The level of multifunctional coupling and coordination of cultivated land ranges from 0.22 to 0.65. Only 31.13% of counties have a high coupling degree between multiple functions. The production-ecological function in the upstream regions show a coordinated development trend. The social-ecological function in the midstream regions is well coordinated, and the production-social function and production-ecological function in downstream regions towards collaborative development. 3) According to the dominant functional types and the characteristics of multifunctional coupling and coordination, the cultivated land of Yellow River Basin is divided into 7 multifunctional zones, involving 149 with multifunctional advantage zones, 19 with P-S functional composite zones, 21 with P-E functional composite zones, 21 with S-E functional composite zones, 74 with social functional dominant zones, 29 with ecological functional dominant zones, 44 with grain functional dominant zones, and 22 with remediation key zones. The results can provide decision support for differentiated management of cultivated land in the Yellow River Basin and mutual promotion between functions.

KEYWORDS

trade-off and synergy, functional zones, cultivated land, land system function trade-off degree, Yellow River Basin

1 Introduction

As the fundamental resource and spatial carrier for human survival and development, the functional expansion of cultivated land is closely linked to social and economic reforms, as well as changes in human needs (Zhang et al., 2023; Zou et al., 2021). With China transitions from an agricultural to a modern industrial society and then progresses towards an ecological civilization, the multifunctionality of cultivated land has emerged as an inevitable trend in response to continuously rising human demands (Wu et al., 2024; Dong and Zhao, 2019; Qian et al., 2020). Cultivated land has gradually played a role in stabilizing food production, maintaining social stability, and ensuring ecological security, evolving from initially addressing the basic needs of food and clothing, to promoting industrialization and urbanization, and then to fostering rural revitalization and ecological civilization construction, all while striving to achieve the goal of sustainable development (Xiong et al., 2021; Zhu et al., 2020). However, the scarcity of cultivated land resources has led to increasingly fierce land conflicts and spatial competition between food security, ecological protection, and urban development, seriously affecting the potential of cultivated land production, diminishing its social contribution value, and causing ecosystem degradation, which violates the scientific concept of sustainable use of cultivated land (Lv et al., 2023). The current management model for cultivated land production functions struggles to accommodate the diverse practical demands of farmland utilization (Fang et al., 2018). Therefore, exploring the multifunctionality of cultivated land utilization and achieving coordinated multifunctional utilization of farmland has become an urgent practical issue in balancing the interests of multiple parties and enhancing the effectiveness of farmland protection.

The existing literature on the multifunctionality of cultivated land primarily focuses on conceptual explanations (Song and Li, 2019; Wei et al., 2022), functional classification and indicator system construction, influencing factors exploration (Zhang et al., 2021; Liu et al., 2023), analysis of coupling and coordination relationships, and spatial zoning optimization (Jiang et al., 2021; Niu et al., 2022; Luo et al., 2023). The methods have gradually evolved from initial qualitative explanations and analysis of concepts to functional interaction and driving mechanism analysis based on mathematical statistics, while using ArcGIS software to achieve spatial regulation of functional zoning (Fei et al., 2023; Wang et al., 2023; Sylla et al., 2020; Qian et al., 2022). Due to the fact that the various functions of cultivated land do not work independently, but rather have a competitive and mutually reinforcing relationship. Thus, trade-off collaborative analysis is applied to identify the interrelationships and mutual benefits between various dimensions of farmland functions, in order to propose targeted coordinated management measures. In view of the trade-off and synergy between the functions of cultivated land, some scholars have not only understood the relationships between the functions through the correlation coefficient, but also realized the spatial expression of this correlation, identified the spatial association of each partition in the region, and realized the function optimization partition of cultivated land (Qian et al., 2022; Gao et al., 2021).

The Yellow River Basin, as a region in northern China with abundant reserve resources of cultivated land, nurtures 12% of the country's population. Land use conflicts, such as agricultural non-point source pollution, soil degradation, and the "Non-grain" and "Non-agriculture" utilization of cultivated land, have posed a serious threat to the protection of cultivated land in river basins. The management of cultivated land in the Yellow River Basin from the perspective of multi-function has become an important means to ensure regional sustainable development. Analyzing the trade-off and synergy relationship of each function and putting forward targeted suggestions to reduce trade-offs and increasing synergy play important role in maximizing the multifunctional utilization benefits of cultivated land in the Yellow River Basin. At present, most scholars have always paid attention to the multifunctional evaluation of land use in the Yellow River Basin (Niu P. et al., 2022). Only a few of studies focus on the cultivated land. Meanwhile, the study areas involve a section of the Yellow River Basin, for instance, Henan Province and Gansu Province. How is the functional utilization of cultivated land in the entire Yellow River Basin? Can we improve the utilization efficiency of cultivated land in the Yellow River Basin through zoning management and control to achieve ecological protection in the basin? The objectives of this study were: (1) to assess the spatial and temporal differentiation characteristics of multifunction of cultivated land in the Yellow River Basin; (2) to obtained the trade-off and synergy relationship between the functions of each dimension; (3) to divide the functional division of cultivated land and put forward the corresponding control strategy.

2 Materials and methods

2.1 Study area

The Yellow River Basin covers 1,900 km^2 from east to west, and 1,100 km^2 from north to south. It flows through 9 provinces, involving 44 cities (prefectures, leagues) and 424 counties (banners), as shown in Figure 1. The terrain shows a three-step decline, high in the west and low in the east. There are significant spatial differences in climate conditions, with an annual precipitation of 116–1,038 mm and an annual temperature of −13°C–15°C. The temperature and precipitation are relatively high in the southeast region, while they are relatively low in the northeast and northwest regions. The cultivated land area in the Yellow River Basin was approximately 2.50 × 10^5 km^2 in 2020. A total of 379 counties were selected to study with considering the concentrated distribution of cultivated land, regional connectivity, and the convenience of zoning management. Among them, there were 54 in Gansu Province, 59 in Henan Province, 35 in Inner Mongolia Autonomous Region, 22 in Ningxia Hui Autonomous Region, 14 in Qinghai Province, 37 in Shandong Province, 84 in Shanxi Province, and 74 in Shaanxi Province. The specific counties are shown in Figure 1.

2.2 Data sources

The vector data for the Yellow River Basin and the administrative boundary, and the land use status data at 1 km

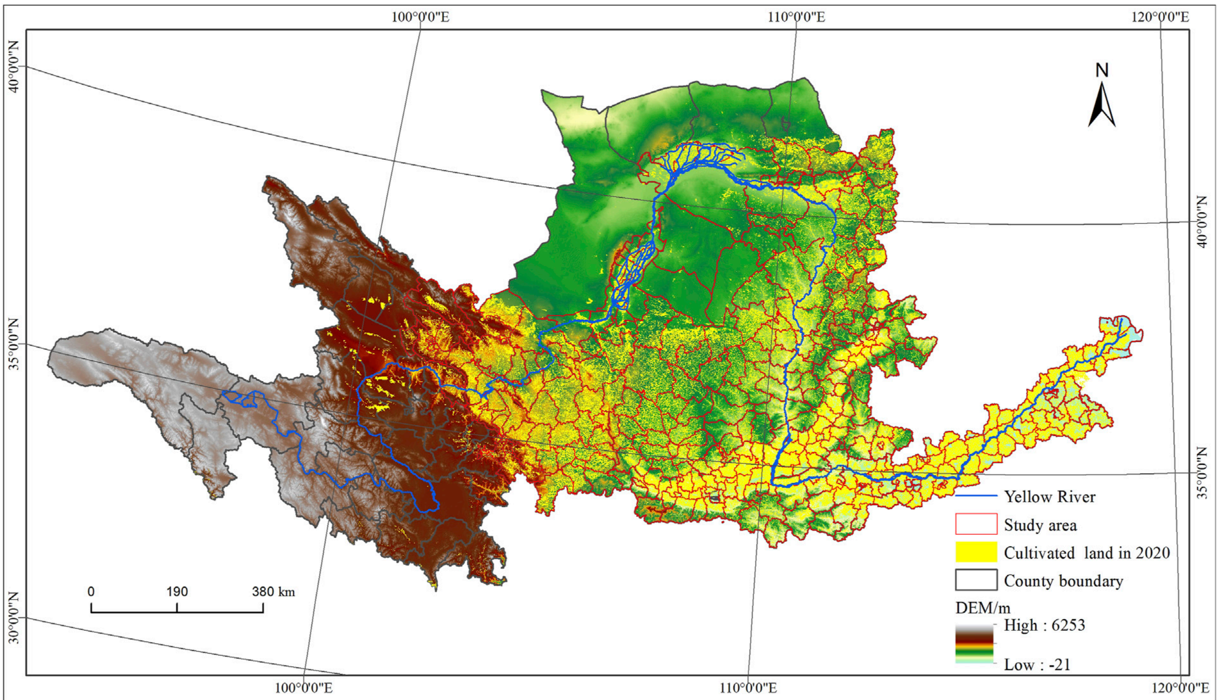

FIGURE 1
Distribution of cultivated land in the Yellow River Basin.

resolution (2010, 2020) were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). Land use types were reclassified into six categories using ArcGIS 10.8 software: cultivated land, forest land, grassland, water area, construction land, and unused land. All spatial data were processed into Albers projection. The socioeconomic statistics of counties and banners were obtained from statistical yearbook, economic and social survey yearbook, economic statistical yearbook and county statistical yearbook of the corresponding years, provinces and cities. The missing data was replaced by data from adjacent years.

TABLE 1 Multifunctional evaluation index system for cultivated land.

Function types	Specific index	Index description	Index attribute	Index weight	Functional weight
PF	Grain crop yield	Grain yield/cultivated land area	+	0.124	0.488
	Economic crop yield	Economic crop yield/cultivated land area	+	0.117	
	Average agricultural output value of cultivated land	Total agricultural output value/cultivated land area	+	0.169	
	Land reclamation rate	Cultivated land area/total land area	+	0.078	
SF	Agricultural practitioners proportion	Agricultural employed population/Total regional population	+	0.061	0.254
	Family agricultural income proportion	Family agricultural income/rural *per capita* net income	+	0.055	
	Agricultural mechanization level	Total power of agricultural machinery/agricultural employed population	-	0.079	
	The carrying capacity of rural labor force	Agricultural employed population/cultivated land area	-	0.059	
EF	Farmland ecosystem diversity	Total sown area of crops/cultivated land area	+	0.054	0.258
	Chemical load of cultivated land use	Chemical fertilizer application/cultivated land area	-	0.067	
	Carbon sequestration function	Natural carbon sequestration/cultivated land area	+	0.081	
	Ecological land proportion	Cultivated land area/the difference between the total land area and the construction land area	+	0.056	

2.3 Multi-functional evaluation of cultivated land

2.3.1 Construction of index system

According to both the previous studies and the national regional ecological protection and high-quality development requirements, the function of cultivated land was divided into three categories, namely, production, social security, and ecology (Wang et al., 2023). Considering the principles of science, systematic, operable, and objectivity, and combining the actual situation of cultivated land in the Yellow River Basin, a total of 12 indices were finally selected to construct the multifunctional evaluation index system of cultivated land, containing grain crop yield, land reclamation rate, and other indicators (Wang and Chen, 2022; Zhou et al., 2022) (Table 1).

The production function (PF) of cultivated land reflects the crop output capacity of cultivated land resources and makes a great contribution to ensuring food supply, which is the most basic function. The three aspects of crop yield, output value, and utilization status were the main basis for index selection. The yield per unit area of grain and economic crops reflects the physical production level of cultivated land. The average output value represents the economic production level of cultivated land. Land reclamation rate characterizes the degree of cultivated land development and renewal to reflect the utilization status. The social function (SF) states that cultivated land, as a production factor for farmers to survive, mainly plays a role in maintaining life and providing employment security. To indicate the function of cultivated land to carry rural surplus labor force and meet the needs of promoting rural social and economic development, this study selects the proportion of agricultural practitioners, the proportion of family agricultural income, the *per capita* level of agricultural mechanization, and the carrying capacity of rural labor force. The ecological function (EF) reveals the regional ecological security ability of cultivated land to regulate climate, water conservation, and soil and water conservation. It is determined by four factors: farmland ecosystem diversity, chemical load of cultivated land use, carbon sequestration function and proportion of ecological land. Considering the major crops of Yellow River Basin, the cultivation areas of wheat, corn, oilseed, and vegetable were used to calculate the diversity index of farmland ecosystem (Niu et al., 2022). The calculation formula is shown below to elaborated in Equations 1, 2:

$$H_q = -\sum_{i=1}^{4} P_q \cdot l_n P_q \tag{1}$$

$$P_q = \frac{S_q}{S} \tag{2}$$

where H_q is the diversity index of farmland ecosystem, P_q is the ratio of crop q to total sown area, S_q is the sown area of crop q, and S is the total sown area.

According to existing research, the natural carbon sequestration of cultivated land is obtained by the following formulas to by Equation 3:

$$A_c = \sum_{i=1}^{m} A_{c_i} = \sum_{i=1}^{m} \left[C_{pi} \times Y_i \times (1 - W_i) \times (1 + R_i) \right] \Big/ H_i \tag{3}$$

where A_c is the natural carbon sequestration of cultivated land, A_{c_i} is the carbon absorption capacity, C_{pi}, Y_i, W_i, R_i, and H_i respectively refer to carbon content rate, economic outputs, water coefficient, top-root ratio, and economic coefficient of crop i. The m value is 4, which means that wheat, corn, oilseed, and vegetable are selected to calculate the natural carbon sequestration. The related parameters of these crops were from Chen et al. (2016).

2.3.2 Index processing

To ensure the comparability between the various indices, the range normalization method was applied to convert the original data into dimensionless data. The specific calculation formula for the positive and negative indices are expressed as Equations 4, 5:

$$\text{Positive indices: } X_{ij} = \frac{x_{ij} - x_{jmin}}{x_{jmax} - x_{jmin}} \tag{4}$$

$$\text{Negative indices: } X_{ij} = \frac{x_{jmax} - x_{ij}}{x_{jmax} - x_{jmin}} \tag{5}$$

where X_{ij} means the standardized value, x_{ij} means the actual value of the jth index of the ith county, and x_{jmax} and x_{jmin} mean the maximum and minimum values of the jth index, respectively.

2.3.3 Weight determination

Entropy weight method and analytic hierarchy process were used to determine the index layer weight comprehensively and accurately (Fang et al., 2018). Among them, the determination of functional indicator weights using Analytic Hierarchy Process were from the relevant literature (Zhang et al., 2023; Luo et al., 2023), and obtained by Yaahp software. The entropy weight is calculated by Equations 6–11:

$$Y_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{6}$$

$$e_j = -k\sum_{i=1}^{m}\left(Y_{ij} \cdot lnY_{ij}\right) \tag{7}$$

$$k = \frac{1}{lnm} \tag{8}$$

$$d_j = 1 - e_j \tag{9}$$

$$W_{kj} = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{10}$$

$$W_j = \frac{\left(W_{aj} + W_{kj}\right)}{2} \tag{11}$$

where Y_{ij} is the percentage of the jth indicator for year i, e_j is index information entropy, d_j is the difference coefficient of index j, W_{aj} is the analytic hierarchy weight, W_{kj} is the entropy weight, W_j is the comprehensive weight of index j, and m is the number of samples. The results have been shown in Table 1.

2.3.4 Multi-functional value of cultivated land

The comprehensive weighting method was used to calculate the multi-functional scores of cultivated land in counties of the Yellow River Basin, with Equation 12:

$$F = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(X_{ij} \cdot W_j\right) \tag{12}$$

where F is the multi-functional value of cultivated land.

2.4 Trade-off and synergy evaluation of cultivated land utilization function and partition

The multifunctional zoning ways of cultivated land are shown in Figure 2; Table 2. Firstly, the coupling and coordination relationship

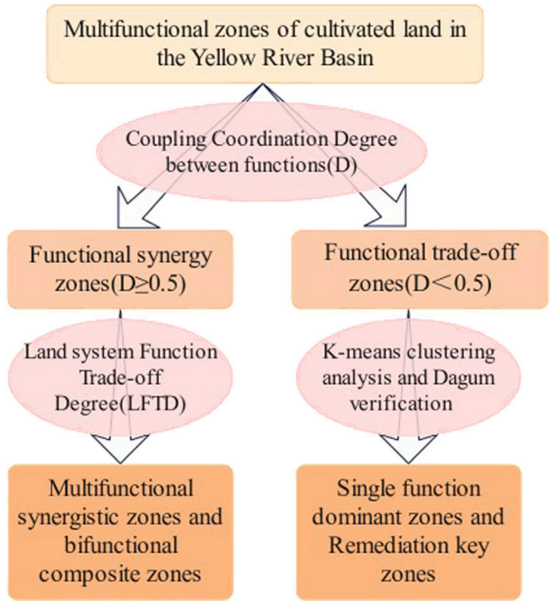

FIGURE 2
Multifunctional zoning ways of cultivated land.

is analyzed between the PF, SF, and EF of cultivated land in the Yellow River Basin. The functional synergy and trade-off zones are obtained on the basic of the coupling coordination degree. Then, the multifunctional synergy zones and the functional composite zones are distinguished combined with the Land system Function Trade-off Degree (LFTD). As shown in Table 2, the LFTD values of PF, SF, and EF are higher than 0 in the multifunctional synergy zones. For the composite zones of production-social (P-S) function, production-ecological (P-E) function, and social-ecological (S-E) function, their corresponding LFTD values are more than 0. In terms of the functional trade-off zones, it includes the single function dominant zones and remediation key zones and is realized by the K-means clustering analysis (Zhao et al., 2024) and Dagum verification (Zhang et al., 2019).

2.4.1 Coupling coordination degree

Coupling Coordination Degree model has been widely applied in the study of coupling and coordination relationship between three or more subsystems. Farmland is a complex system, with production, social security, and ecological functions. By coupling and coordinating the multifunctional evaluation of cultivated land based on its inherent coupling relationship, it is possible to comprehensively evaluate the quality of cultivated land from the perspective of overall development level (Wei et al., 2022). The specific formulas are expressed as Equations 13–15:

$$C = \sqrt[3]{\frac{F_P \times F_S \times F_E}{\left(F_P + F_S + F_E\right)^3}} \tag{13}$$

$$T = W_P F_P + W_S F_S + W_E F_E \tag{14}$$

$$D = \sqrt{C \times T} \tag{15}$$

where C, T and D mean coupling degree, coordination degree, and coupling coordination degree, F_P, F_S, and F_E are functional values of production, social, and ecology, and W_P, W_S, and W_E are 0.488,

TABLE 2 The multifunctional zoning foundation of cultivated land.

D	$LFTD_{PS}$	$LFTD_{PE}$	$LFTD_{SE}$	Zones
≥0.5	>0	>0	>0	Multifunctional advantage zones
	>0	<0	<0	P-S functional composite zones
	<0	>0	<0	P-E functional composite zones
	<0	<0	>0	S-E functional composite zones

0.254, and 0.258, respectively. The corresponding functional values in 2020 was selected to calculate the C and T. According to the existing research (Zhou et al., 2025), it expresses a coupling relationship with the D value at least 0.5, but an imbalance relationship with the D value lower 0.5.

2.4.2 Land system function trade-off degree

The trade-off synergy theory has been widely used in the study of ecosystem service relationships. Trade-off represents that different ecosystem services are negatively correlated in the same period of time, and the two are in a state of ups and downs. Synergy represents a positive correlation between different ecosystem services, with the same increase or decrease. As an integral part of the ecosystem, cultivated land is inevitable in the situation of multi-functional trade-off and coordination. The trade-off of cultivated land utilization indicates that there are opposite trends of change between different functions. However, the synergy means that there are similar trends. Land system Function Trade-off Degree (LFTD) originates from the ecosystem service balance model, which reflects the direction and degree of interaction between farmland use functions through data linear fitting, thus achieving its balance and collaborative analysis (Niu P. et al., 2022). The specific formula is as follows:

$$\mathrm{LFTD}_{XY} = \frac{LFC_{xa} - LFC_{xb}}{LFC_{ya} - LFC_{yb}} \tag{16}$$

where LFC_{xa} and LFC_{xb} mean the functional value of the *x*th type land system at time a and time b, and LFC_{ya} and LFC_{yb} mean the functional value of the yth type land system at time a and time b. There is a synergy relationship between xth type and yth type with the LFTD value greater than 0, but a trade-off relationship with the LFTD value lower than 0. The absolute value of LFTD reflects the level of trade-off/synergy.

3 Results

3.1 Spatio-temporal distribution of multifunctional cultivated land in the Yellow River Basin

The functional scores of cultivated land in 379 counties in the Yellow River Basin are shown in Figure 3. In terms of production capacity, the PF values were in the range of 0.01–0.47 from 2010 to 2020. The production capacity presented a stable trend of cultivated land in the Yellow River Basin, with the PF values lower than 0.2 in more than 73.88% of counties. There were higher PF values in the Ningxia Plain, Hetao Plain, and the middle and lower regions of the Yellow River Basin, which indicates that the yields of food crops and economic crops are relatively greater in these regions. A significant increasing trend of production capacity was found in Weihui City, Fengqiu County, Huojia County in Henan Province, Kundulun District, Qingshan District in Inner Mongolia Autonomous Region, and Qingtongxia City, Yongning County in Ningxia Hui Autonomous Region. In contrast, the production capacity tended to decrease in Wenshang County, Daiyue District, Shen County, Yanggu County and Feicheng County in Shandong Province in the last 10 years. For social function, the SF values were 0.04–0.23 from 2010 to 2020. There was an increasing trend of social function in 61.48% of counties, which is mainly attributed to the enhancement of mechanization levels and the increase in family agricultural incomes (He, 2021). Meanwhile, this means that the living standards of farmers who rely on cultivated land for survival have improved, and life and employment can be basically guaranteed in these counties. In particular, the upward trend was more obvious in Mei County, Jingyang County, and Tongguan County in Shaanxi Province, and Ruyang County, Yiyang County, and Hua County in Henan Province. However, the social security capacity exhibited a downward trend in Lingwu City in Ningxia Hui Autonomous Region, Xintai City and Qihe County in Shandong Province. As for ecological functions, the EF values ranged from 0.03 to 0.23 between 2010 and 2020. Cultivated land utilization in the Yellow River Basin had a positive impact on the ecology in 64.91% of counties with the rising PF values. The ecological function of cultivated land tended to increase in Wangyi District, Huayin City and Hancheng City in Shanxi Province, Hegong District and Shangjie District, but decrease in Qi County, Qingxu County and Taigu County in Shanxi Province, Yiyuan County, Liangshan County and Yanggu County in Shandong Province. On the whole, the multifunctional values of cultivated land in the Yellow River Basin was generally in the range of 0.17–0.85 during the study period, and a significant spatial differences were showed among the all counties. The change value of multi-function score of cultivated land in 233 counties was greater than 0, indicating that the production capacity, social security capacity and ecological protection capacity of cultivated land in the Yellow River Basin have gradually increased in the last 10 years. Due to the rich resources of agricultural and sideline products and good ecological environment in the downstream region of the Yellow River, it is an important agricultural planting area, a main producing area of high-quality agricultural products and a core area of grain in China (Chen et al., 2022). Meanwhile, agriculture is also the basis for the survival of regional farmers. Therefore, the multifunctional values of cultivated land in the downstream region was higher than that in the upstream region and midstream region.

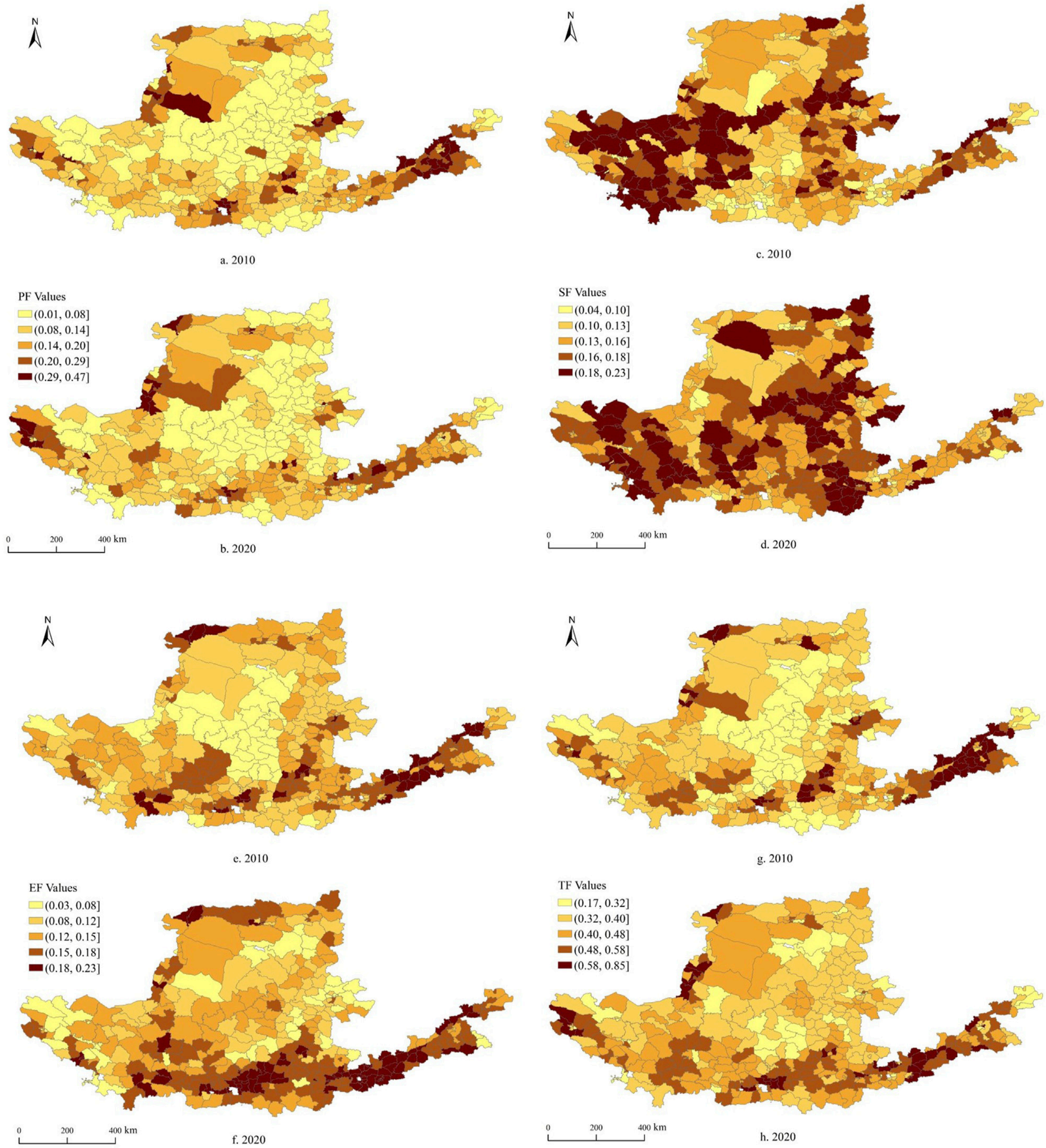

FIGURE 3
The functional values of cultivated land in the Yellow River Basin.

3.2 Trade-off and synergy analysis of multifunctional cultivated land in the Yellow River Basin

The trade-off and synergistic relationship between the functions of cultivated land in the Yellow River Basin is shown in Figure 4. Overall, the D values in 31.13% of counties were greater than or equal 0.5, which suggests that there is a coupling relationship between production function, social function, and ecological function in these regions. On the contrary, it expresses an imbalance relationship between these three functions in 68.87% of counties with the D values lower than 0.5. It means that the multifunctionality of cultivated land in the Yellow River Basin has not been fully utilized during the research period. From 2010 to 2020, the number of counties with the LFTD values greater than 0 between the production-ecological function, social-ecological

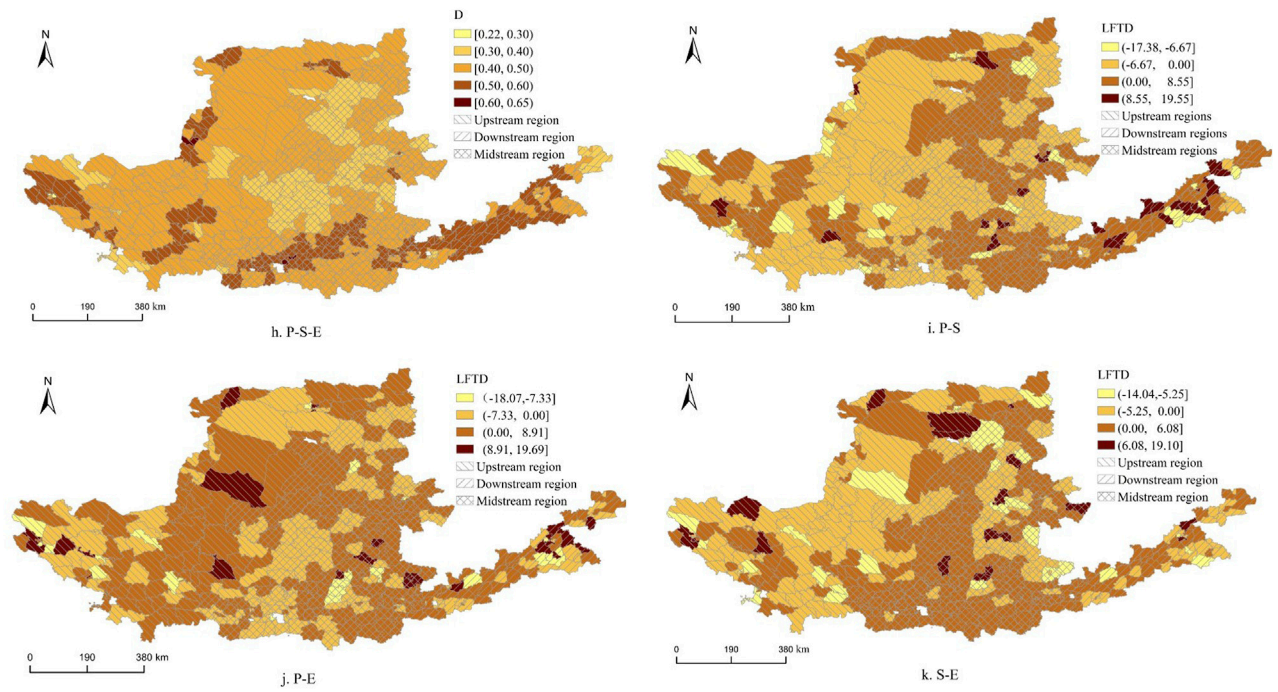

FIGURE 4
The collaborative and trade-off degree between the functions of cultivated land in the Yellow River Basin.

function and production-social function of cultivated land in the Yellow River Basin accounted for 63.06%, 62.27%, and 53.30% of the total number of study area, respectively. It is proved that there is a better synergistic change trend between the functions. The upstream regions of the Yellow River are dominated by mountains, and the distribution of cultivated land is relatively small. The LFTD values were higher than 0 in 63.03% of the upstream counties. It shows that the good maintenance of cultivated land ecosystem service function has a mutual gain effect on cultivated land production capacity and product quality in the upstream regions during 2010–2020. It is inseparable from the national commitment to the protection of the water supply areas and ecological security barriers in the upstream regions of the Yellow River (Pang et al., 2024). However, for the production-social function and social-ecological function, a trade-off relationship was appeared in 57.98% of the upstream counties with the corresponding LFTD values less than 0. This was due to the fact that the income, employment opportunities and other social security benefits obtained by cultivated land use are relatively small for the livestock-based farmers. The cultivated land in the midstream regions of the Yellow River is mainly distributed in Shaanxi Province, Shanxi Province and Henan Province. There is a mutual gain relationship between the two functions in counties over 53.4% of midstream regions with the corresponding LFTD values greater than 0. Reasonable agricultural production structure and high output capacity not only enhance the diversity of cultivated land ecosystem, but also increase the farmers' income.

The terrain of the lower Yellow River is mainly plain, which results in the better natural conditions and convenient agricultural mechanization. Therefore, the LFTD values between the two functions was higher than 0 in counties over 62.32% of downstream regions. In particular, the synergetic relationship of production-ecological function was the most intense with the counties proportion more than 72.46%. In these regions, regional farmers mainly used cultivated land to grow traditional food crops.

3.3 Preliminary zoning and verification of cultivated land functions in the Yellow River Basin

According to the multifunctional zoning ways, multifunctional advantage zones, P-S functional composite zones, P-E functional composite zones, and S-E functional composite zones were obtained on the basic of the coupling coordination degree and the land system function trade-off degree. For the functional trade-off zones, the optimal classification number of multi-functional clustering algorithm for cultivated land is 4 categories referring to the elbow method (Figure 5) (Li, 2023). Based on the K-means clustering results of cultivated land functions in 2020, the functional trade-off zones were divided into grain function dominant zones, social function dominant zones, ecological function dominant zones, and remediation key zones (Figure 6), and its corresponding PF values, SF values, and EF values were relatively high in these function dominant zones. All the function values were low in the remediation key zones. The rationality of the clustering partition scheme was tested in accordance with the Gini coefficient (Table 3) of the multi-functional type partition of cultivated land. From the perspective of the source and contribution rate of the overall regional gap of the cultivated land function index, the three functions that contribute the most to the overall regional disparities were the interregional disparities, and their contribution rates were all greater than 50%. The

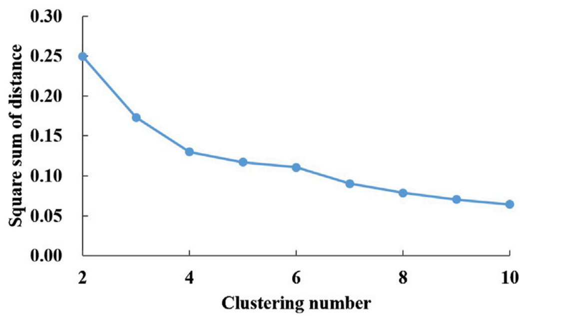

FIGURE 5
Square sum of distance under different numbers of clusters.

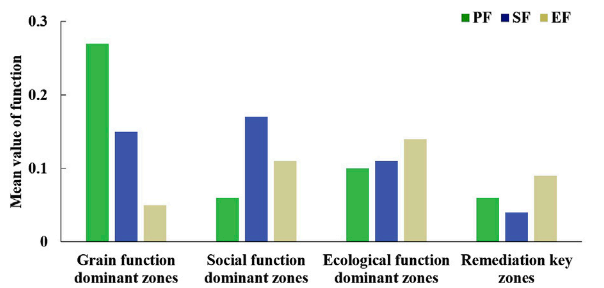

FIGURE 6
Clustering results of cultivated land functional trade-off zones in 2020.

interregional contribution rate of PF was as high as 74.64%. Therefore, the K-means clustering zoning scheme had a small gap in the functional zones of cultivated land, and the interregional gap is the main reason for the overall regional differences in the functions of cultivated land.

3.4 Multi-functional zoning of cultivated land in the Yellow River Basin

There were 7 categories of cultivated land functional zones in the Yellow River Basin and the specific distribution was shown in Figure 7.

A total of 149 counties, accounting for 39.31% of the selected counties, were in the multifunction advantage zones. Among them, 81.21% of counties were in the midstream and downstream regions of the Yellow River Basin. On one hand, for the counties around the city center, in virtue of the higher level of urbanization and denser population, human beings have a strong demand for the production quality, economic benefits, ecological maintenance and other functions of cultivated land in these regions. Meanwhile, because of better economic benefits and output, stable agricultural population and sufficient agricultural subsidies can maintain the good social effect of cultivated land, so multiple functions can be coordinated development. However, the fragmentation of cultivated land is serious with the impact of rapid urbanization. How to integrate cultivated land into the urban ecosystem is an important direction for the adjustment of cultivated land use in these regions. Some approaches, such as urban agriculture or green infrastructure construction, can help achieve the coordinated development of cultivated land production functions and urban ecological functions. On the other hand, in the counties far away from large cities, cultivation and management are relatively convenient owing to its high contiguity. Due to being a traditional grain producing area, agricultural technology has been effectively promoted, and the utilization efficiency of cultivated land is high. The input of high-yielding materials has been controlled and shown a downward trend, and the overall efficiency of cultivated land is high. In addition, because of their distance from cities, these regions have a better ecological environment and cultivated land can maintain a certain ecological maintenance function. The development of ecological agriculture and the application of sustainable farming techniques can ensure food production while enhancing ecological functions.

The composite zones involved 61 counties, including 19 with P-S function, 21 with P-E function, and 21 with S-E function. The P-S function composite zones were mainly in the upstream and downstream regions. The agricultural population in these zones has a high degree of dependence on cultivated land. High value-added crops and characteristic agriculture are planted, and ecological compensation policies are applied to protect regional ecology. Most of the P-E function composite zones were located in the upstream regions, especially in the Ningxia Plain. Water-saving irrigation technology can be promoted and ecological agricultural models such as crop rotation, intercropping, and organic agriculture are being applied in these zones. The S-E function composite zones were mainly distributed in the midstream regions. These regions are far away from the economic development center, the urbanization degree is relatively low and the overall economic level is relatively backward. Ecotourism projects are developed based on the favorable ecological environment and agricultural landscape, aiming to enhance the regional economic level.

There were 147 counties of dominant zones, containing 74 with social function, 29 with ecological function and 44 with grain function in Yellow River Basin. For the social functional dominant zones, the fragile ecological environment of the Loess Plateau is a restrictive factor for regional ecology and agricultural development. The relevant departments should focus on the combination of ecological compensation and cultivated land protection compensation policies, mobilize local subjective enthusiasm for environmental protection and cultivated land protection, and compensate for the loss of opportunity cost of land use conversion in specific areas. The ecological functional dominant zones were in the upstream. Dry land is the main type and it is difficult to realize agricultural modernization. The utilization efficiency and comprehensive benefits are far lower than other regions. Measures such as ecological restoration and returning farmland to forests and grasslands should be taken to enhance regional ecological functions, while exploring local characteristic agricultural models. As for the grain function dominant zones in the upstream, the degree of intensive utilization of cultivated land is very high, and there is even a trend of excessive intensification. Excessive input of pesticides

TABLE 3 Gini coefficient and contribution rate of cultivated land functional trade-off zones.

Function	Gini coefficient				Contribution rate		
	Total	Intraregional Gini coefficient G_W	Interregional gini coefficient G_b	Super variable density gini coefficient G_t	Intraregional contribution rate G_w	Interregional contribution rate G_t	Super variable density contribution rate G_t
PF	0.138	0.020	0.103	0.015	14.49%	74.64%	10.87%
SF	0.124	0.021	0.086	0.017	16.94%	69.35%	13.71%
EF	0.126	0.028	0.067	0.031	22.22%	53.17%	24.60%

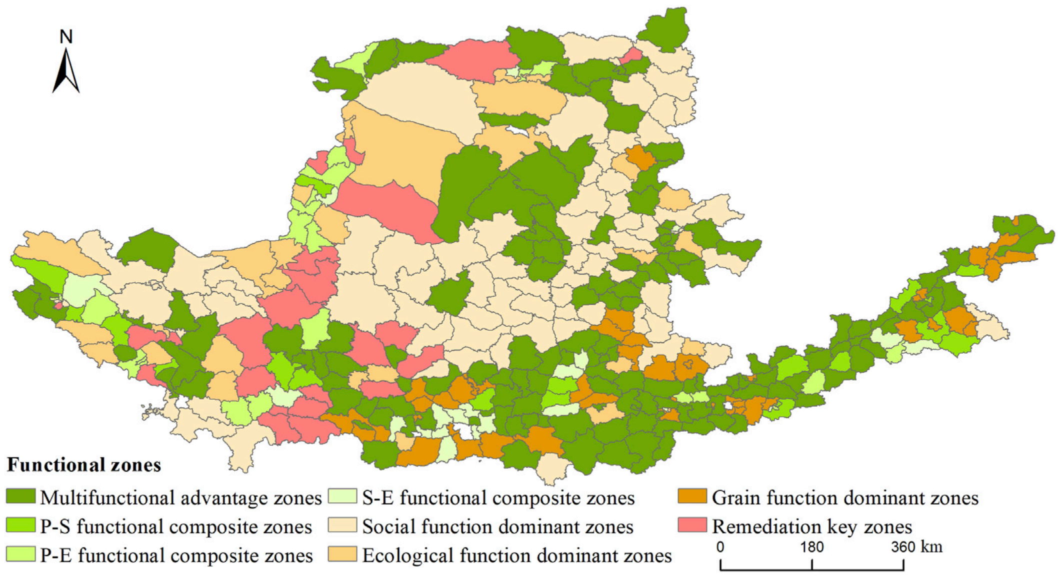

FIGURE 7
Multifunctional zones of cultivated land in the Yellow River Basin.

and fertilizers has a significant impact on cultivated land and its surrounding ecological environment. Therefore, the food security and ecological maintenance functions in these regions are often strongly imbalanced. It can be solved through precision agriculture technology and green production methods. In addition, there were 22 counties with the low functional values. A poor utilization condition of cultivated land and scarce resources were found in these regions, and the development path is limited because of the geographical and geomorphic features. Thus, a worse multifunctional synergy was present. With the rise of agricultural production costs and the gradual weakening of regional agriculture in the national economic system, many young and middle-aged rural laborers have shifted to urban areas and the secondary and tertiary industries. The continuous loss of agricultural population has led to the long-term inefficient utilization of cultivated land resources, resulting in relatively weak regional cultivated land production functions and limited paths for functional improvement. The government can increase financial subsidies and technical support to improve the utilization conditions of cultivated land and enhance production functions.

4 Discussions

Due to the increasing demand for diversified food by humans, cultivated land needs to play multiple functions in addition to maintaining food security. Promoting the coordinated development of multifunctional cultivated land is an important way to advance regional cultivated land protection and utilization, and achieve sustainable agricultural development. The dynamic changes in the trade-off and synergy of multifunctional utilization of cultivated land through system analysis are beneficial for improving the comprehensive utilization efficiency of cultivated land in Yellow River Basin. The evolution trend of cultivated land functions and the balance and synergy between them in the downstream region of the Yellow River are basically consistent with the research of Niu H. P. et al. (2022). For the Gansu Province located upstream region, the cultivated land functions in Lanzhou city, Dingxi city, and Baiyin city are in an imbalance relationship, which is in accord with the research of Wang and Yang (2024). Compared with other regions in China, such as the Yangtze River Basin and the Pearl River Delta, the Yellow River Basin faces more significant challenges in balancing ecological protection and agricultural production due to its fragile ecosystem and lower average income levels. For the Yangtze River Basin, it has achieved a higher level of multifunctional synergy in cultivated land utilization, largely due to its advanced agricultural infrastructure and higher economic development level (Li, 2023). Similarly, the Pearl River Delta region has focused on integrating urban development with agricultural modernization, resulting in a more balanced development of production, social, and ecological functions of cultivated land (Zhang et al., 2024). Globally, the multifunctional utilization of cultivated land in the Yellow River Basin shares similarities with regions like the Nile River Basin in Africa, where water scarcity and soil degradation are critical issues. However, the Yellow River Basin has made significant progress in ecological restoration and sustainable agricultural practices, which sets it apart from other regions facing similar challenges (Jones and Thornton, 2015).

Compared with existing research, the cultivated land protection zones of the entire Yellow River Basin and differentiated management measures based on the trade-off and synergy relationship were obtained by this study. In general, more than half of the counties have good collaborative development relationships between functions, which suggesting that there is a relatively good utilization condition of cultivated land in the Yellow River Basin. Meanwhile, it can meet the needs of the transformation of human dietary structure. As for the cultivated land in the dominant zones, on the premise of exerting its dominant function, other functions can be improved by improving the relatively weak production, social, and ecological conditions in the zones. These zones can be used as dynamic control zones for cultivated land utilization, timely supplementing the demand for corresponding functional farmland based on the needs of food security, social development, and ecological protection. For the remediation key zones, the production function of cultivated land has not been fully valued, and efforts should be made to improve the quality of regional cultivated land, promote the development of modern agriculture, and achieve the coordinated development of multiple functions.

The multifunctionality of cultivated land is constrained by various factors, and currently there is no unified standard for the multifunctionality connotation of cultivated land. Due to subjective factors and the difficulty of obtaining data, the evaluation index system for multifunctionality of cultivated land constructed is not comprehensive enough in this study. Furthermore, the comparison with other regions in China and globally highlights the need for a more standardized and universally applicable framework for evaluating cultivated land multifunctionality. Therefore, the subsequent research should pay attention to start from a smaller scale, refine the multifunctional categories of cultivated land, and construct a more suitable evaluation index system. In the future, key factors affecting the balance and coordination of multifunctional cultivated land can be further identified, and more precise and detailed countermeasures can be proposed for the actual utilization of cultivated land in different regions.

5 Conclusion

Based on the indicator system constructed from three aspects of production, society and ecology, this study analyzed the spatial evolution trend of cultivated land functional level and the trade-off and synergy relationship between functions from 2010 to 2020, divided the functional zones, and proposed management measures of cultivated land in the Yellow River Basin. The main conclusions were as follows:

1) In the past 10 years, 61.47% of counties in the Yellow River Basin have shown a slight increase in the multifunctional level of cultivated land. Among them, the production function of cultivated land was strong and basically in a stable state. The social and ecological functions of cultivated land were showing an increasing trend, particularly in the midstream and downstream regions.
2) Overall, the coupling and synergy between the production, social, and ecological functions of cultivated land in the Yellow River Basin was relatively low. The production and ecological functions of cultivated land in the upstream region showed a trend of coordinated development. The social and ecological functions of cultivated land in the midstream region were well coordinated, while the production, social, and ecological functions of cultivated land in the downstream region were well coordinated.
3) The cultivated land in the Yellow River Basin was divided into 7 functional zones, including 149 with multifunctional advantage zones, 19 with P-S functional composite zones, 21 with P-E functional composite zones, 21with S-E functional composite zones, 74 with social functional dominant zones, 29 with ecological functional dominant zones, 44 with grain functional dominant zones, and 22 with remediation key zones. The existing favorable conditions of agricultural production can be maintained in the future utilization of cultivated land for the advantage zones and composite zones. As for the dominant zones and remediation zones, improving the corresponding production conditions and ecological environment to meet the demand for farmland utilization in social development is the main remediation path.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. Requests to access these datasets should be directed to Aman Fang fangaman@henau.edu.cn

Author contributions

AF: Writing–original draft, Writing–review and editing, Formal Analysis, Funding acquisition, Methodology. YS: Investigation, Writing–review and editing. WC: Funding acquisition, Methodology, Writing–review and editing. LS: Funding acquisition, Supervision, Writing–review and editing. JW:

Investigation, Writing–review and editing. YM: Investigation, Resources, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was funded the Henan Philosophy and Social Science Planning Project (No. 2023CJJ153), Natural Science Foundation project of Henan Province (Grant No. 242300420602), and National Key R&D Program of China (2021YFD1700900).

Conflict of interest

Author JW was employed by Henan Province Fifth Geological Brigade Co., Ltd.

The remaining 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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Chen, L., Hao, J. M., Wang, F., Yin, Y. Y., Gao, Y., Duan, W. K., et al. (2016). Carbon sequestration function of cultivated land use system based on the carbon cycle for the Huang-Huai-Hai Plain. *Resour. Sci.* 38 (6), 1039–1053. doi:10.18402/resci.2016.06.04

Chen, S., Hou, M. Y., Li, Y. Y., Deng, Y. J., and Yao, S. B. (2022). Spatial-temporal matching patterns for grain production using water and energy resources and damping effect in the Yellow River Basin. *Trans. Chin. Soc. Agric. Eng.* 38 (18), 246–254. doi:10.11975/j.issn.1002-6819.2022.18.027

Dong, P. Y., and Zhao, H. F. (2019). Study on trade-off and synergy relationship of cultivated land multifunction: a case of Qingpu District, Shanghai. *Resour. Environ. Yangtze Basin* 28 (2), 368–375. doi:10.11870/cjlyzyyhj201902013

Fang, Y., Wang, J., Kong, X. S., Wu, R. T., Li, B. L., and Liu, L. L. (2018). Trade-off relation measurement and zoning optimization of multi-functionality of cultivated land use: a case study of Henan province. *Chin. Land Sci.* 32 (11), 57–64. doi:10.11994/zgtdkx.20181019.151512

Fei, X., Shao, Y. P., Xu, B. G., Huan, L., Xie, X. F., Xu, Y., et al. (2023). Evaluation and zoning of cultivated land quality based on a space–function–environment. *Land* 12 (1), 174. doi:10.3390/land12010174

Gao, X., Song, Z. Y., Li, C. X., Cha, L. S., Liang, S. Y., and Tang, H. Z. (2021). Spatial differentiation characteristics of cultivated land multifunctional value under urban-rural gradient. *Trans. Chin. Soc. Agric. Eng.* 37 (16), 251–259. doi:10.11975/j.issn.1002-6819.2021.16.031

He, B. (2021). "Research on the coupling and coordinated development of agricultural economy and ecological environment in the middle and lower reaches of the Yellow River,". Master' Thesis (Taiyuan, China: Shanxi Normal University).

Jiang, Y., Yang, C. M., Nie, Y., Wang, R., and Wu, Y. E. (2021). Spatio-temporal evolution and coupling coordination analysis of farmland multi functions in county regions of Hubei province, China. *Mountain Research* 39 (6), 891–900. doi:10.16089/j.cnki.1008-2786.000647

Jones, P. G., and Thornton, P. K. (2015). Representative soil profiles for the Harmonized World Soil Database at different spatial resolutions for agricultural modelling applications. *Agric. Syst.* 139, 93–99. doi:10.1016/j.agsy.2015.07.003

Li, Y. (2023). "Multifunctional evaluation and zoning of cultivated land on the perspective of demand and supply: a case study of the Yangtze River middle reaches urban agglomeration,". Master' Thesis (Nanchang, China: Jiangxi Normal University).

Liu, Y., Wan, C. Y., Xu, G. L., Chen, L. T., and Yang, C. (2023). Exploring the relationship and influencing factors of cultivated land multifunction in China from the perspective of trade-off/synergy. *Ecol. Indic.* 149, 110171. doi:10.1016/j.ecolind.2023.110171

Luo, S. D., Lai, Q. B., Wang, X. D., Wang, Y. P., and Zhao, Y. F. (2023). Control and management of Cropland regionalization in Fujian Province of China using multi-functional evaluation and trade-off/synergy relationships. *Trans. Chin. Soc. Agric. Eng.* 39 (13), 271–280. doi:10.11975/j.issn.1002-6819.202302160

Lv, L. G., Han, X., Long, H. L., Zhou, B. B., Zang, Y. Z., Wang, J., et al. (2023). Research progress and prospects on supply and demand matching of farmland multifunctions. *Resour. Sci.* 45 (7), 1351–1365. doi:10.18402/resci.2023.07.06

Niu, H. P., Zhao, X. M., Xiao, D. Y., An, R., and Liu, M. M. (2022). Spatial-temporal pattern evolution and trade-off relationship of cultivated land multifunction in the Yellow River Basin (Henan Section). *Trans. Chin. Soc. Agric. Eng.* 38 (23), 223–236. doi:10.11975/j.issn.1002-6819.2022.23.024

Niu, P., Zhou, J. X., Yang, Y. F., and Xia, Y. T. (2022). Evolution and trade-off in the multifunctional cultivated land system in henan province, China: from the perspective of the social-ecological system. *Front. Ecol. Evol.* 10. doi:10.3389/fevo.2022.822807

Pang, C. Y., Wen, Q., Ding, J. M., Wu, X. Y., and Shi, L. N. (2024). Ecosystem services and their trade-offs and synergies in the upper reaches of the Yellow River basin. *Acta Ecol. Sin.* 44 (12), 5003–5013. doi:10.20103/j.stxb.202306281376

Qian, F. K., Chi, Y. R., and Lal, R. (2020). Spatiotemporal characteristics analysis of multifunctional cultivated land: a case-study in Shenyang, Northeast China. *Land Degrad. and Dev.* 31 (14), 1812–1822. doi:10.1002/ldr.3576

Qian, F. K., Chi, Y. R., Xu, H., Pang, R. R., Wang, S. Z., Li, H. X., et al. (2022). Study on evolution of trade-off and synergy relationship of multifunctional cultivated land from 2006 to 2020: a case of shenyang city. *China Land Sci.* 36 (10), 31–39. doi:10.11994/zgtdkx.20220919.110225

Song, X. Q., and Li, X. Y. (2019). Theoretical explanation and case study of regional cultivated land use function transition. *Acta Geogr. Sin.* 74 (5), 992–1010. doi:10.11821/dlxb201905012

Sylla, M., Hagemann, N., and Szewrański, S. (2020). Mapping trade-offs and synergies among peri-urban ecosystem services to address spatial policy. *Environ. Sci. Policy* 112, 79–90. doi:10.1016/j.envsci.2020.06.002

Wang, L. L., Hu, Q. Y., Liu, L. M., and Yuan, C. C. (2023). Land use multifunctions in metropolis fringe: spatiotemporal identification and trade-off analysis. *Land* 12 (1), 87. doi:10.3390/land12010087

Wang, X. W., and Chen, H. (2022). Dynamic changes of cultivated land use and grain production in the lower reaches of the Yellow River based on GlobeLand30. *Front. Environ. Sci.* 10, 974812. doi:10.3389/fenvs.2022.974812

Wang, Y. T., and Yang, Q. (2024). Analysis of temporal and spatial evolution characteristics of coupling coordination of cultivated land" production-living-ecological "space in upper reaches of Yellow River-A case study of Gansu province. *J. Agric. Sci. Technol.* doi:10.13304/j.nykjdb.2024.0282

Wang, Z. J., Yang, H., Hu, Y. M., Peng, Y. P., Liu, L., Su, S. Q., et al. (2023). Multifunctional trade-off/synergy relationship of cultivated land in Guangdong: a long time series analysis from 2010 to 2030. *Ecol. Indic.* 154, 110700. doi:10.1016/j.ecolind.2023.110700

Wei, X. D., Lin, L. G., Luo, P. P., Wang, S. N., Yang, J., and Guan, J. (2022). Spatiotemporal pattern and driving force analysis of multi-functional coupling coordinated development of cultivated land. *Trans. Chin. Soc. Agric. Eng.* 38 (4), 260–269. doi:10.11975/j.issn.1002-6819.2022.04.030

Wu, Z. H., Hao, J. M., Chen, H., and Tan, Y. Z. (2024). Multifunctional evaluation and key tradeoffs and synergy relationships of cultivatedland in Hebei province of China. *Trans. Chin. Soc. Agric. Eng.* 40 (14), 199–209. doi:10.11975/j.issn.1002-6819.202403052

Xiong, C. S., Zhang, Y. L., Wang, Y. J., Luan, Q. L., and Liu, X. (2021). Multi-function evaluation and zoning control of cultivated land in China. *Chin. Land Sci.* 35 (10), 104–114. doi:10.11994/zgtdkx.20210916.155106

Zhang, L. G., Lu, R. C., Ma, G. B., and Ma, D. Y. (2024). Multifunctional utilization and optimization strategy of cultivated land in guangxi section of Pearl River-xijiang river economic belt. *Res. Soil Water Conservation* 31 (3), 276–286.

Zhang, L. G., Wang, Z. Q., Chai, J., and Li, B. Q. (2019). Multifunction spatial differentiation and comprehensive zoning of cultivated land in hubei province. *Areal Res. Dev.* 38 (5), 125–130. doi:10.3969/j.issn.1003-2363.2019.05.024

Zhang, S. Y., Hu, W. Y., Li, M. R., Guo, Z. X., Wang, L. Y., and Wu, L. H. (2021). Multiscale research on spatial supply-demand mismatches and synergic strategies of multifunctional cultivated land. *J. Environ. Manag.* 299, 113605. doi:10.1016/j.jenvman.2021.113605

Zhang, Y., Dai, Y. Q., Chen, Y. Y., and Ke, X. L. (2023). Spatial-temporal evolution and driving factors of cultivated land multifunctional coupling coordination development in China. *Trans. Chin. Soc. Agric. Eng.* 39 (7), 244–255. doi:10.11975/j.issn.1002-6819.202209185

Zhao, S. X., Li, Z. Z., and Wang, B. (2024). Trade-off and synergy relationships and regional regulation of multifunctional cultivated land in Henan province. *Transactions of the Chinese Society for Agricultural Machinery*55 (11), 363–374. doi:10.6041/j.issn.1000-1298.2024.11.036

Zhou, X., Wu, D., Li, J. F., Liang, J. L., Zhang, D., and Chen, W. X. (2022). Cultivated land use efficiency and its driving factors in the Yellow River Basin, China. *Ecol. Indic.* 144, 109411. doi:10.1016/j.ecolind.2022.109411

Zhou, Y., Yu, S. J., and Yu, Z. Y. (2025). Spatiotemporal coupling of grain production, economic development, and ecological protection in China′s major grain-producing areas. *Acta Ecol. Sin.* 45 (4), 1–15. doi:10.20103/j.stxb.202311302615

Zhu, C. M., Li, W. Y., Du, Y. Y., Xu, H. W., and Wang, K. (2020). Spatial-temporal change, trade-off and synergy relationships of cropland multifunctional value in Zhejiang Province, China. *Trans. Chin. Soc. Agric. Eng.* 36 (14), 263–272. doi:10.11975/j.issn.1002-6819.2020.14.032

Zou, L. L., Li, Y. R., Liu, Y. S., and Wang, J. Y. (2021). Theory building and empirical research of production-living-ecological function of cultivated land based on the elements. *Geogr. Res.* 40 (3), 839–855. doi:10.11821/dlyj020200400