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Dynamics of spatial associations among multiple land use functions and their driving mechanisms: A case study of the Yangtze River Delta region, China

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ABSTRACT

Land use functions and their interaction analysis has been a hot topic in the field of land change science for better advancing the regional sustainable development. Previous studies focused more on the impacts of land use activities on the natural and semi-natural systems at the regional scale, ignoring the impacts of land-use on the complex social-ecological system and their dynamics at a fine scale. In this study, we applied a LUF classification framework, including agricultural production function (APF), urban-rural living function (ULF) and ecological maintenance function (EMF), to quantify multiple LUFs in Jiangsu Province, an essential part of the Yangtze River Delta region, China, from 2000 to 2020 at the grid scale. We then investigated the dynamics of spatial associations among multiple LUFs and revealed the underlying drivers of these LUFs integrating multisource data and multiple geospatial analysis methods. The results showed that APF-ULF trade-offs increased in northern Jiangsu and decreased in southern Jiangsu from 2000 to 2010; whereas these trade-offs generally increased between 2010 and 2020 across the entire region. APF-EMF trade-offs showed an opposing pattern to APF-ULF during the study period. ULF-EMF trade-offs increased from 2000 to 2020 with strong trade-offs primarily occurring in northern and southwestern Jiangsu. Land cover classes had a substantial impact on all the secondary LUFs. Vegetation cover was correlated with changes in APF and EMF, and distance factors were more important to ULF. Finally, we used the nine secondary LUFs to detect five LUF clusters and proposed distinct LUF management strategies considering the spatial heterogeneity of multiple LUFs in these LUF clusters. We also suggested the mechanisms behind apparent relationships among LUFs are considered into the formulation of land spatial planning and management strategy for facilitating the coordinated development of multiple LUFs.

1. Introduction

In *Transforming Our World: The 2030 Agenda for Sustainable Development,* the seventieth session of the General Assembly in September 2015 described 17 Sustainable Development Goals and 169 targets aimed at balancing the three major dimensions of sustainable development: economic, social and environmental characteristics of places (United Nations, 2015). Land change science in recent years has focused on the causes and consequences of the land change system and its impact on environmental change and sustainable development (GLP, 2005; Turner et al., 2007; Long and Qu, 2018; Long, 2020). As an important part of land change science — land use function (LUF) — is the capacity of the land system to provide goods and services for sustaining human well-being. LUF is viewed as the bridge connecting land cover/land use, natural goods/services, and human needs across the economic, social and environmental dimensions of sustainable development (Fig. 1, Verburg et al., 2009; Fan et al., 2018, 2021). LUFs and their changes may not be observed and monitored based on land cover information

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(Verburg et al., 2009; Long and Qu, 2018; Long et al., 2021). Attempts to assess different types of LUFs integrating land cover, social, economic, ecological information and remote sensing data have been the basis for identifying the changes and their interactions of LUFs, which could help for better understanding land change science (Verburg et al., 2009; Liu et al., 2018).

LUFs and their dynamics are diverse and complex influenced by human decision-making (Bennett et al., 2009; Liu et al., 2018; Fan et al., 2021). These dynamics produce trade-offs among LUFs which occur when one LUF increases at the expense of another (Seppelt et al., 2013; Wang and Dai, 2020), which affect and are affected by economics, society, and the environment. In order to fully consider and meet various human well-beings, we often need to coordinate the relationship among multiple LUFs and explore the spatial characteristics and their dynamics of the trade-offs of these LUFs for improving the overall benefits of land system (Bennett et al., 2009; Bradford and D'Amato, 2012; Zou et al., 2020; Fan et al., 2021). As such, understanding the trade-off relationships among multiple LUFs, their dynamics and drivers will allow for more effectively regulating and managing various LUFs.

Numerous studies have explored LUF classification and evaluation for guiding regional sustainable development. The studies focused more on the functions of agriculture, ecology or landscape (Andersen et al., 2013; La Notte and Rhodes, 2020; Li et al., 2021a; Liang et al., 2021a). In recent years, scholars gradually realized that agriculture is not the only sector with multi-functional characteristics. Ecosystem services and landscape functions only essentially focus on the environmental dimension of sustainable development. Therefore, recent studies began to explore LUF classification and evaluation of LUFs involving the three dimensions of economy, society and environment systems (Liu et al., 2018; Zhang et al., 2019; Zou et al., 2020; Lyu et al., 2022). Previous studies on the interactions among LUFs have focused on trade-offs and spatial variation among natural or semi-natural ecosystem services, such as crop provisioning, climate and water regulation, nutrient cycle support, and cultural services in specific regions (Turner et al., 2014; He et al., 2020; Feng et al., 2021). However, few studies have been conducted on the interactions among multiple LUFs involving complex socio-ecological systems. Hence, it is necessary to investigate spatial associations among various LUFs and explore the dynamics and drivers of LUF trade-offs associated with natural ecosystems and social-economic systems, aims at expanding our understanding of the impact of land-use on the sustainable development of complex socio-ecological systems (Zou et al., 2020; Lyu et al., 2022).

LUFs in previous studies are most commonly quantified using simple statistical method and value evaluation method at the regional scale (Zhou et al., 2017; Fan et al., 2018; Zou et al., 2020). Few studies conducted LUF assessment at a finer scale, which could more accurately identify the ability of land use system to provide human goods and services. The InVEST model consisted of a series of modules and algorithms, which have been widely used to simulate the status and changes of various ecosystem services under land use/cover change scenarios at the grid scale (Sharma et al., 2019; Wu et al., 2019; Sun et al., 2022). Some studies have also focused on the quantification of cultural services. Recreational opportunity spectrum model has become a common method for evaluating cultural services based on human impact on natural landscape, landscape accessibility and water gravity attenuation (Paracchini et al., 2014; Sun and Li, 2017). In addition, net primary productivity has been used as an effective indicator for characterizing the agricultural productivity in previous studies (Pan et al., 2021), and night light index has been proven to have a strong linear relationship with economic development (Cheon and Kim, 2020; Du et al., 2021). These methods and indicators have provided a powerful foundation for quantifying LUFs at a fine scale. In this study, we will quantify various LUFs integrating remote sensing data, statistical analysis and geospatial analysis at the grid scale for more precisely monitoring and analyzing the dynamics of LUFs.

Existing studies on the LUF relationships mainly focused on the trade-offs among natural or semi-natural ecosystem services. The commonly used methods for trade-offs analysis mainly include spatial analysis and statistical analysis. Many studies used correlation analysis to determine the magnitude and direction of the correlation between

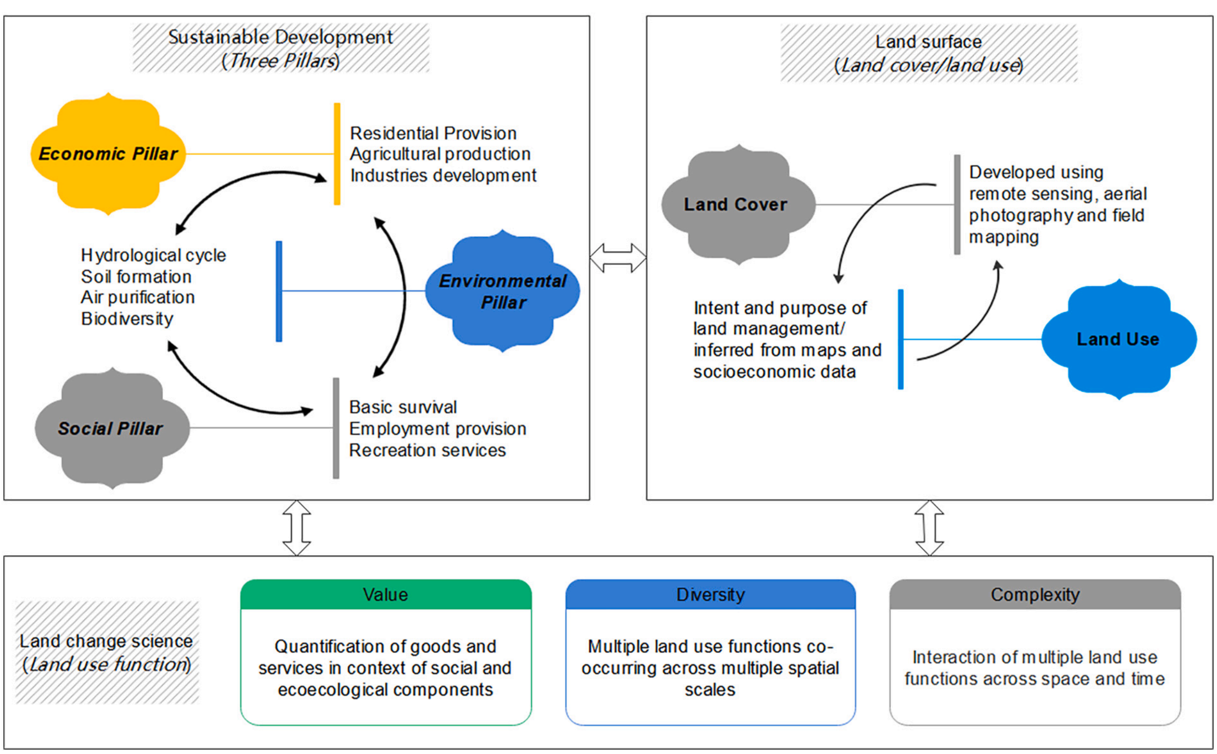

Fig. 1. Illustration of the concept of land use function that connects land cover/land use, natural goods and services, and human needs across the economic, social and environmental dimensions of sustainable development.

two ecosystem services for analyzing the trade-offs between two services (Baró et al., 2017; Sylla et al., 2020; Lyu et al., 2021). Spatial overlay analysis and ecosystem service bundles are also common in the spatial analysis of ecosystem services as they allow for the identification of spatial variation in ecosystem service trade-offs (Raudsepp-Hearne et al., 2010; Li et al., 2017a; Yang et al., 2019). Recently, researchers have begun using constraint lines (Jiang et al., 2018; Li et al., 2021b), root mean square error (RMSE) (Liu et al., 2019a; Feng et al., 2020; Liang et al., 2021b) to analyze the trade-offs in ecosystem services. These methods show the effects of the constraint processes and could quantify the magnitude of the trade-offs for more than two services. However, few studies have applied these methods to identify the associations of multiple LUFs at the grid scale. Here, we attempt to integrate RMSE and correlation analysis into measuring the spatial associations and their dynamics among various LUFs at the grid scale for better understanding the trade-offs among these LUFs.

The Yangtze River Delta region is a globally influential metropolitan area with a high population density and a host of industries (Wu et al., 2017; Yu et al., 2020). Rapid urbanization of the region is at the expense of farmland loss and fragmentation, soil erosion, climate change and habitat degradation, which have restricted regional sustainable development considerably (Liu, 2012; Li et al., 2021c). The development goals of Jiangsu Province are focused on the high-quality and coordinated development of economy, society, and ecology proposed in the *Outline of regional integration development plan in the Yangtze River Delta* (Political Bureau of the Central Committee of the Communist Party of China, 2019). Yet, decreasing/deteriorating agricultural and ecological spaces and extensive use of urban space affected directly or indirectly by different land use activities are still great challenges for sustainable development of Jiangsu Province. Therefore, this paper uses Jiangsu Province as a case study to (1) apply a LUF classification framework for quantifying multiple LUFs and identify the dynamics of spatial associations for these LUFs; (2) detect the correlations and driving mechanisms of various LUFs; and (3) reveal distinct LUF clusters and propose policy implications for potentially better management of multiple LUFs.

2. Study area and data

2.1. Study area

This study takes Jiangsu Province as the study area, which is located in the eastern part of the Yangtze River Delta Region in China, with large amounts of contiguous rich soil, plains cover >80% of the land area (Fig. 2). The climate in Jiangsu ranges from temperate to subtropical, with mild temperatures, moderate rainfall, and four distinct seasons. The region features plentiful natural resources and is located along the Yangtze River, giving Jiangsu a unique advantage in its capacity for rapid urbanization and economic development. From 2000 to 2020, the urbanization rate of permanent residents in Jiangsu Province has increased from 42.25% to 73.44% (1.56% points per year) (Statistical Bureau of Jiangsu Province, 2021), approximately 10% greater than the national average. The per capita GDP has recently exceeded RMB 120,000 in 2020 (Statistical Bureau of Jiangsu Province, 2021), reaching the international standard of high-income areas.

Rapid urbanization and economic growth have led to a series of restrictions for sustainable development of the region, such as decreased land allocated to high-quality farmland and increased disorderly spread of urban areas into natural spaces. Therefore, green space has rapidly reduced, and ecosystem services continue to deteriorate (Long et al., 2014; Zhang et al., 2021). How to optimize the allocation of regional resources and environment for alleviating the conflicts between economic growth, social transformation and environmental protection in Jiangsu, such a well-developed region, has become a focal point of discussion in the field of sustainable development.

2.2. Data sources

Data used in this study include (1) land cover data and Digital Elevation Model (DEM); (2) soil data; (3) meteorological data, i.e., precipitation, air relative humidity; (4) remote sensing data, i.e., MODIS data (e.g., Normalized Difference Vegetation Index, Leaf Area Index,

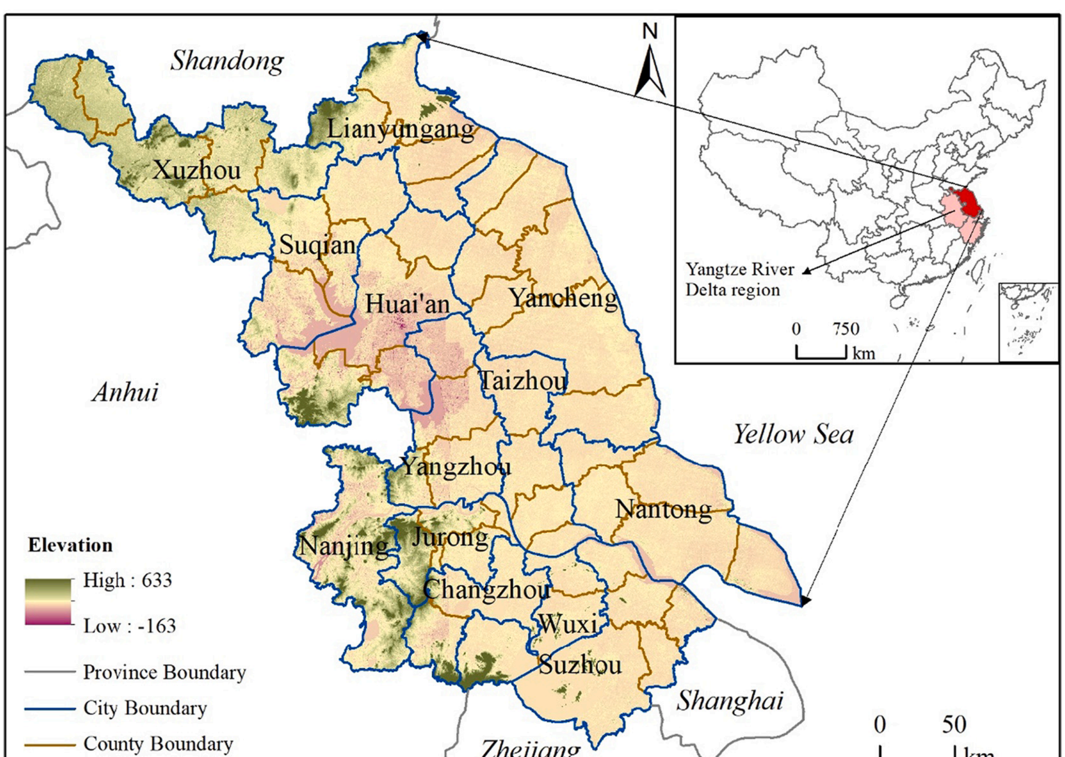

Fig. 2. Location, administrative division and elevation of the study area.

Evapotranspiration, Net Primary Productivity) and night light data; (5) land survey data, i.e., ecological red line; (6) and socio-economic data, i.e., demographic data, road data, and statistical data (e.g., crop yield, aquatic products yield, and gross domestic product). Sources and spatial resolution of these data are shown in Table 1.

3. Methodology

3.1. Quantification and spatial analysis of various LUFs

As the first nationwide strategic, integrative, and fundamental plan of China for land development and protection, the *National Land Planning Outline* (2016–2030) in China determines that the land space includes three types: agricultural, urban-rural, and ecological space. Each land space has distinct development goal and dominant activity which results in various LUFs. Agricultural space is an area where food security is the principal regional development goal. Agricultural production is the main land use activity in this space, providing agricultural products, e.g., crops and aquatic products for human survival. Urban-rural space is an area with the main goal of securing socio-economic development. The critical function in this space is urban-rural living which provides essential living security (e.g., residential and economic support, outdoor recreation) for humans. Ecological space is the area where the main development goal is to ensure ecological security through environmental protection. Ecological maintenance to provide ecological products and services (e.g., water regulation, soil retention, carbon sequestration, and habitat conservation) is the primary function in this space. Thus, we proposed a LUF classification framework that includes three primary functions — agricultural production, urban-rural living, and ecological maintenance — based on land space types in this study (Table 2).

Crops are the most important supply products in agricultural production systems, and the supply of aquatic products has also become an important component of improving human dietary structure. As such, we divided agricultural production function into two secondary functions of crop provisioning and aquatic product provisioning. Residence is the basis for maintaining the basic operation of human life. Industrial and commercial development can provide a material basis to meet the needs of human life. Recreation is a necessary condition to guarantee the physical and mental health of human beings and improve the quality of human life. With this regard, urban-rural living function was divided into three secondary functions, i.e., residential support, economic support, outdoor recreation. Ecosystem stores precipitation inside the system to meet the needs of each ecological component in the system for water sources and continuously provide water to the outside, while increasing soil erosion resistance and maintaining soil nutrients (Jiang et al., 2019; Xu et al., 2020). Ecosystem also can absorb and fix carbon dioxide in the atmosphere, and play a regulatory role in slowing down the warming trend (Baldocchi and Penuelas, 2019; Wen et al., 2019). Rapid urban sprawl in Jiangsu has aggravated the habitat fragmentation and degradation (Li et al., 2014; Chen et al., 2021). Thus, ecological maintenance function was divided into four secondary functions of water regulation, soil conservation, climate regulation, habitat conservation.

Table 1
Type, sources and spatial resolution of data used in this study.

Type	Source	Spatial resolution
Land cover data	GlobeLand30	30 m × 30 m
DEM	Geospatial Data Cloud	30 m × 30 m
Soil data	Soil Science Database of China	1:100, 0000
Precipitation	National Meteorological Information Center of China	Station observation
Air relative humidity		
Normalized Difference Vegetation Index (NDVI)	National Aeronautics and Space Administration of United States	500 m × 500 m
Leaf Area Index (LAI)		1 km × 1 km
Evapotranspiration		500 m × 500 m
Net Primary Productivity (NPP)		1 km × 1 km
Night light data	National Earth System Science Data Sharing Platform in China	500 m × 500 m
Ecological red line	Jiangsu Land Survey and Planning Institute	1:25, 0000
Demographic data	Oak Ridge National Laboratory of United States	1 km × 1 km
Road data	Gaode Map	1:25, 0000
Crop yield	Statistical Yearbook of Jiangsu Province	County scale
Aquatic product yield		
Gross Domestic Product		

We also used quantitative indicators to characterize each secondary LUF. The criteria for the indicator selection are: (1) the indicator must be able to accurately identify the presence of the secondary LUF in the study area, (2) the indicator must be able to be measured at the grid scale, and (3) the data for the indicator must be publically available. Values of the nine secondary LUF indicators were further normalized using minimum and maximum method such that values ranged from zero to one to enable a comparison across the grid scale. Then, we used Delphi method to determine the weight of each secondary LUF indicator and employed weighted average method to calculate the value of each primary LUF. The calculation formula for the primary LUF is as follows:

$$LUF_i = w_{i1} \cdot LUF_{i1} + w_{i2} \cdot LUF_{i2} + \cdots + w_{in} \cdot LUF_{in} \tag{1}$$

where LUF_i indicates the benefit of the i^{th} primary LUF; LUF_{in} indicates the benefit of the n^{th} secondary LUF relevant to the i^{th} primary LUF; and w_{in} indicates the weight of the n^{th} secondary LUF relevant to the i^{th} primary LUF.

Spatial autocorrelation analysis was used to characterize spatial distribution of primary LUFs in this study. Hot spot analysis tool in ArcGIS was used to identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots) for the supply of primary LUFs. This tool calculates the Getis-Ord Gi* statistic for each feature in the dataset. The Getis-Ord local statistic is given as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}x_j - \overline{X}\sum_{j=1}^{n} w_{ij}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij}\right)^2\right]}{n-1}}} \tag{2}$$

where x_j is the attribute value for feature j, w_{ij} is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{3}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j}{n} - (\overline{X})^2} \tag{4}$$

The Gi* statistic returned for each feature in the dataset is a z-score. The resultant z-scores indicate where features with either high or low values cluster spatially. For statistically significant positive z-scores, the larger the z-score is, the more intense the clustering of high values (hot spots). For statistically significant negative z-scores, the smaller the z-score is, the more intense the clustering of low values (cold spots).

3.2. Trade-off analysis among multiple LUFs

LUF trade-offs are the average deviations of each LUF from the mean benefits of various LUFs (Bradford and D'Amato, 2012). We define a trade-off as scenario in which a management option results in high benefit in some LUFs and low benefit in others within a given spatial extent. We used the RMSE value of individual LUF benefit for investigating the magnitude of LUF trade-offs between two LUFs in this study (Bradford and D'Amato, 2012; Liu et al., 2019a; Feng et al., 2020). The

Table 2
Land use function classification and quantification methods used in the study. NPP_i, $W_{(area)i}$ indicate NPP, water area of the county i, respectively; NPP_{ij}, $W_{(area)ij}$ indicate NPP, water area at the grid j of the county i, respectively; $CP_{(yield)i}$, $APP_{(yield)i}$ indicate the yield of crop and aquatic product of the county i, respectively.

Primary function	Secondary function	Description	Indicator	Quantification method	Unit	Weight
Agricultural production function	Crop provisioning	The ability to provide grain supply for humans	Crop yield	$\frac{NPP_{ij}}{NPP_i} \times CP_{(yield)i}$	kg	0.60
	Aquatic product provisioning	The ability to provide aquatic products for humans	Aquatic product yield	$\frac{W_{(area)ij}}{W_{(area)i}} \times APP_{(yield)i}$	kg	0.40
Urban-rural living function	Residential support	The ability to support human habitation	Population density	LandScan Global Population Database	person	0.40
	Economic support	The ability to provide economic security	Output value of secondary and tertiary industries	Output value of secondary and tertiary industries have strong linear relationship with night light (Cheon and Kim, 2020; Du et al., 2021)	CNY	0.40
	Outdoor recreation	The ability to provide human recreation services	Recreation Potential	Recreation Potential (Paracchini et al., 2014)	–	0.20
Ecological maintenance function	Water regulation	The ability to supply and guarantee water resources for humans	Water conservation	InVEST (Tallis et al., 2011)	mm	0.25
	Soil conservation	The ability to conserve soil integrity	Soil retention	RUSLE (Wischmeier and Smith, 1978)	kg	0.25
	Climate regulation	The ability to regulate climate	Carbon sequestration	NPP have strong linear relationship with carbon sequestration (Lyu et al., 2021)	Mg	0.25
	Habitat conservation	The ability to provide protect habitat and ensure its quality	Habitat quality	InVEST (Tallis et al., 2011)	–	0.25

RMSE is calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n-1} \times \sum_{i=1}^{n} \left(LUF_i - \overline{LUF}\right)^2} \tag{5}$$

where LUF_i is the benefit of the i^{th} LUF, and $\overline{LUF}$ is the mean benefit of n number of LUF. A higher RMSE value represents a larger trade-off for LUFs.

In the case of two dimensions, RMSE is simply the distance from the 1:1 line (Fig. 3). Points O_1 and O_2 locate on the “1:1 line”, indicating a zero trade-off. However, point O_2 is the ideal outcome as it shows a high benefit for both individual LUFs and yields a low trade-off, whereas point O_1 is the least desirable outcome that where neither LUF benefits and yields a low trade-off. In addition, regions A, B, C, and D in Fig.2 represent areas where trade-offs occur. The lower right portions of A and B, as well as the upper left portions of parts C and D are farther away from the 1:1 line, meaning that larger trade-offs exist in these regions.

We also used correlation analysis to further investigate the spatial relationships among multiple secondary functions. The matrix of correlation coefficients was performed using “corrplot” (Wei et al., 2017) packages in R software (Team, R C, 2021).

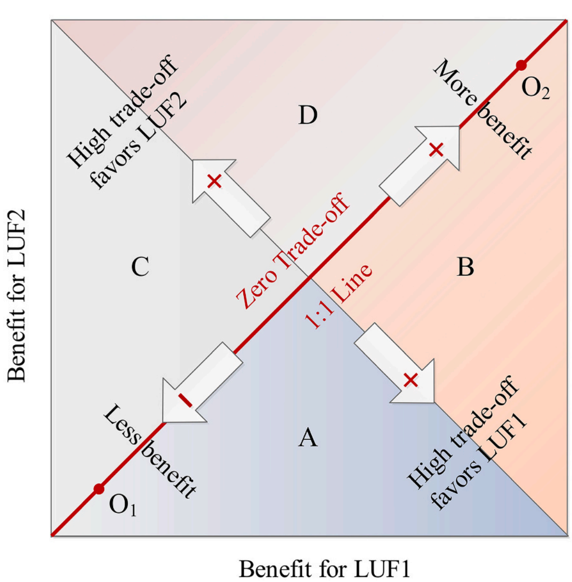

Fig. 3. Sketch map of benefits and trade-offs between two LUFs.

3.3. Driving mechanism analysis for LUFs

The diversity of LUF is the result of the joint action of natural factors and anthropic factors in the process of historical development of man-land relationship areal system. Previous studies have shown that LUFs are affected by natural resource endowment, socio-economic conditions and policy factors of the region (Liu et al., 2021; Lyu et al., 2021; Zhu et al., 2021). Considering the characteristics of the study area and the availability of data, the 12 potential exploratory variables (Table 3) concerning LUFs are selected in this study based on their inclusion in previous studies (Lyu et al., 2021; Liu et al., 2021; Wang et al., 2021a). Furthermore, a geographical detector model was used to investigate the determinant power of potential explanatory variables following Wang et al. (2010) and Song et al. (2020). We used the factor detector, the core part of the geographical detector, to quantify the relative importance of different potential explanatory variables associated with LUFs following Song et al. (2020). The q-statistic for each potential exploratory variable was used to measure the spatial heterogeneity of LUFs (Wang et al., 2016), and is calculated as follows:

Table 3
Overview of potential drivers for LUFs.

Drivers	Code	Unit	Quantification method/ Sources
Elevation	Elev	m	DEM
Terrain slope	Slope	°	Slope Tool in ArcGIS
Precipitation	Prec	mm	Interpolation Tool in ArcGIS
Air relative humidity	Humid	%	Interpolation Tool in ArcGIS
Land cover classes	LCC	–	GlobeLand30
Vegetation cover	VC	%	NDVI
Distance to the city center	Dcity	m	Near Tool in ArcGIS
Distance to the county center	Dcounty	m	
Distance to road	Droad	m	
Distance to water area	Dwater	m	
Aggregation index	AI	–	Fragstats
Shannon diversity index	SHDI	–	

$$q_i = 1 - \frac{\sum_{j=1}^{m} N_{ij}\sigma_{ij}^2}{Ni\sigma_i^2} \tag{6}$$

where N_i and σ_i represent the number and population variance of observations for variable x_i in the whole study area, respectively; N_{ij}, σ_{ij} represent the number and population variance within the j^{th} sub-region of variable x_i. The q value will range between zero and one, increasing as the relative contribution of the explanatory variable increases. The factor detector analysis was performed using the "GD" package (Song et al., 2020) in R software (Team, R C, 2021).

3.4. Cluster analysis

We used the average value of each secondary function in the whole study area as the criterion to determine if a grid could offer the secondary function strongly. The grid cell was assigned as one if the function value was higher than the average value for that function in the entire study area; otherwise, the grid cell was assigned as zero. For each secondary function, the summed value for each grid cell was used to conduct a cluster analysis at the county scale. We assigned each county to a distinct LUF cluster determined by the spatial distribution of multiple secondary functions using the self-organizing map (SOM) method. SOM were performed using "kohonen" (Wehrens and Buydens, 2007; Wehrens and Kruisselbrink, 2018) packages in R software (Team, R C, 2021). Then, we applied ArcGIS software and the "vegan" package (Oksanen et al., 2013) in R software to map the spatial distribution of LUF clusters and make rose wind diagrams displaying the proportions of areas capable of strongly providing the nine secondary LUFs for each cluster in Jiangsu.

4. Results

4.1. Spatiotemporal changes of distinct LUFs

The spatial distribution and hotspot patterns among the three primary LUFs differed across the landscape and over time (Fig. 4). Agricultural production function (APF) was highest in southeast and central regions of Jiangsu in 2000; however, the hotspots migrated northward during the study period. Areas in northern Jiangsu (e.g., Huai'an and Yancheng) had high APF in 2010 and 2020, whereas southern Jiangsu

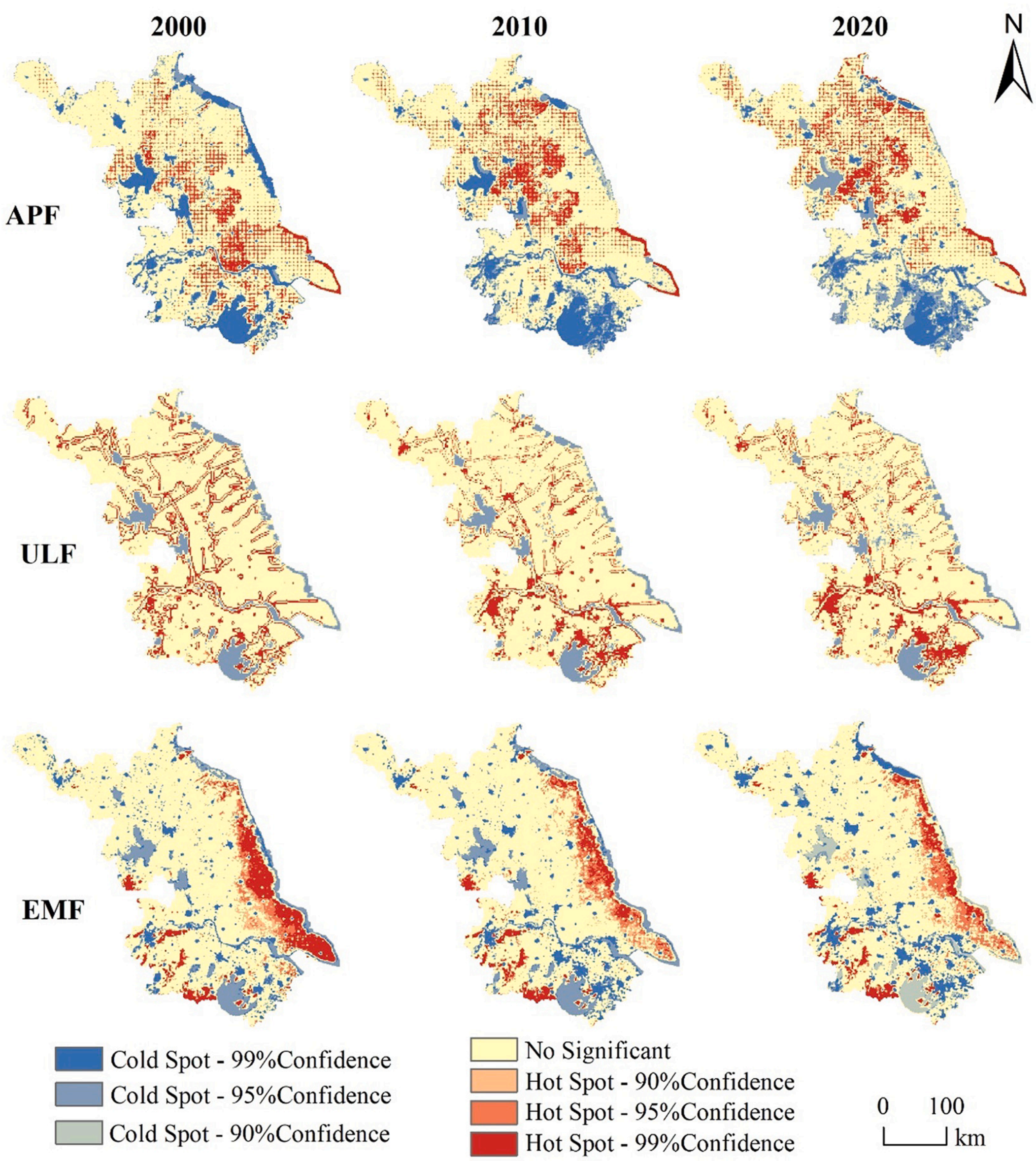

Fig. 4. The dynamic of spatial hot and cold spots of the three primary LUFs from 2000 to 2020.

has increased APF coldspots from 2000 to 2020.

The hotspots of urban-rural living function (ULF) were concentrated in Nanjing and Suzhou and were scattered throughout central and northern Jiangsu in 2000. New ULF hotspots mainly appeared in southern Jiangsu from 2000 to 2020; likely due to the high population density and fast-growing economy during the period. However, ULF hotpots occurred in northern Jiangsu decreased during the study period. Ecological maintenance function (EMF) had hotspots in the eastern coastal area and southwest mountainous area of Jiangsu during 2000–2020 (Fig.4). EMF hotspots in eastern Jiangsu decreased from

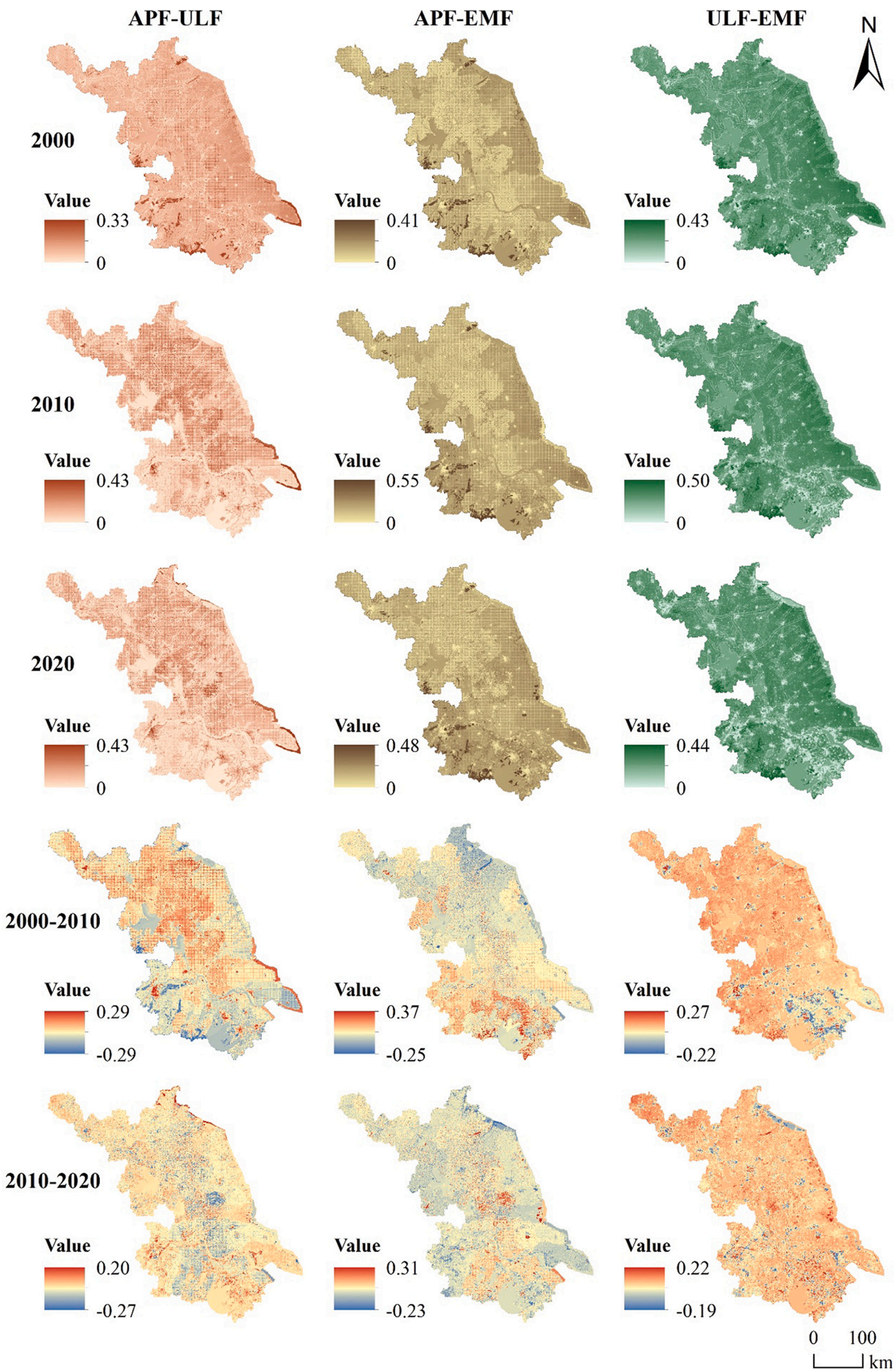

Fig. 5. Spatial distribution and changes of RMSE values indicating the trade-offs of the three primary LUFs.

2000 to 2020, and EMF coldspots increased in southern Jiangsu during the period.

4.2. The dynamic of spatial associations among multiple LUFs

The trade-offs differed considerably among distinct pairs of LUFs and varied over time, as indicated by the spatial distribution and changes of RMSE values for multiple LUF (Fig. 5). APF and ULF showed large trade-offs in southwest Jiangsu and the eastern coastal area of Jiangsu in 2000. The magnitude of APF-ULF trade-offs decreased substantially in southern Jiangsu and increased in central and northern Jiangsu from 2000 to 2010. The areas with RMSE values lower than 0.1 for the APF-ULF trade-offs in 2000, 2010, 2020 account for 66.67%, 73.34%, 77.73% of the whole study area, respectively, indicating the trade-offs for APF-ULF present a general decrease trend in Jiangsu during the study period.

Compared with APF-ULF, APF-EMF and ULF-EMF had more considerable trade-offs and varied more significantly among years of the study period. APF had stronger trade-offs with EMF in southwest Jiangsu from 2000 to 2020. APF-EMF trade-offs increased significantly in southern Jiangsu and decreased in northeastern Jiangsu during the study period. In the past decade, APF-EMF trade-offs decreased in Jiangsu except for certain cities along the Yangtze River. The RMSE values for ULF-EMF trade-offs were generally high in the whole area but were higher in eastern and southwestern Jiangsu during the study period. The magnitude of ULF-EMF trade-off showed a decrease trend in southeast Jiangsu (i.e., Suzhou, Wuxi, Changzhou), from 2000 to 2020.

Among the 36 pairs of the nine secondary functions, 22, 24, and 22 pairs were significantly correlated ($p < 0.05$) in 2000, 2010, and 2020, respectively (Fig. 6). The correlations among the nine secondary LUFs differed and varied slightly over time. Crop provisioning was strongly positively correlated with climate regulation whereas was negatively correlated with aquatic product provisioning and habitat conservation during the study period. Crop provisioning had also an increased negative correlation with economic support from 2000 to 2020.

Residential support had a strong positive correlation with economic support, and these two functions were negative correlated with habitat conservation. The negative correlation between habitat conservation and residential support was stable throughout the study period; whereas the correlation between habitat conservation and economic support increased from 2000 to 2020. The correlation between habitat conservation and climate regulation was less negative in 2020 than in 2000. Climate regulation was positively correlated with outdoor recreation and water regulation, but it was negatively correlated with aquatic product provisioning, residential support, and economic support. Habitat conservation and aquatic product provisioning had stable positive correlations during the study period. Soil conservation had a weak positive correlation with water regulation and was no significant correlation with the other secondary during the period.

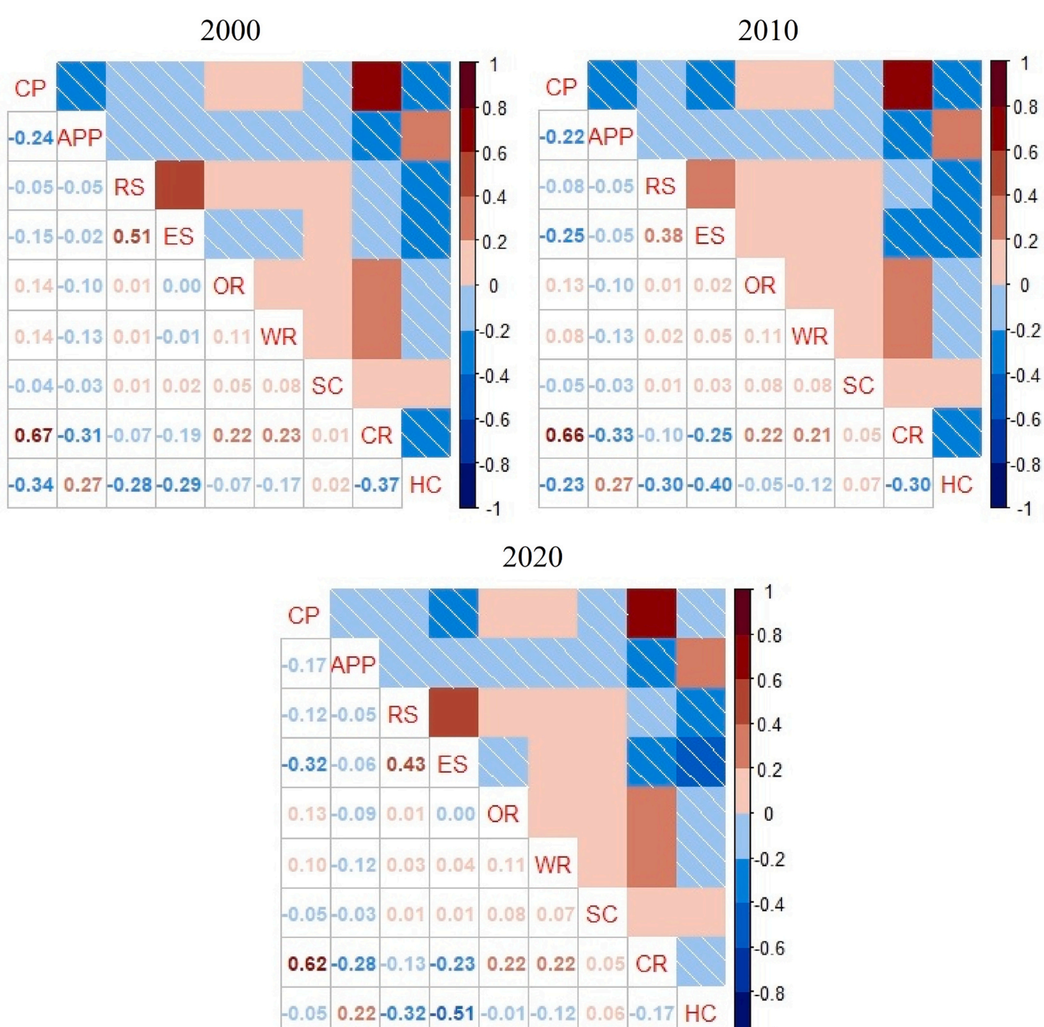

Fig. 6. Correlation plots and coefficients for pairs of the nine secondary land use functions. CP—crop provisioning, APP—aquatic product provisioning, RS—residential support, ES—economic support, OR—outdoor recreation, WR—water regulation, SC—soil conservation, CR—climate regulation, HC—habitat conservation.

4.3. Drivers of LUFs

The individual impact of each driver on different secondary LUFs varied over time (Fig. 7). The land cover classes present the largest impact on residential support, economic support, outdoor recreation, water regulation, and habitat conservation. The impacts of land cover classes on residential support, economic support, outdoor recreation increased during 2000–2020. Land cover classes also greatly impacted crop provisioning, aquatic product provisioning, soil conservation, and climate regulation. Vegetation cover had the most considerable impact on crop provisioning, aquatic product provisioning, and climate regulation, while elevation had the largest impact on soil conservation.

The four proximity factors had moderate impacts on crop provisioning, aquatic product provisioning, and habitat conservation. Distance to the city center and the county center had large impacts on residential support and economic support which increased during the study period. Distance to road and distance to water area had moderate impacts on outdoor recreation, water regulation, and climate regulation. Moreover, the aggregation and shannon diversity index had decreased moderate impacts on crop provisioning and habitat conservation; however, these two drivers had small impacts on water regulation and climate regulation. Elevation had a relatively small effect on habitat conservation, climate regulation, outdoor recreation, water regulation, crop provisioning, and aquatic product provisioning. Precipitation had a significantly greater impact on crop provisioning and a significantly smaller impact on aquatic product provisioning from 2000 to 2020. The slope had a moderate impact on soil conservation and a small impact on climate regulation, habitat conservation, and outdoor recreation.

4.4. Spatial distribution of LUF clusters

Five LUF clusters were detected among the nine secondary functions (Fig. 8). The spatial distribution of five LUF clusters and their profiles for the supply of the nine LUFs are significantly different among the three years.

Cluster 1 was dominated by crop provisioning, water regulation, and

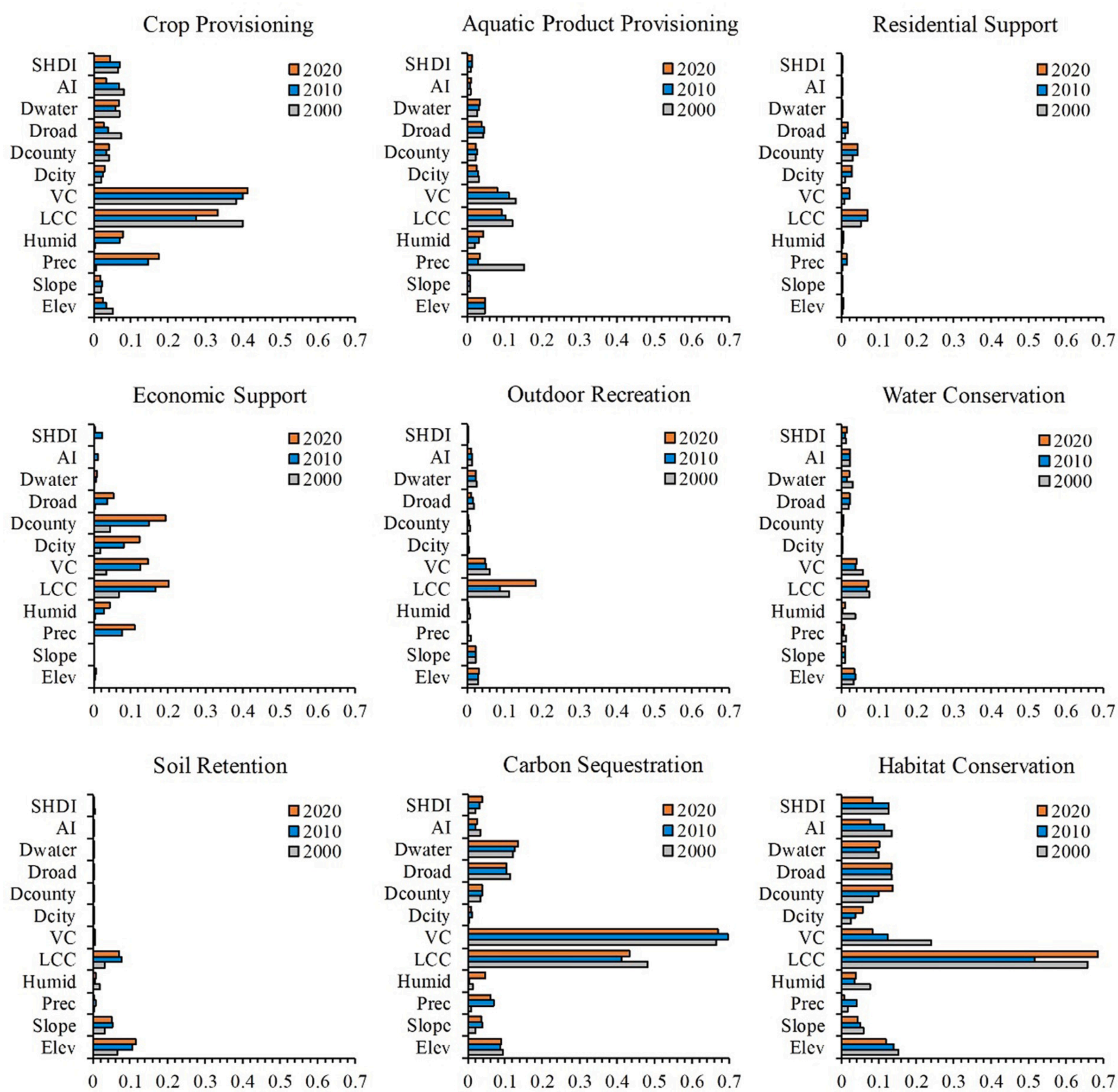

Fig. 7. The relative impacts of 12 potential drivers on each secondary LUF. Elev—Elevation, Slope—Terrain slope, Prec—Precipitation, Humid—Air relative humidity, LCC—Land cover classes, VC—Vegetation cover, Dcity—Distance to the city center, Dcounty—Distance to the county center, Droad—Distance to road, Dwater—Distance to water area, AI—Aggregation index, SHDI—Shannon diversity index.

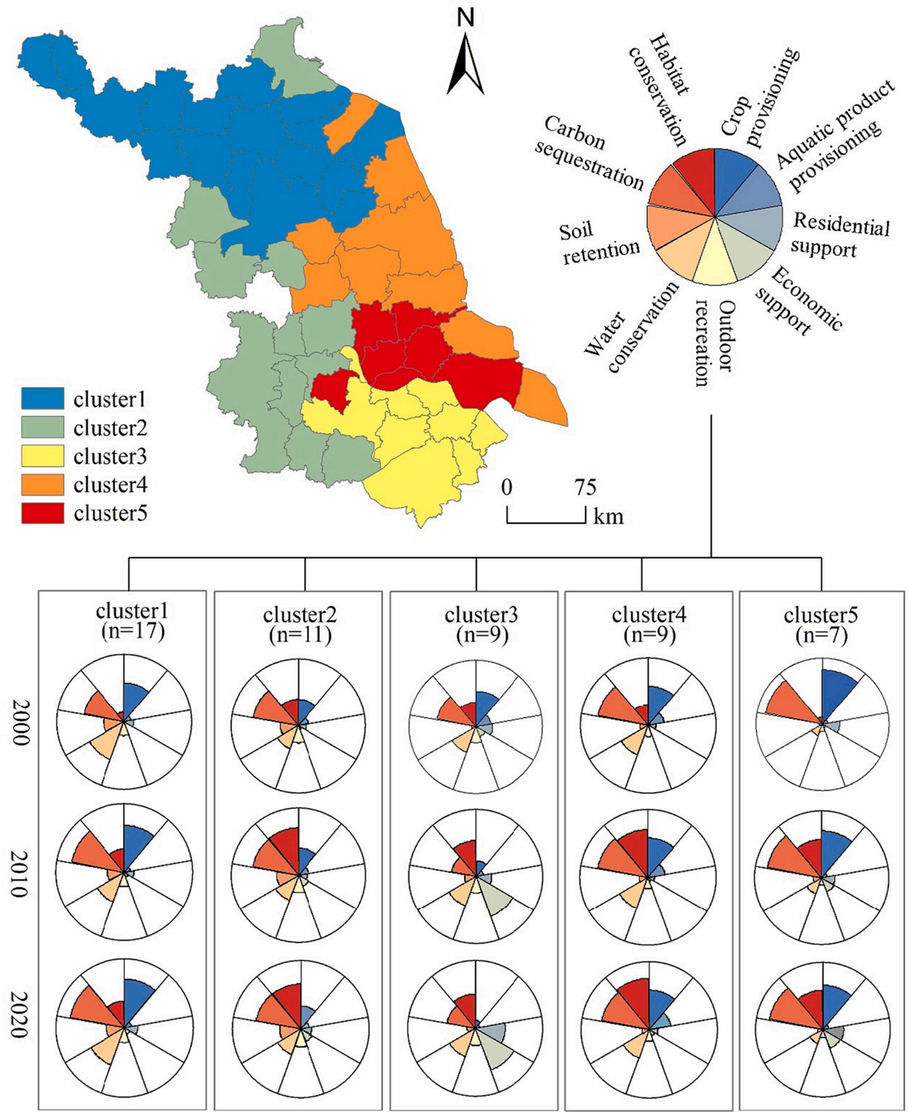

Fig. 8. Spatial distribution of LUF clusters and the proportions of areas that capable of supporting the nine secondary functions for each cluster in Jiangsu. A sector in rose wind plots represents a region that could offer a secondary function shown in the higher right corner. A higher surface area indicates a higher proportion of area that could offer the secondary function. The number of counties per cluster is indicated with n. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climate regulation but had a low amount of the three secondary functions of ULF. Cluster 1 occurred mainly in the northern plains of Jiangsu, which are covered by contiguous cropland. The supply of crop provisioning, water regulation, and climate regulation in cluster 1 gradually increased from 2000 to 2020, and the supply of habitat conservation increased greatly at the same time. Cluster 2 was located in the hilly southwest area of Jiangsu that is heavily wooded. This cluster was characterized by high climate regulation, habitat conservation, outdoor recreation, and a low degree of crop provisioning. Residential and economic support increased slightly in Cluster 2 during the study period. Cluster 3 mainly occurred in the southeast plain with high residential and economic support, which increased from 2000 to 2020; however, crop provisioning decreased from 2000 to 2020 in Cluster 3. Cluster 4, in the eastern coastal area, had the highest aquatic product provisioning of the five clusters. Both Cluster 5, along the Yangtze River, and Cluster 4 had large crop provisioning and climate regulation capacities. Habitat conservation in Cluster 4 and Cluster 5 significantly increased during the study period. Cluster 5 was also characterized by relatively high residential and economic support.

5. Discussions

5.1. Understanding the interactions and drivers of multiple LUFs

Trade-offs for multiple LUFs are closely related to the variations of different LUFs over space and time (Raudsepp-Hearne et al., 2010; Zhang et al., 2019). In our study, APF had low trade-offs with ULF in the northern region of Jiangsu in 2000, and prominently increased from 2000 to 2010, which is largely due to a substantial increase in APF and a static, relatively low ULF. The APF hotspots shifted northward from 2000 to 2010, which could be explained by the increasing high-quality farmland through advances in agricultural technology and land consolidation engineering measures in northern Jiangsu during this period (Liu et al., 2019b; Liang et al., 2021a), resulting in increased crop provisioning. The higher population density and economic output in southern Jiangsu from the rapid urbanization and industrialization experienced in the region contributed to a much greater value for ULF in southern Jiangsu which increased further from 2000 to 2020. ULF in northern Jiangsu was generally low and increased slowly. Additionally, outdoor recreation was greater in southern Jiangsu due to the unique natural environment.

APF had large trade-offs with EMF in southern Jiangsu, especially in the hilly areas, due to the high benefit of EMF and low benefit of APF.

The hotspot distribution of EMF in southwest Jiangsu was highly associated with high soil conservation and habitat quality. High soil conservation in southern Jiangsu may come as a result of having a relatively large forested area. El Kateb et al. (2013) and Astuti et al. (2019) have demonstrated that forest cover has a positive, linear relationship with surface runoff, which contributes greatly to high soil conservation. Southwest Jiangsu has high-quality habitat, which is consistent with the findings of the study conducted by Xiao et al. (2020). This is mostly the result of abundant forests and favourable climatic conditions in the area. Additionally, the loss of highly productive cultivated land and cultivated land fragmentation from construction projects (Deng et al., 2015; Liu et al., 2019b) eventually led to monotonically decreasing APF from 2000 to 2020 in southwest Jiangsu. Land reclamation projects were carried out to improve agricultural productivity in the eastern coastal area of Jiangsu (Yao, 2013; Wang et al., 2014a) during the study period. However, these projects may have threatened or degraded the local ecosystems and ecotopes in coastal Jiangsu (Bao et al., 2019; Wang et al., 2014b). Then, the average deviation from the mean benefit of APF and EMF kept shrinking during the study period, resulting in decreased trade-offs for APF and EMF in the region.

The occurrence of high ULF in southern Jiangsu came as a result of a more dense population and intensive industry (Luo et al., 2018). This agrees with the findings of those studies following Liu et al. (2010) and Zhang et al. (2020) around urbanization and urban land use efficiency in Jiangsu. ULF increased around the original downtowns of cities in southern Jiangsu as population growth and industrial regions expanded from 2000 to 2020. High trade-offs for ULF and EMF mainly occurred in central and northern Jiangsu. This could be explained by relatively low-density industrial development, scattered population distribution and more natural reserves (e.g., Elk National Nature Reserve, Red-Crowned Crane Nature Reserve) with less human influence, resulting in a relatively low benefit of ULF and high benefit of EMF in these regions. It is also noteworthy that the trade-offs for ULF and EMF around the original downtowns of cities in southeast Jiangsu decreased from 2000 to 2010. The likely explanation is rapid urbanization and economic growth causing a series of negative effects on climate, biotopes, and natural spaces (Zhang et al., 2017; Zhang et al., 2021), resulting in decreased EMF in southeast Jiangsu.

5.2. Policy implications for better management of multiple LUFs

Understanding the relationships among multiple LUFs could improve our ability to better management of these LUFs (Bennett et al., 2009). We detected spatial heterogeneity and potential drivers for various LUFs and revealed the spatial associations of these LUFs in our study. Here, we propose some policy implications for better and more effectively managing various LUF that aims to optimize land spatial allocations and improve the total land use benefits.

Different LUF management strategies and land spatial regulation measures need to be applied for distinct LUF clusters considering the spatial heterogeneity of multiple LUFs. Cluster 1, located in northern Jiangsu, should accept the industry transfer of the Yangtze River Delta Region as well as develop the industries with local characters for improving industrial output efficiency and contributing to population agglomeration to increase ULF in the region. Forest coverage and water surface area should be increased for providing more suitable and high-quality habitat to species (Zhu et al., 2020) in this region. Also, policy-maker could further optimize the layout of agricultural industries and strengthen the treatment of agricultural non-point source pollution. Meanwhile, the construction of well-facilitated and contiguous farmland should be encouraged for continuing to improve crop provisioning (Jin et al., 2017) to maintain high APF in the region.

In both Clusters 2 and Cluster 3, located in the south of Jiangsu, it is necessary to effectively allocate agricultural production factors, and develop advantageous and characteristic agriculture for improving the effective supply of agricultural products. Cluster 2 was covered by a relatively large forested area and, consequently, had the high benefit of EMF and outdoor recreation. Thus, open green ecological space should be reserved around towns and development zones, and ecological isolation zones or ecological corridors could also be considered in the region for reducing the interference of urbanization on the natural environment (Bai et al., 2019). Also, we suggest to develop strategic emerging industries and advanced manufacturing industries, and strengthen the construction of characteristic industrial bases and industrial clusters for improving the level of industrial agglomeration and intensive development in Cluster 2. For Cluster 3, more efforts should be devoted to the ecological restoration and environmental governance for improving the provision of ecological maintenance function (Li et al., 2017b; 2020) in the area, especially in Taihu Lake and the Yangtze River.

In Cluster 4, located in the coastal area of Jiangsu, our suggestion is to make good use of tidal flat resources, and properly arrange land for agriculture, ecology, tourism, port industry, etc., for improving the land use overall benefits. The local government should strengthen the cultivation of central cities and accelerate the construction of port cities, towns and industrial parks near the sea for increasing the ULF in this cluster. In the process of urbanization and industrialization, it is also necessary to improve pollutant discharge standards and reduce the pollution of the water ecosystem caused by the development of the port industry in the coastal areas (Wang et al., 2021b; Yu et al., 2021). in Cluster 4. Cluster 5 along the Yangtze River has the potential to offer high crop provisioning and should focus on the implementation of land consolidation projects for stabilizing crop provisioning. Additionally, it will be an efficient way to develop eco-efficient factory aquaculture of aquatic products for optimizing the agricultural structure in this region. We also suggest that ecological engineering programs increase land vegetation cover (e.g. forest, woodland, shrubs) with high carbon storage capacity (Hou et al., 2014; Zhao et al., 2019) in Cluster 5.

Furthermore, understanding the mechanisms behind apparent relationships among LUFs are necessary for facilitating the coordinated development of multiple LUFs that should be considered into the formulation of land spatial planning and management strategy. APF and ULF focus more on generating indispensable benefits for socio-economic systems in our study. Trade-offs between APF and ULF will inevitably result from the low value of one function and the high value of the other function. In this context, the trade-offs are enhanced by true interactions between the two functions (Bennett et al., 2009). Thus, for alleviating or eliminating the trade-offs of APF and ULF, it is imperative to advance high-standard farmland construction for improving the efficiency of agricultural production efficiency and for promoting the redevelopment of inefficient and unused urban-rural construction land (Liu et al., 2014; Long and Qu, 2018; Long et al., 2018). Conversely, EMF presents large trade-offs with both APF and ULF in the regions covered by tidal flat wetland or forest where the values of EMF were high during the study period. Both APF and ULF showed decreased trade-offs with EMF in eastern coastal area of Jiangsu and southeastern Jiangsu; this is mostly a result of increased APF and ULF come at the cost of EMF, which lead to ecosystem degradation and finally restricts the sustainable development of the land system. Consequently, decision-makers must pay attention to maintaining the stability of the natural ecosystem while improving agricultural productivity and accelerating urban development. Ecological restoration and protection could effectively enhance ecosystem resilience (i.e., increased ecosystem C sequestration, vegetation cover, and decreased soil erodibility (Qi et al., 2013; Lu et al., 2018) need to be regarded as a positive way to improve EMF in the processes of agricultural production and urban-rural development.

5.3. Limitations and prospects

Our study provides a feasible way to detect and understand the spatial associations among multiple LUFs; however, some uncertainties still need to be addressed in future research. First, the indicators selected to characterize LUFs in this study should be fully considered and integrated with the multiple interactions between humans and socio-ecological systems. Second, some LUFs, like forest product provisioning and employment support, are difficult to quantify at the grid scale as data availability and qualification methods are limited (Zhu et al., 2021). Thus, a more comprehensive and systematic indicator system needs to be explored and quantified for LUF analysis in future studies. In addition, RMSE and correlation analysis have been proven to be convenient and effective methods for identifying the magnitude and direction of trade-offs for various LUFs in previous studies (Baró et al., 2017; Feng et al., 2020; Lyu et al., 2021). Yet, the threshold of associations among multiple LUFs are not able to be determined by either RMSE values or correlation coefficients in the regions with LUF changes across years (Liu et al., 2019c; Lyu et al., 2021). Thus, in future, we should further explore the constraint effects and capture the thresholds among multiple LUFs with non-linear thinking for better understanding the LUF associations and taking appropriate measures to decrease the trade-offs among multiple LUFs.

6. Conclusions

In this study, we established a LUF classification and evaluation index system to quantify multiple LUFs in Jiangsu Province between 2000 and 2020 at the grid scale using a series of geospatial analysis methods. The study further investigated the spatial variations of the relationships among multiple LUFs and the underlying drivers of these LUFs. Finally, we detected distinct LUF clusters and made suggestions to better manage multiple LUFs for regional sustainable development.

Spatial distribution of the three primary LUFs and their spatial relationships differed between 2000 and 2020. The hotspots of APF shifted from the south to the north of Jiangsu during the study period. The hotspots of ULF and EMF were distributed in the southern region and eastern coastal area, respectively. APF and ULF increased trade-offs in the north but decreased trade-offs in the south from 2000 to 2010. However, APF has generally increased trade-offs with ULF in Jiangsu during the period 2010–2020. The dynamic of APF-ULF trade-offs is opposite to that for APF-EMF, which decreased in the north and increased in the south from 2000 to 2010 whereas decreased in Jiangsu from 2010 to 2020. Trade-offs between ULF and EMF generally increased during the study period with the strongest trade-offs occurring in northern and southwestern Jiangsu. Furthermore, the correlations among the nine secondary functions and the main drivers for these LUFs were significantly different and had small varieties over time. Land use classes had a large impact on all the nine secondary functions. Vegetation cover was especially correlated with crop provisioning, aquatic product provisioning, outdoor recreation, climate regulation, and habitat conservation. Distance factors had significant impacts on residential and economic support. Finally, five LUF clusters with distinct distributions of the nine secondary functions were detected, and we suggest that different LUF management strategies considering the spatial heterogeneity of multiple LUFs should be applied for distinct LUF clusters. Also, the mechanisms behind apparent relationships among LUFs should be considered into the formulation of land spatial planning and management strategy for facilitating the coordinated development of multiple LUFs.

CRediT authorship contribution statement

Yeting Fan: Conceptualization, Formal analysis, Funding acquisition, Project administration, Writing – original draft. **Xiaobin Jin:** Data curation, Project administration, Resources, Supervision. **Le Gan:** Formal analysis, Funding acquisition, Methodology, Software, Validation. **Laura H. Jessup:** Formal analysis, Methodology, Visualization, Writing – review & editing. **Bryan C. Pijanowski:** Conceptualization, Methodology, Resources, Writing – review & editing. **Jinhuang Lin:** Data curation, Investigation, Visualization. **Qingke Yang:** Formal analysis, Funding acquisition, Investigation, Validation. **Ligang Lyu:** Funding acquisition, Project administration, Resources, Supervision.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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