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Exploring an integrated framework for “dynamic-mechanism-clustering” of multiple cultivated land functions in the Yangtze River Delta region

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A R T I C L E I N F O

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A B S T R A C T

Coordinating multiple cultivated land functions (CLFs) has become a key challenge for land system science. Identifying the dynamic evolution and mechanisms of multiple CLFs will help to formulate targeted cultivated land management policy for achieving the sustainable development of highly urbanized areas. This study quantified four primary CLFs, i.e., agricultural production function (APF), social security function (SSF), ecological service function (ESF), and landscape aesthetic function (LAF) at the prefecture-level cities of the Yangtze River Delta region and then explored an integrated framework for “dynamic-mechanism-clustering” of these CLFs. The results showed that four primary CLFs varied substantially across the prefecture-level cities and presented significant changes over time. The slope has a great negative impact on multiple CLFs. Precipitation was negatively correlated with APF and ESF, rural residents’ income and distance to the road showed negative correlations with SSF and LAF. The areas covered by large-scale contiguous cultivated land presented the strongest cultivated land multifunctionality, whereas the highly urbanized areas and the areas with considerable forest land showed weak cultivated land multifunctionality. We suggested that decision-makers should consider the underlying drivers of multiple CLFs for better cultivated land management and promoting the sustainable use of cultivated land.

1. Introduction

Cultivated land provides the fundamental guarantee for human survival and socioeconomic development (Lai et al., 2020; Zhou et al., 2021). In the context of the rapid development of China’s industrialization and urbanization over the past forty years, the expansion of urban space dominated by land urbanization has caused a large loss of cultivated land resources (Fang & Yu, 2020; Huang et al., 2019; Sun et al., 2020). Along with the concentration of population, capital, industry and other factors to cities and towns, the problems of non-agriculturalization, non-grain and marginalization of cultivated land have become increasingly prominent in China (Deng et al., 2015; Liang et al., 2022; Liu & Zhou, 2021; Song & Pijanowski, 2014; Zhang et al., 2018, 2023). Cultivated land degradation, soil erosion, and habitat fragmentation have also been common occurrences in China, especially in well-developed areas (Han et al., 2020; Liu et al., 2015, 2019; Wu et al., 2017). The traditional management of cultivated land that only focuses on the production function of cultivated land has been difficult to meet the growing needs of people (Li et al., 2023; Liu et al., 2020; Peng, Hu, Qiu, et al., 2019). Exploring new cultivated land management strategies considering the multifunctionality and multiple values of cultivated land has become a topic widely concerned by academia and decision-makers (Bretagnolle et al., 2018; Hodbod et al., 2016; Jiang et al., 2020; Liang & Li, 2020; Song et al., 2015; Zhang et al.,

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2018).

Cultivated land functions (CLFs) are the ability of different cultivated land uses to provide goods and services (Jiang et al., 2020; Pérez-Soba et al., 2008, pp. 375–404; Zhang et al., 2018). Cultivated land is not only an important factor in agricultural production to provide food and fiber for human survival but also a key resource for supporting human life, and providing economic and employment security (Kremen & Merenlender, 2018; Liu et al., 2018). The connotation of CLF has also been further expanded to promote the development of agricultural social-ecological system based on the relevant research in the field of ecosystem services and landscape functions (Bretagnolle et al., 2018; Costanza et al., 2017; De Groot et al., 2010; Liang et al., 2020; Long et al., 2014; Lovell et al., 2010). The CLFs concept therefore links directly the production, social, ecological, landscape functions to the cultivated land uses, concerning the economy, society and environment dimensions of sustainability.

The Global Land Project (GLP) regards multifunctionality as a fundamental framework for analyzing the coupling relationship among the economic, social and ecological systems of land use (GLP, 2005). The GLP believes that the multifunctionality of land use is of great significance in clarifying the dynamic mechanisms and pathways of human environmental coupling system changes, as well as sustainable land development (GLP, 2005). With the intensification of the human-land relationship, the multifunctional use of cultivated land provides a new way to alleviate the contradiction between cultivated land protection and socio-economic development that aims to better promote the regional sustainable development (De Groot, 2006; Lovell et al., 2010; Peng et al., 2015; Lai et al., 2020; Qian et al., 2020). However, CLFs are characterized by diversity and complexity, and are subject to human decision-making; there have been dynamic changes in the relationships among different types of CLFs over time, mainly manifested as a trade-off relationship (one function increases and the other decreases) or a synergy relationship (one function increases and the other also increases, Bennett et al., 2009; Fan et al., 2021). Moreover, the diversity of CLF is influenced by the combined effects of natural factors and human factors in the human-land relationship territorial system during the historical development process. Thus, it is indispensable to explore the dynamic evolution of multiple CLFs and their relationships for more effective decision-making to improve the overall benefits of human beings. It is also of great significance to further identify the causes for the changes of CLFs and their impact on sustainable development for a better understanding of land change science.

The Yangtze River Delta (YRD) region is a traditional agricultural region, Jiangsu and Zhejiang provinces were once famous granaries. The YRD region is also one of the regions with the most active economic development in China. With the continuous advancement of industrialization and urbanization in the YRD region, the quantity of cultivated land in the region has decreased significantly. The region coveres 12.65 million hectares of cultivated land with only 0.055 ha of cultivated land per capita that is significantly lower than the national level of cultivated land per capita (0.093 ha). The sustainable utilization of cultivated land in the YRD region is also facing the following severe challenges, such as, the decrease of cultivated land quality, the low efficiency of cultivated land use, and agricultural non-point source pollution (Hou et al., 2019; Sun et al., 2018; Zhu & He, 2021). Additionally, the disorderly expansion of urban and rural construction land has a non-negligible impact on the increase of cultivated land fragmentation in the region (Liu et al., 2019; Long et al., 2007; Zhou et al., 2022). With the increasingly negative impact of human activities on the cultivated land system gradually expanded, coordinating the relationship between food security, resource and environmental constraints and economic development has been a key issue of cultivated land protection research in the YRD region. Thus, this study takes the YRD region as an example, and attempts to explore the spatial-temporal characteristics and influencing factors of multiple CLFs in the YRD region. First, we establish a classification and evaluation system to quantify the multiple CLFs. Then, we further identify the spatial-temporal characteristics of multiple CLFs and the interactions among these CLFs in the region. Subsequently, we reveal the influencing factors of multiple CLFs and the multifunctionality of cultivated land in the YRD region. Finally, we propose some policy implications that aims to provide a reference for decision makers to use, manage and protect cultivated land more effectively, as well as discuss the contributions, limitations of this study and the future prospects for CLF analysis.

2. Literature review and research framework

2.1. Literature review

The concept of CLF originally originated from the agricultural sector and refers to the original and primary function of material production (Hodbod et al., 2016; Peng et al., 2015, 2017; Potter & Tilzey, 2007). Scholars have made some explorative studies on the connotation, classification and management of CLFs in the existing literature (Andersen et al., 2013; Bretagnolle et al., 2018; Jiang et al., 2020; Moon, 2015; Qian et al., 2020; Song et al., 2015; Song & Ouyang, 2012; Zhang et al., 2018, 2021). Andersen et al. (2013) constructed a classification system for four functions including production, housing, biological protection, and entertainment and leisure based on the farm scale. Song et al. (2015) discussed the connotation of CLF and the change process of CLF in China under the policy guidance, and proposed the practical path of multifunctional management of cultivated land. Some studies have also established the framework of cultivated land function classification from the perspectives of production (economy), society, ecology and culture (Jiang et al., 2020; Qian et al., 2020; Zhang et al., 2018). Some scholars have conducted studies on CLF assessment focus on either socio-economic or ecological aspects of cultivated land use and to quantify each CLF using value evaluation or indicator evaluation (Gu & Song, 2022; Jiang et al., 2020; Li et al., 2023; Peng et al., 2015; Pywell et al., 2011; Qian et al., 2020; Zhang et al., 2018; Zhu et al., 2020). Pywell et al. (2011) confirmed the value of ecological restoration as a potentially useful means of enhancing ecosystem function within intensive farmland systems. Jiang et al. (2020) have conducted a CLF assessment, which refer to production function, economic function, ecological function, social security function, and cultural landscape function, from the product perspective using the comprehensive weighting method.

In existing studies, socio-economic and environmental statistical data are the most commonly used data for CLF assessment that could provide effective support for the assessment of the production function and social function of cultivated land (Gu & Song, 2022; Jiang et al., 2020; Qian et al., 2020; Zhang et al., 2018; Zhu et al., 2020). Limited by data used in previous studies, the simple statistical analysis methods and comprehensive weighting method were most commonly used for quantifying each CLF and identifying the cultivated land multifunctionality, respectively (Jiang et al., 2020; Song et al., 2022; Zhang et al., 2018). These methods provide alternative approaches to the CLF assessment. In recent years, fine-scale data, such as land use and land cover data, meteorological data, soil data, and remote sensing data have been proven to be available for assessing the ecosystem services and monitor their changes (Dobbs et al., 2018; Feng, Zhao, et al., 2020; Renard et al., 2015; Wang, Hu, et al., 2022; Zhang et al., 2022). Geospatial analysis methods (e.g., InVEST, RUSLE) also have been widely applied to quantify various ecosystem services at a fine scale for better identifying the ecosystem issues in a specific region (Feng, Zhao, et al., 2020; Grafius et al., 2016; Hoyer & Chang, 2014; Peng, Hu, Wang, et al., 2019; Wang, Hu, et al., 2022; Wu et al., 2019).

The diversity of CLF is the result of the joint impact of natural factors and human factors on the regional system of human-land relationship (De Groot, 2006; Gutzler et al., 2015; Chen et al., 2021; Xie et al., 2021; Kang et al., 2023). It is important to explore the influencing factors of multiple CLFs when it comes to the interrelationship analysis between human society and natural ecosystems. Previous studies have concentrated on the spatial characteristics of multiple CLFs or cultivated land multifunctionality (Chen et al., 2022; Gu & Song, 2022; Liang et al., 2020; Qian et al., 2020; Song et al., 2015,2022; Zhu et al., 2020). The correlation analysis is the most commonly used method for revealing the interrelationships between two functions. Additionally, some scholars either tried to explore the reasons for the spatial variation of the value of the cultivated land multifunction based on the impact of different kinds of individual CLFs or analyzed the impact of socio-economic factors (e.g., urbanization processes, agricultural machinery level) on the cultivated land multifunction (Chen et al., 2022; Jiang et al., 2020; Zhang et al., 2018).

In summary, the research on CLF has received widespread attention from the academic community, and has achieved significant progress in both theoretical and methodological aspects. However, the existing studies tend to focus on a certain aspect of dynamic, mechanism or clustering of CLFs, lack of an integrated analysis refers to dynamic, interaction, driver and clustering of CLFs. To my knowledge, there are still some deficiencies in the selection of evaluation indicators, evaluation methods, and correlation analysis of multiple CLFs. First, the selection of the CLF evaluation indicators often lacked scientific and universal criteria in the previous studies and failed to well characterize the actual value of each CLF. The production function of cultivated land in some previous studies was characterized using the indicators considering socio-economic factors, such as output value of crops (Gu & Song, 2022; Zhu et al., 2020), weakening the material production function of cultivated land itself. Environmental impact indicators were commonly used to characterize the ecological function of cultivated land, such as the intensity of pesticide and fertilizer use, and the distance to the nearest town (Gu & Song, 2022; Qian et al., 2020; Xiang et al., 2019). These indicators may affect the ecological function and the production function simultaneously, but it is difficult to effectively represent the ecological value of cultivated land. Second, the statistical data used in previous studies are difficult to be directly used to accurately identify the ecological function of cultivated land, such as water conservation, soil conservation, and climate regulation. The simplicity of the CLF evaluation method also has a certain degree of limitation on the understanding of the CLF connotation and characteristic. In addition, the correlation analysis is unable to measure the relationships for more than two functions and also cannot identify the spatial variation of the relationships among multiple CLFs at the regional scale. There is also a lack of analysis on the mechanism of complex socio-ecological factors affecting the various types of CLFs.

Thus, in this study, we aim to explore an integrated framework of "dynamic-mechanism-clustering" of multiple CLFs for revealing the spatial-temporal characteristics and their trade-offs of multiple CLFs as well as the underlying mechanism of these CLFs in the YRD region, a highly urbanized area. Our study first attempts to apply the "agricultural production-social security-ecological service-landscape aesthetic" classification framework of CLF for more effectively assessing and better identifying the key socioeconomic and ecological issues of cultivated land system from 2000 to 2020 combining multi-source data (e.g., land use and land cover, socioeconomic, environmental, and remote sensing information) at the fine scale with multiple geospatial analysis methods. Then, we introduce root mean squared error (RMSE) to quantitatively reveal the magnitude of the trade-off among the four primary CLFs at the prefecture-level cities during the study period and further identify the potential socio-ecological influencing factors of these CLFs. Finally, we explore the clustering of multiple CLFs to reveal the cultivated land multifunctionality of the study area.

2.2. Research framework

The interaction between human activities and natural environment reflects the utilization and influence of human activities on the land system, which runs through all stages of socioeconomic development. With the deepening of integration between human activities and natural environment, the complexity of the impact of human activities on the land system is increasing. The multifunctionality of cultivated land is coupled with the socioeconomic development stage, characterized by the differences in the provision of human well-being by cultivated land systems. There are differences in the lifestyles and consumption demands of human groups under the different stages of socioeconomic development; therefore, the human demands and concerns for the functions of cultivated land are also various.

In this context, our study classified the CLFs into four primary functions, i.e., agricultural production function, social security function, ecological service function, and landscape aesthetic function. Then, we took the YRD region as a case study area to explore the dynamic evolution of multiple CLFs (e.g., the temporal variation characteristics of multiple CLFs from 2000 to 2020 and the spatial variation characteristics of multiple CLFs at the prefecture-level). We measured the magnitude of the trade-offs among multiple CLFs to reveal the internal associations of these CLFs and their spatial-temporal characteristics. We also constructed an index system of potential influencing factors associated with multiple CLFs, including environmental factor, geographical location factor, socioeconomic factor, agricultural modernization factor, and to explore the direction and degree of influence for these external drivers of multiple CLFs. We finally calculated the aggregated CLF value and the number of CLF with relevant supply to identify the clustering of multiple CLFs for revealing the cultivated land multifunctionality. The detailed research framework is shown in Fig. 1.

3. Methodology and data resource

3.1. Study area

The YRD region is located in eastern China, bordering on the Yellow Sea and the East China Sea (Fig. 2). The region covers an area of 358,000 square kilometers, including Shanghai (a city directly under the central government), Jiangsu Province (JS), Zhejiang Province (ZJ), and Anhui Province (AH), with a total of 41 prefecture-level cities. The YRD region has the highest river network density in China, with an average river network length of 4.8–6.7 km per square kilometer. The region is crisscrossed by rivers, lakes and developed agriculture. Jiangsu and Anhui are China's important agricultural provinces. The production scale of grain crops such as rice in the YRD region is large. Anhui and Jiangsu are the main producing areas of cotton and rapeseed in China. In recent years, grain production in the region has shown an upward trend for a long time. The grain yield of the region accounts for more than 12% of the nation's total grain yield in 2020 (National Bureau of Statistics, 2021).

The YRD region is also one of China's most active economic development regions, with a population of 235 million in 2020 (National Bureau of Statistics, 2021). In 2020, the gross domestic product of the YRD region reached 24.5 trillion RMB; the urbanization rate of the permanent population has exceeded 60% (National Bureau of Statistics, 2021). The region has produced nearly 1/4 economic output of China with less than 4% of the land area. However, extensive and unrestrained over-development, and urban space disorderly sprawl, resulting in too fast and too much reduction of agricultural and ecological spaces, which negatively affects the layout optimization and utilization efficiency of regional land space. The sharp increase in domestic and industrial solid waste has led to aggravated soil pollution of cultivated land. Some farmland soils are seriously polluted by polycyclic aromatic hydrocarbons or heavy metals in the region.

3.2. Quantification and spatial-temporal variation analysis of CLFs

Considering the availability of data and the realizability of CLFs quantification methods, this study selected 15 indicators for characterizing and quantifying the multiple CLFs (Table 1). Agricultural

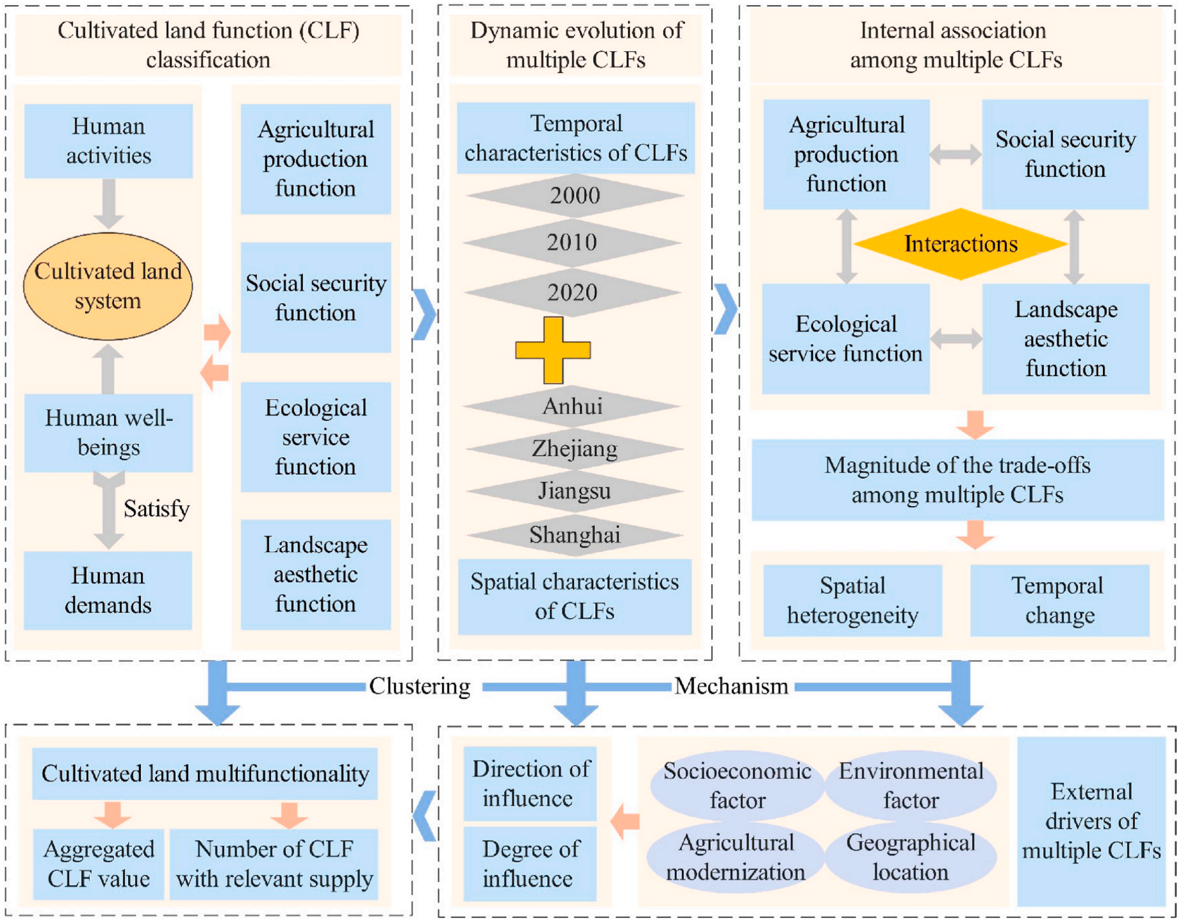

Fig. 1. Research framework of this study.

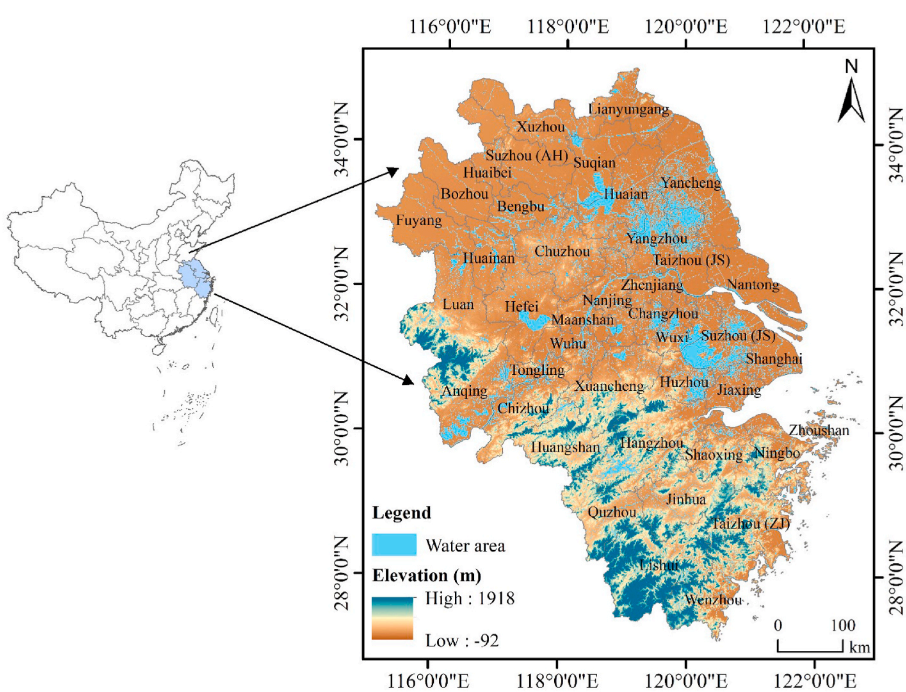

Fig. 2. Location map of the study area.

Table 1
The indicators for characterizing the multiple CLFs and their calculation methods.

Function	Indicator	Calculation method	Unit	Attribute
Agricultural production function	Grain yield per unit area	Total grain yield/ Total sown area of grain	kg/km^2	+
	Cotton yield per unit area	Total cotton yield/ Total sown area of cotton	kg/km^2	+
	Oil crop yield per unit area	Total oil crop yield/Total sown area of oil crop	kg/km^2	+
	Vegetable yield per unit area	Total vegetable yield/Total sown area of vegetable	kg/km^2	+
	Melon yield per unit area	Total melon yield/ Total sown area of melon	kg/km^2	+
Social security function	Cultivated land area per capita	Total cultivated land area/Total rural population	km^2/ Person	+
	Agricultural output value per capita	Total agricultural output value/Total rural population	RMB/ Person	+
	Proportion of agricultural employees	Agricultural employees/Total rural population × 100%	%	+
Ecological service function	Water yield	InVEST	mm	+
	Soil retention	RUSLE	kg	+
	Carbon sequestration	Net Primary Productivity (NPP)	g	+
	Habitat quality	InVEST	–	+
Landscape aesthetic function	Average patch area	Fragstats	km^2	+
	Landscape shape index	Fragstats	–	–
	Aggregation index	Fragstats	%	+

production function (APF) refers to the ability of the cultivated land systems to provide various agricultural products for humans. Thus, the yields per unit area of the main agricultural products, i.e., grain, cotton, oil crop, vegetable, and melon, are selected as indicators for characterizing APF. Social security function (SSF) refers to the ability of cultivated land system to ensure basic human life. Cultivated land is the basic guarantee for rural residents' survival and could provide humans employment opportunities. Cultivated land area per capita, agricultural output value per capita and proportion of agricultural employees are considered for characterizing SSF. Ecological service function (ESF) refers to the ability of the cultivated land systems to provide ecological products or services for humans. The indicators used in previous studies for quantifying ecosystem services, e.g., water yield, soil retention, carbon sequestration, and habitat quality, are selected for characterizing ESF in this study. Landscape aesthetic function (LAF) refers to the ability to create visual aesthetics for humans. Generally, large, regular, continuous cultivated land can provide a more aesthetic landscape for human appreciation. Consequently, three indicators, i.e., average patch area, landscape shape index, and aggregation index of cultivated land, are used to characterize LAF. The calculation methods of the indicators are presented in Table 1.

Then, we standardized each indicator using the maximum and minimum value method combined with the attribute of each indicator to enable the comparison of the indicators at the prefecture-level. The calculation method is as follows,

$$\text{for positive indicators}: X_{ij\_std} = \frac{X_{ij} - X_{i\_min}}{X_{i\_max} - X_{i\_min}} \quad (1)$$

$$\text{for negative indicators}: X_{ij\_std} = \frac{X_{i\_max} - X_{ij}}{X_{i\_max} - X_{i\_min}} \quad (2)$$

where X_{ij}, X_{ij_std} represents the value and the standardized value of the ith CLF indicator for the prefecture-level city j, respectively; X_{i_max}, X_{i_min} represents the maximum value and the minimum value of the ith CLF indicator for the prefecture-level city j, respectively.

In addition, a simple unweighted summation of the standardized indicators' values was used to calculate each primary CLF value at the prefecture-level. We calculated the change rate of each primary CLF from 2000 to 2020 at the prefecture-level to further reveal the spatial-temporal variation of the CLFs. The calculation formula for the change rate is as follows:

$$CLF_{kj\_cr} = \frac{CLF_{kj\_T_2} - CLF_{kj\_T_1}}{CLF_{kj\_T_1}} \times 100\% \quad (3)$$

where CLF_{kj_cr} represents the change rate of the kth function for the prefecture-level city j during the period of T_1-T_2; CLF_{kj_T1}, CLF_{kj_T2} represents the value of the kth function for the prefecture-level city j at the time of T_1 and T_2, respectively.

3.3. Interaction analysis among multiple CLFs

The interactions among multiple CLFs are commonly characterized as trade-offs or synergies (Bennett et al., 2009; Fan et al., 2021). A trade-off was regarded as a negative correlation, and a synergy was regarded as a positive correlation in the paired CLFs from the perspective of the traditional statistical method (Chabert & Sarthou, 2020; Feng et al., 2020; Sun et al., 2022). However, a correlation analysis only can identify the general interaction between two functions in the whole area. In this study, we used root mean squared error (RMSE) of individual CLFs to reveal the magnitude of the trade-off among multiple CLFs at the prefecture-level, and a trade-off represents an outcome of high value in some CLFs and low value in others. RMSE could measure the average difference between each individual CLF value and the mean CLF value, and thus describes the magnitude of the trade-off between two or more CLFs (Bradford & D'Amato, 2012; Feng, Zhao, et al., 2020). The calculation method of RMSE is as follows:

$$\text{RMSE}_j = \sqrt{\frac{1}{n-1} \times \sum_{k=1}^{n} \left(CLF_{kj} - \overline{CLF_j}\right)^2} \quad (4)$$

where CLF_{kj} is the value of the kth CLF for the prefecture-level city j and $\overline{CLF_j}$ is the average value of n CLFs for the prefecture-level city j. A higher RMSE value indicates a larger average difference between each individual CLF value and the mean CLF value, and the situation represents a greater trade-off among multiple CLFs.

3.4. Influencing factors analysis of CLFs

Spatial-temporal variations of CLFs are affected by the natural environment and human activities. Considering the public perception and relevant research (Jiang et al., 2020; Liang and Li, 2020; Li et al., 2021; Peng et al., 2017; Zhang et al., 2018), we selected ten potential influencing factors in this study for exploring the determinants of multiple CLFs, and these factors were further divided into four types, i.e., environmental factor, geographical location factor, socioeconomic factor, and agricultural modernization factor. Detailed descriptions of these influencing factors are shown in Table 2.

We conducted a redundancy analysis (RDA) to explore the relationship between multiple CLFs and the potential influencing factors and identify the significant influencing factors of the CLFs at the prefecture-level using the software Canoco 5.1.

Table 2
Description of influencing factors of CLFs.

Type	Influencing factor	Code	Unit
Environmental factor	Slope	Slope	°
	Annual precipitation	Prec	mm
	Cultivated land quality	Quality	Grade
Geographical location	Distance to the nearest road	Dis_road	m
	Distance to the nearest water area	Dis_water	m
Socioeconomic factor	Urbanization rate	Urban	%
	Per capita disposable income of rural residents	Income	RMB/person
	Proportion of non-agricultural industry output	Industry	%
Agricultural modernization	Total power of agricultural machinery per unit area	Power	kw/km^2
	Agricultural chemical fertilizer application amount per unit area	Fertilizer	kg/km^2

Table 3
Spatial resolution and sources of data used in this study.

Data type	Data name	Spatial resolution	Data source
Land use/land cover data	GlobeLand30	30m × 30 m	National Geomatics Center of China
Environmental data	DEM	30m × 30 m	Geospatial Data Cloud
	Precipitation	Meteorology station	Meteorological Administration Meteorological Data Center of China
	Soil data	1:100,0000	Soil Database of China
	Watershed data	1:25,0000	Resource and environmental science and data center of Chinese Academy of Sciences
	Road data	1:25,0000	Gaode Map
	Cultivated land quality	1:10,0000	Ministry of Natural Resources of the People's Republic of China
Remote sensing data	Leaf Area Index	1km × 1 km	U.S. National Oceanic and Atmospheric Administration
	Net Primary Productivity	1km × 1 km	
	Normalized Differential Vegetation Index	500m × 500 m	
	Evapotranspiration	500m × 500 m	
Socioeconomic data	Crop yield Sown area of crops Population Agricultural output value Non-agricultural industry output value Agricultural employees Disposable income of rural residents Total power of agricultural machinery Agricultural chemical fertilizer application amount	Prefecture-level	Statistical Bureau of Shanghai, Jiangsu, Zhejiang, Anhui

3.5. Cultivated land multifunctionality analysis

We used aggregated CLF value and the "richness" in CLFs to indicate the cultivated land multifunctionality in the study area. Aggregated CLF value was calculated using a simple unweighted summation of the values of the four primary CLF at the prefecture-level. The "richness" in CLFs was measured using the number of CLF with substantial supply in each prefecture. The prefecture-level city was assigned as one if it could supply a CLF substantially; otherwise, it was assigned as zero. A substantial CLF supply in the prefecture-level city refers to the CLF value in this prefecture-level city being equal or higher than the average CLF value of the whole study area.

3.6. Data sources

In this study, we collected and applied multi-source datasets to quantify the multiple CLFs and measure the potential influencing factors. Data description, including the data type, resolution, and source could be found in Table 3. We used land use/cover change datasets of 2000, 2010 and 2020 in the YRD region to extract the spatial information of cultivated land for quantifying the cultivated land area per capita, average patch area, landscape shape index, aggregation index and measuring the agricultural modernization factors. The indicators of ecological service function were quantified using environmental and remoting sensing data. We used socioeconomic data from 2000 to 2020 to quantify the indicators of agricultural production function and social security function. The potential influencing factors, including environmental factor, geographical location factor, and socioeconomic factor were measured by combining with the land use/land cover, environmental and socioeconomic data.

4. Results

4.1. Spatial-temporal characteristics of CLFs

Four primary CLFs (APF, SSF, ESF, and LAF) varied substantially across the prefecture-level cities and presented significant changes over time as shown in Figs. 3 and 4. APF was prominently higher in Shanghai and the central and north of Jiangsu than in the other areas of the YRD region in 2000. Generally, a significant decrease occurred in APF from 2000 to 2020 in the whole study area. For more than one-third of the cities, the decrease rate of APF value was higher than 40% in the study period. The decreased rates of APF values in the study area were more prominent during 2000–2010 than in 2010–2020. APF in the south of Zhejiang, i.e., Jinhua, Lishui, and Taizhou, increased from 2010 to 2020. In 2020, higher values of APF were located in Shanghai and Jiangsu.

Anhui and northern Jiangsu had the higher SSF from 2000 to 2020. Low values of SSF were mainly located in the southeast of Zhejiang in 2000. SSF decreased in the south of Jiangsu and the northeast of Zhejiang and increased in the southwest of Anhui and the south of Zhejiang from 2000 to 2010. During 2010–2020, SSF showed a significant increase in Jiangsu, and decreased SSF was found in Zhejiang, especially in eastern Zhejiang. The values of SSF in the cities of Hangzhou, Jiaxing, Ningbo, Shaoxing, Taizhou, and Zhoushan have decreased by more than 20% from 2010 to 2020.

Higher values of ESF were mainly distributed in the south-central part of Anhui and the north of Zhejiang in 2000. ESF showed an overall increase in the study area during 2000–2010. Increased ESF was mainly found in Shanghai, eastern Anhui and southern Zhejiang, whereas decreased ESF was found in southern Jiangsu, central Zhejiang, and northern Anhui during 2010–2020. Especially, ESF value in Shanghai increased by 20.15% during 2010–2020, which showed the most prominent increase in the period.

High values of LAF were mainly distributed in Jiangsu, Anhui and Shanghai, while the low values were distributed in Zhejiang during the study period. The increased rates of LAF in 14 prefecture-level cities and the decreased rates of LAF in 10 prefecture-level cities have exceeded 10% from 2000 to 2020. LAF showed a prominent increase in Anhui and a prominent decrease in Zhejiang during this period. The LAF values

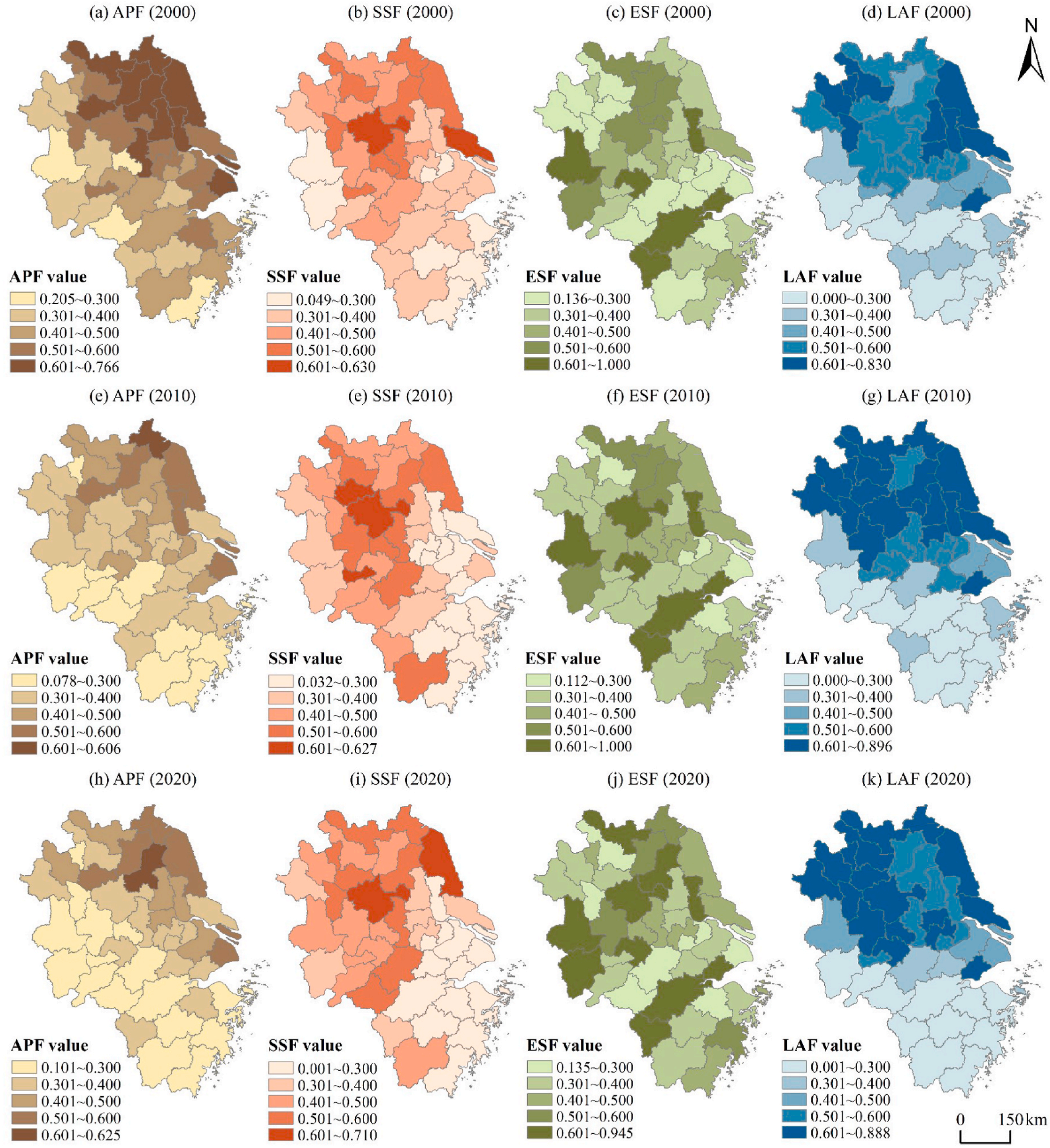

Fig. 3. The values of multiple CLFs from 2000 to 2020 at the prefecture-level in the YRD region.

presented an overall increase in the study area between 2000 and 2010. The LAF values increased significantly in southwestern Anhui and decreased significantly in Zhejiang and central Jiangsu during 2010–2020.

4.2. Spatial-temporal characteristics of trade-offs among multiple CLFs

We mapped the spatial distribution of the RMSE values and their changes for the trade-offs among the four primary CLFs (Fig. 5). The RMSE values of the trade-offs among multiple CLFs for the YRD region ranged from 0 to 0.4. In 2000, the RMSE values of CLF trade-offs in 36 prefecture-level cities were lower than 0.2. The highest RMSE values for CLF trade-offs were distributed in Lu'an, Anhui Province in 2000. In addition, Shanghai, Hangzhou, Bozhou, and Suzhou (AH) also had high RMSE values for CLF trade-offs in 2000. The significantly increased RMSE values in central and southern areas of Anhui from 2000 to 2010 indicated the increased trade-offs of CLFs occurred in these areas. The increased CLF trade-offs during 2000–2010 also be found in Zhejiang.

In 2020, the high RMSE values for CLF trade-offs were mainly distributed in northwest Anhui and northern Zhejiang. The RMSE values for CLF trade-offs in 10 prefecture-level cities were more than 0.2. The CLF trade-offs showed prominent increases in the central and southern Anhui, whereas they presented prominent decreases in the central and northern Jiangsu from 2010 to 2020. Shanghai and southeast Jiangsu (including Suzhou (JS), Wuxi and Nantong) presented a slight decrease (decrease rate less than 20%) for CLF trade-offs. Generally, during the study period, the RMSE values of CLF trade-offs had a remarkable increase in Zhejiang, especially in northern Zhejiang. Also, central and southern Anhui showed a prominent increase in the RMSE values of CLF trade-offs during 2000–2020. The CLF trade-offs showed an overall increase in Shanghai and Jiangsu from 2000 to 2020.

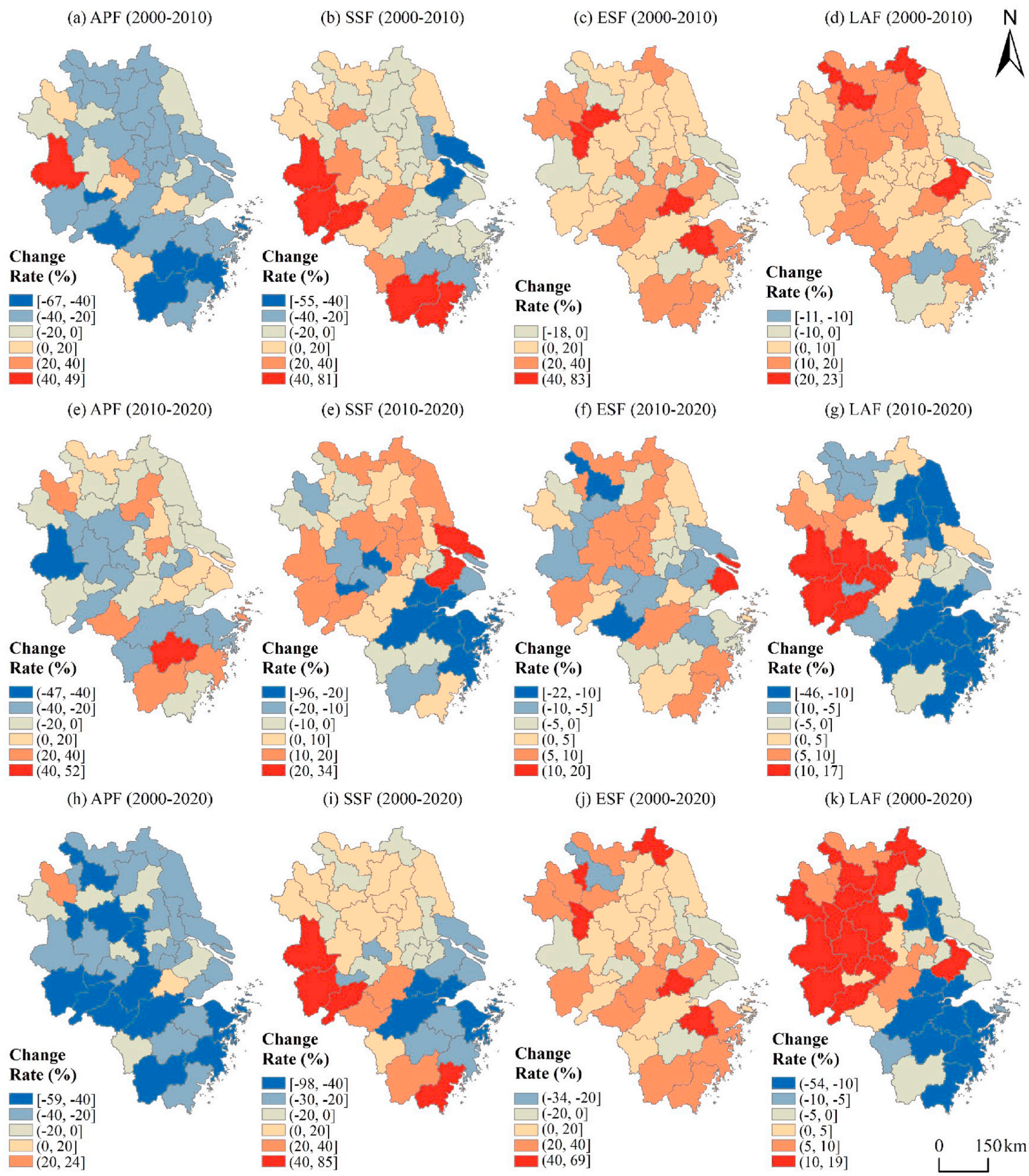

Fig. 4. Change rates of the values of multiple CLFs from 2000 to 2020 at the prefecture-level in the YRD region.

4.3. Influencing factors of CLFs

The two-dimensional ordination diagrams shown in Fig. 6 were obtained from RDA analysis, indicating the relationships between the potential influencing factors and the multiple CLFs in 2000, 2010, and 2020. The permutation test results for all three years are 0.002. The explanatory variables account for 67.7%, 72.9% and 83.2% in the years 2000, 2010 and 2020, respectively, in the YRD region. The two RDA axes explained 80.34%, 82.67%, and 94.42% of the cumulative variance in 2000, 2010, and 2020, respectively. The findings indicated that the selected influencing factors had statistically significant correlations with multiple CLFs in the years of 2000, 2010, 2020 in the YRD region.

The analysis revealed that APF was significantly positively correlated with agricultural chemical fertilizer application amount between 2000 and 2020. Agricultural chemical fertilizer application amount also had a positive relationship with ESF in 2000 and 2010, which can be attributed to the improvement of soil quality that benefits soil retention and water conservation (Jia et al., 2022). We also found that APF was negatively correlated with slope, precipitation, and total power of agricultural machinery. High APF usually occurs in plain areas with flat terrain and appropriate rainfall. Slope and total power of agricultural machinery were also negatively correlated with SSF and LSF during the study period.

Urbanization rate and non-agricultural industry output were negatively correlated with APF in 2000 and negatively impacted on SSF in 2010 and 2020. The loss of cultivated land accounted for urban expansion and directly impacted on the decrease in agricultural productivity. Non-agricultural industry development has resulted in a decline in the comparative benefits of agricultural production and employees. Rural residents' income and distance to the nearest road

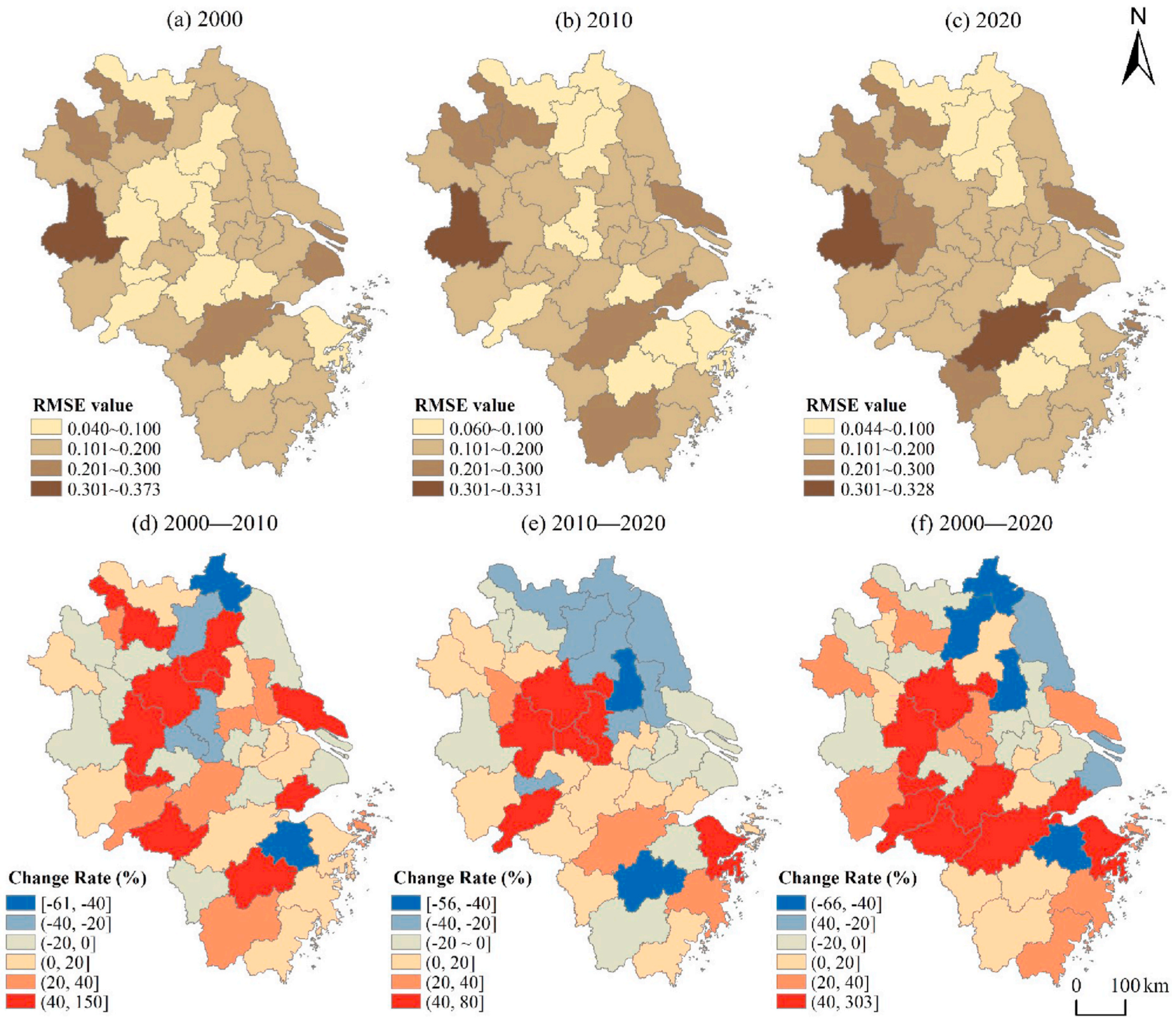

Fig. 5. The RMSE values and their change rates of the trade-offs among multiple CLFs at the prefecture-level during 2000–2020 in the YRD region.

showed negative correlations with SSF and LAF in 2010 and 2020. In addition, cultivated land quality had a negative correlation with APF during 2000–2020 and was negatively correlated with ESF in 2000 and 2010. Slope and precipitation presented negative correlations with ESF in 2010. The distance to the nearest water area positively impacted on SSF and LAF in 2010 and 2020.

4.4. Cultivated land multifunctionality

Overlap analysis showed that high aggregated CLF values were mainly distributed in the central and northern parts of Jiangsu and Anhui (Fig. 7), including the areas with large-scale concentrated and contiguous cultivated land during the study period. These prefecture-level cities also could provide the most CLFs with relevant supply (values ≥mean). On the contrary, highly urbanized prefecture-level cities (e.g., Suzhou, Wuxi, and Shanghai) and those characterized by forest land covers showed few CLFs with relevant supply (e.g., southern Anhui and southeast Zhejiang, Fig. 7). Low aggregated CLF values were found mainly in southern Zhejiang where prefecture-level cities mostly covered by forest land.

The aggregated CLF values showed an overall increase in Anhui from 2000 to 2020, which could be attributed to the increased SSF, ESF, and LAF within this period (Fig. 8(a)). In contrast, Shanghai and southeast Zhejiang had significant decreases (decrease rates exceeded 10%) in the aggregated CLF values from 2000 to 2020 since the decreased APF and SSF during this period (Fig. 8(a)). From 2000 to 2010, Shanghai, Zhejiang, and Jiangsu presented decreasing trends in the aggregated CLF values due to the rapidly decreasing APF. During the study period, Shanghai only could provide APF with relevant supply (values ≥mean, Fig. 8(b)). More than 90% of prefecture-level cities in Jiangsu could provide APF and LAF in a relevant amount (values ≥mean) during 2000–2020. Few prefecture-level cities in Zhejiang could provide APF, SSF, and LAF with relevant supplies from 2000 to 2020. Anhui has the least prefecture-level cities that can provide a relevant amount of ESF within the study period. However, more than 75% of prefecture-level cities in Anhui could provide SSF with relevant supply, and the amount of these prefecture-level cities showed an increasing trend from 2000 to 2020. The prefecture-level cities that could provide LAF in a relevant amount also accounted for two-thirds of the total amount of prefecture-level cities in Anhui during the study period.

5. Discussions

5.1. Contributions and comparisons with previous studies

The CLF is a link between cultivated land's outputs (or services) and the related activities of cultivated land uses (Song et al., 2015). To date, most studies on CLFs have focused on the evaluation of multiple CLFs and cultivated land multifunctionality using statistical data and comprehensive weighting method (Gu & Song, 2022; Jiang et al., 2020; Qian et al., 2020; Song et al., 2022; Zhang et al., 2018; Zhu et al., 2020). Our study tried to integrate multi-source data, including land cover,

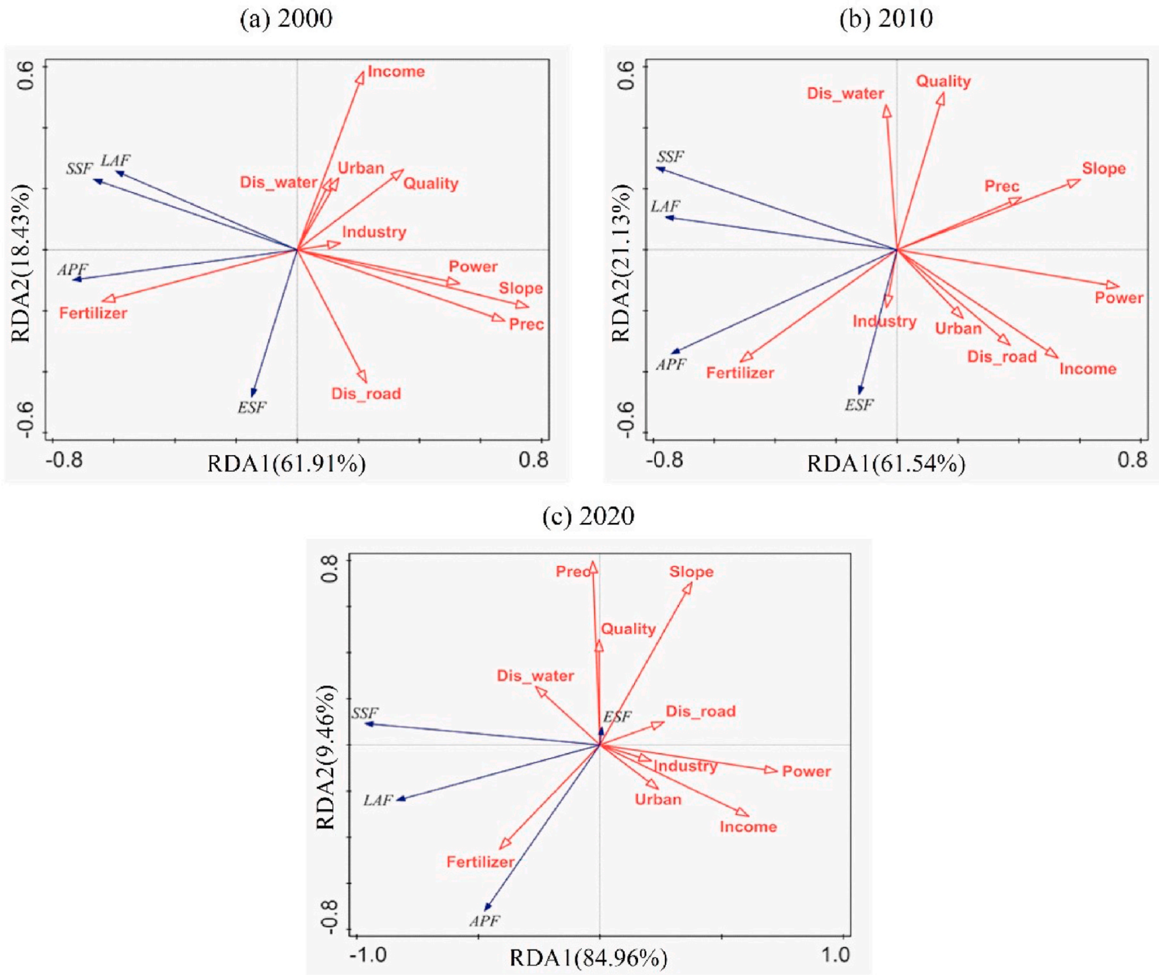

Fig. 6. RDA two-dimensional ordination diagrams indicate the relationships between the potential influencing factors and the multiple CLFs from 2000 to 2020. The blue arrow line indicates the CLFs, and the red arrow line indicates the potential influencing factors.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

social economy, natural environment, and remote sensing information, based on geospatial analysis and landscape ecology methods for scientifically evaluating the different types of CLFs and identifying the spatial-temporal characteristics of multiple CLFs. We found that the multiple CLFs in the YRD region showed significant spatial and temporal variation between the northern and the southern parts. Generally, the value of aggregated CLF was higher in the northern part than those in the southern part of the YRD region. CLFs assessment and identification of their spatial-temporal characteristics in our study could be used to assist in strategic planning of cultivated land protection for improving the multifunctional value cultivated land use and achieving sustainable development of the region.

Jiang et al. (2020) revealed the relationship between cultivated land multifunction and related socio-economic factors from the perspective of qualitative analysis. An et al. (2022) revealed the influencing factors of cultivated land multifunctionality using Geographical Detector. Existing studies have focused more on the influencing factors of cultivated land multifunction rather than the drivers of the different types of CLFs. Our study conducted a redundancy analysis to quantitatively explore the relationship between multiple CLFs and the potential influencing factors for better clarifying the drivers of the different types of CLFs that aims to provide a reference for decision-makers to formulate cultivated land management strategies for promoting the coordinated development of multiple CLFs.

Our study indicated that slope has a great negative impact on multiple CLFs and precipitation was negatively correlated with APF and ESF. This finding was consistent with the conclusions of previous studies that steep terrain and high variability in rainfall and runoff are more prone to soil erosion (Li & Zhang, 2021; Sun et al., 2014), as well as excessive runoff and soil erosion on sloping farmland have been proven to pose serious threats to agricultural productivity (Huo et al., 2020). Our study revealed that APF was significantly positively correlated with agricultural chemical fertilizer application amount, which was in accord with the findings of Huang and Jiang (2019) and Sun et al. (2019). The total power of agricultural machinery was regarded as a positive factor in improving grain crops in previous studies (Chai et al., 2019; Zuo et al., 2014); however, increasing mechanization has restricted labor-intensive crops production (Qiao, 2017), such as cotton, vegetable and melon, which could be an explanation for a negative correlation between APF and total power of agricultural machinery in our study. We also found the total power of agricultural machinery were negatively correlated with SSF and LSF. This mainly lies on the labor-intensive crop production contributed more to the agricultural employment in the region (Huang et al., 2006; Yu et al., 2019), and high total power of agricultural machinery mainly occurred in developed areas of the YRD region where cultivated land fragmentation makes it hard to form a continuous and regular cultivated land landscape (Jiang et al., 2021).

Cultivated land quality was considered to be negatively correlated with APF and ESF during the study period. It could be due to a high frequency of abandonment and occupation of the high-quality cultivated

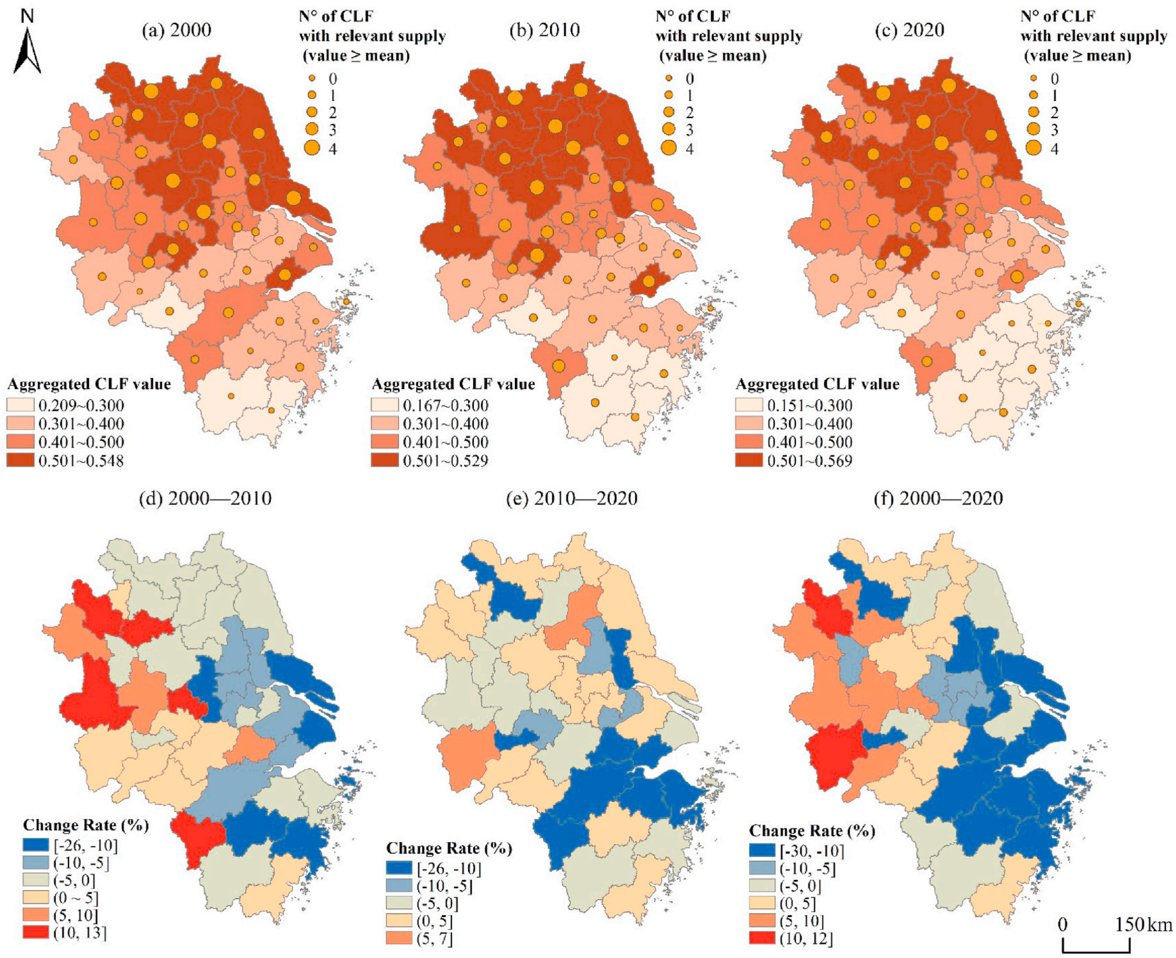

Fig. 7. Aggregated CLF value and the number of CLF with relevant supply (value ≥ mean) (a)–(c); and the change rates of the aggregated CLF value (d)–(f) at the prefecture-level from 2000 to 2020 in the YRD region.

land in the YRD region, leading to the decreasing agricultural productivity and the deteriorating ecological functions (e.g., soil erosion and habitat loss, Liu et al., 2010; Zhu et al., 2021). Rural residents' income and distance to the road showed negative correlations with SSF and LAF. According the findings in Xu et al. (2019) and Zhang et al. (2020), the increased off-farm income undermines traditional agricultural activities and lead to cultivated land abandonment, consequently the quantity of cultivated land and agricultural employees may decrease and cultivated land may also present a fragmented distribution. This could be an explanation for the decreases in SSF and LAF in the YRD region. Moreover, cultivated land near the road is more likely to be occupied for urban expansion (Guzman et al., 2020; Liang et al., 2018); consequently, cultivated land area is continuously decreasing, and the distribution of cultivated land presented fragmentation. The nearer distance to the water area indicates less difficulty in obtaining irrigation water that is more beneficial to agricultural production for increasing the agglomeration of cultivated land and improving the agricultural output (Li et al., 2017), thus the distance to the nearest water area has a positive correlation with SSF and LAF.

5.2. Policy implications

5.2.1. Strengthening the application of modern agricultural technology

Topographical conditions are the decisive factor limiting the large-scale operation of cultivated land and the increased labor productivity in agricultural production (Liang et al., 2021; Tan, Chen, et al., 2021; Wang et al., 2018). The fragmented cultivated land in hilly areas, such as the southern Zhejiang, determines that small-scale and labor-intensive operations characterize agricultural production. Thus, sloping farmland is proposed to be transformed into terraced fields that small machines could operate to improve agricultural productivity and landscape continuity based on a series of land consolidation engineering measures (Huo et al., 2020; Tan, Zhao, et al., 2021). Modern irrigation projects, such as drip irrigation, should also be encouraged to apply in agricultural production of hilly areas to improve the utilization rate of irrigation water for increasing the APF of cultivated land (Jiang et al., 2019). Moreover, the new business entities (e.g., large professional households, family farms and professional cooperatives) could carry out centralized and continuous cultivated land consolidation relying on the transfer of land management rights to transform small pieces of land into large fields that will convenient for mechanized operations to improve agricultural production efficiency (Xu et al., 2018; Zhou et al., 2019).

5.2.2. Preventing cultivated land non-agriculturalization and developing characteristic agriculture

The dynamic balance policy of cultivated land, that is, to supplement cultivated land with the same quantity and quality as the cultivated land occupied by construction, should still be strictly implemented for preventing non-agricultural use of cultivated land to stabilize the quantity of cultivated land in the YRD region (Wu et al., 2017; Zhou et al., 2021). The local government should make efforts to carry out cultivated land restoration, comprehensive land consolidation, high-standard farmland construction and cultivated land reserve resource exploitation for increasing the quantity of cultivated land and guide the centralized

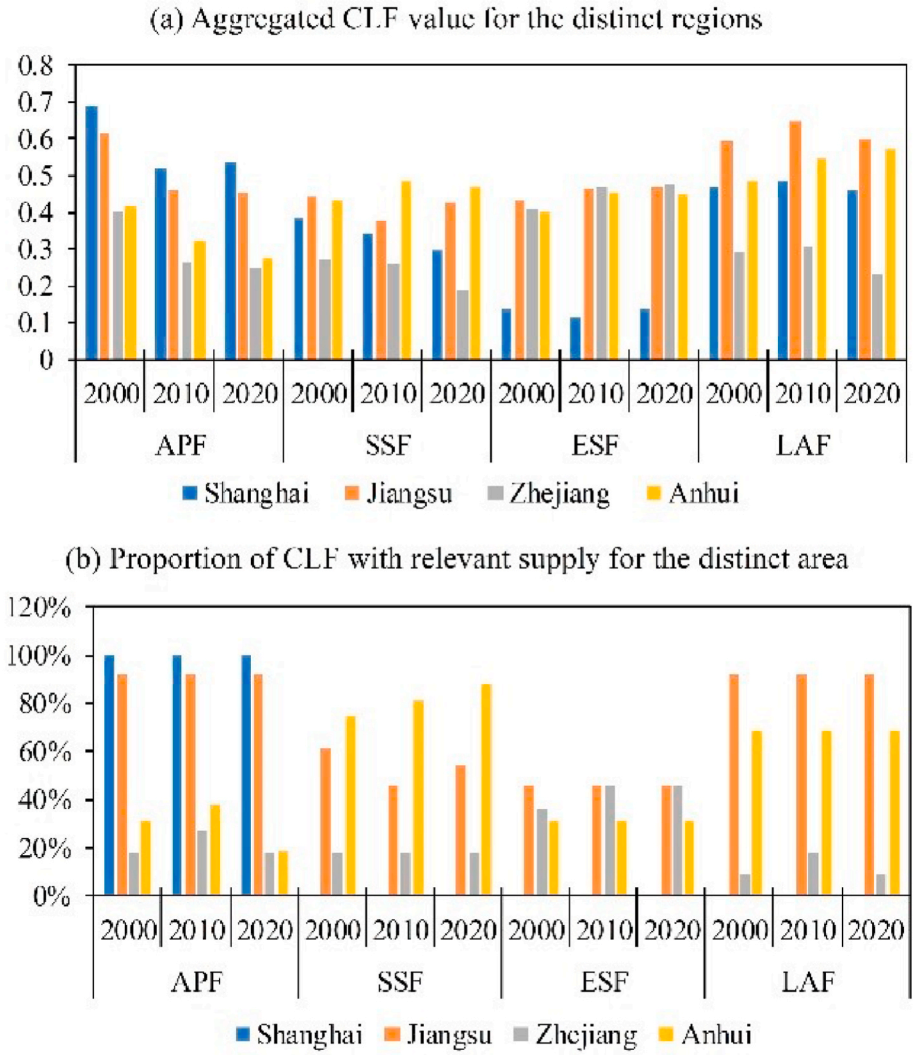

Fig. 8. Aggregated CLF value and proportions of different CLFs with relevant supply (value ≥ mean) from 2000 to 2020 in the whole area and the distinct area of the YRD region.

distribution of cultivated land (Liu et al., 2019). These efforts also could increase the farming income and improving the landscape aesthetic value. The construction of key projects in the process of urbanization should avoid permanent basic farmland and occupy less or no cultivated land as possible. In addition, policymakers should pay more attention to the development of characteristic agriculture (e.g., tea and premium fruit) and e-commerce considering local conditions for improving the agricultural output and increasing the income of rural residents (Liu et al., 2016; Ma et al., 2022).

5.2.3. *Promoting ecological governance and protection of cultivated land*

Cultivated land protection should be integrated into the social economic system and natural ecosystem simultaneously to improve the ecological value of cultivated land. In ecologically sensitive and fragile areas of the YRD region, organic green agriculture and circular agriculture characterized by low consumption, low emission and high efficiency should be vigorously advanced to restore and improving the ESF of cultivated land (Liu, Sun, et al., 2020). Following the laws of ecosystem integrity and biodiversity, the ability of the rural ecological infrastructure construction and management should be improved to restore the biological community and ecological chain of the field, such as ecological ditches, ecological corridors, shelter forest networks, etc. (Cui et al., 2020; Feng, Xiu, et al., 2020). It will also be an effective way to develop the treatment technology of agricultural non-point source pollution and green production technology of agricultural resources for achieving the ecological function protection and restoration of cultivated land. The government should formulate cultivated land protection policies oriented to ecological value for better exploring ecological compensation, property right transaction, green finance and other ways to encourage social capital to participate in the development of ecological agriculture (Gao et al., 2019; Wang, Wu, & Yu, 2022).

5.3. *Limitations and prospects*

Limited to the complexity of the cultivated land system and the availability of data, the CLF classification framework and indicators used to characterize the multiple CLFs in this study still need to be further improved for more widely use in other research. In the future, we will continue to optimize the landscape aesthetic function indicators of cultivated land and explore the quantitative indicators and methods of cultural functions of cultivated land. Moreover, limited to the length of an article, this study only focuses on the prefecture-level for quantifying and analyzing the characteristics and mechanisms of multiple CLFs. It is also important to conduct more studies on the characteristics and mechanisms of multiple CLFs at the micro-scale of villages, households and even grid for the sustainable utilization and accurate management of cultivated land. Therefore, a multiscale analysis will be necessary to apply in future studies for further exploring the characteristics and mechanisms of multiple CLFs.

6. Conclusion

In this study, we quantitatively measured the supply of four CLFs in the YRD region from 2000 to 2020 at the prefecture-level, and further analyzed the spatial-temporal characteristics and their trade-offs of multiple CLFs as well as revealed the underlying mechanism of these CLFs. We also mapped the spatial distribution of cultivated land multi-functionality and proposed some policy implications. The results showed that APF showed an overall decrease during 2000–2020 and was higher in Shanghai and the north of Jiangsu and Anhui. Higher SSF mainly distributed in Anhui and the north of Jiangsu and generally presented an increase in these areas from 2000 to 2020. The south of Anhui and the north of Jiangsu had higher ESF, while Jiangsu and the northeast of Anhui had higher LAF during the study period. Higher trade-offs of multiple CLFs mainly occurred in the northwest of Anhui and northern Zhejiang. The slope has a great negative impact on multiple CLFs. Precipitation was also negatively correlated with APF and ESF. Rural residents' income and distance to the nearest road showed negative correlations with SSF and LAF while the distance to the nearest water area positively impacts on SSF and LAF. The areas covered by large-scale concentrated and contiguous cultivated land presented the strongest cultivated land multifunctionality. The highly urbanized areas and those characterized by forest land covers showed weak cultivated land multifunctionality. We finally suggested that decision-makers should consider the underlying drivers of multiple CLFs in policy formulation of cultivated land management for promoting the coordinated development of multiple CLFs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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