Spatial identification and multilevel zoning of land use functions improve sustainable regional management: A case study of the Yangtze River Economic Belt, China

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Abstract: The quantitative identification and zoning management of land use functions (LUFs) are important starting points for solving the problems of resource allocation and sustainable development. In this study, with the Yangtze River Economic Belt (YREB) as a case study area, LUFs were grouped into three primary categories: economic function (ENF), social function (SCF), and ecological function (ELF). The least square error model was adopted to identify the morphological changes of LUFs. A two-dimensional discriminant matrix of the dynamic degree of LUF change and terrain niche index was constructed to explain the terrain gradient effect of LUFs. Bivariate local spatial autocorrelation was used to analyze the trade-offs in 2018 between ELF and ENF, and ELF and SCF. Finally, a new multilevel zoning scheme for LUFs was proposed. The results showed that from 1990 to 2018, ENF increased rapidly in cities along the Yangtze River, the overall level of SCF declined, and ELF in the
south of the Yangtze River was better than that in the north. LUFs’ morphological zoning exhibited significant regional differences. SCF-ELF combination areas and ELF dominance areas were mainly optimized in the second-level zoning. The areas with weak ELF were concentrated in the east of the YREB. Based on these results, nine kinds of LUF zonings and six kinds of major functional zonings were devised, and policy allocation was arranged for each zoning to improve the efficiency of spatial zoning management. Our research provides a reference for large-scale regional sustainable development and land use zoning management.

**Keywords:** Land use functions; Morphological changes; Terrain gradient analysis; Trade-off analysis; Multilevel zoning; Policy allocation; Yangtze River Economic Belt

1. Introduction

China is a vast territory, but the space suitable for human activities is limited (Liu et al., 2014). Due to the huge population, the small per capita land resources, and the low efficiency and severe damage of land resource utilization for a long time, land use has not been able to fulfill its due economic, social, and environmental functions. Inefficient and extensive land use affects the sustainable development of society and the economy. Over the past 40 years of reform and opening up, with the accelerating process of industrialization and urbanization in China and the increasing intensity of land space development, the contradiction between social and economic development and resource and environment support is becoming increasingly prominent (Liu et al., 2022). In the face of the global concern about the man–land contradiction and China’s sustainable development, how to rationally use land resources, give full play to land use functions (LUFs), and achieve economic–social–ecological sustainable development has become a focus for scholars and government managers (Nguyen et al., 2015).

LUFs originated from agricultural multifunctionality and covered the economic, social, and environmental dimensions of regional sustainability. They refer to the capacity to provide private and public products or services through diversified land uses (Pérez-Soba et al., 2008; Paracchini et al., 2011). They usually include economic, social, and environmental functions (Zhang et al., 2019). In recent years, there has been extensive research on LUFs, mainly focusing on the concept and theoretical framework (Zhen et al., 2009), index system construction, and spatial identification (Fan et al., 2018; Zou et al., 2020), temporal and spatial evolution (Zhou et al., 2017; Liu et al., 2018), influencing factors (Fan et al., 2021; Zhu et al., 2021), trade-off analysis, and sustainable land management (Xue et al., 2019; Zou et al., 2021; Lyu et al., 2022). The research scale tended to be administrative-unit-based, at province (Huang et al., 2022) or city level (Li et al., 2021). Some scholars believe that this approach cannot effectively explain the spatial heterogeneity of land use problems, and choose a more refined research scale, such as township (Duan et al., 2021) and grid (Liu et al., 2021). We believe that the scale effect of LUFs is similar...
to that of ecosystem services (Hein et al., 2006), and stakeholders at different scales focus on different priorities. On a fine scale, more attention is paid to the economic and social functions of land use, such as economic output and employment support (Meng et al., 2022). On a large scale, more emphasis is placed on main regional functions, such as the ecological barrier function of the Yunnan-Guizhou Plateau, and the food production function of the Jianghan Plain (Yang et al., 2022). Therefore, in a large area, such as the Yangtze River Economic Belt (YREB), we should use higher-level administrative units as evaluation units to study the effect of LUFs.

Spatial zoning was intended to manage a specific area, using a particular method to divide the area into several areas with the smallest difference within the area and the largest difference between the areas (Nian et al., 2014). This approach can effectively coordinate multiple sustainable development goals, involving socioeconomic systems and land use systems (Fei et al., 2017). At present, spatial zoning is widely used in agriculture (Peng et al., 2015), ecosystem services (Brown and Quinn, 2018), landscape (Rodríguez-Loinaz et al., 2015), land resource management (Liu and Zhou, 2021) and other fields. The zoning of LUFs is a hot issue in current research, providing an effective method for the efficient management of land space (Lyu et al., 2022). Scholars tended to carry out functional zoning for specific areas from the perspective of the trade-off analysis of LUFs (Liu et al., 2021). Other scholars have proposed a zoning scheme that combines dominant regional functions and LUFs’ trade-off analysis (Zhang et al., 2022). In general, the research on LUF zoning lacks a systematic and comprehensive approach.

The YREB was selected as the research area in this study due to its unique geographical location and huge development potential (Wu et al., 2020). We designed a progressive multilevel zoning scheme based on analyzing the morphological changes of LUFs, the terrain gradient effect of LUF changes, and the trade-off effect of LUFs. We also established corresponding land use policies for each zoning, helping to support sustainable territorial spatial management in the YREB. Specifically, this study includes four steps: (1) Based on multisource data and a spatial analysis model, constructing the corresponding evaluation index system, quantitatively analyzing the LUFs of each evaluation unit from 1990 to 2018, and identifying the morphologies of LUFs in different years; (2) Building a two-dimensional discriminant matrix of dynamic degree of LUF change and terrain niche index, dividing different spatial regions; (3) Revealing the trade-off effect of LUFs and identifying weak ecological function areas; (4) Putting forward a comprehensive zoning scheme of LUFs, and the corresponding land use policies.

2. Study area and data

2.1. Study area
The YREB spans the major eastern, central, and western regions of China, includes nine provinces and two municipalities, and covers a total area of about 2.05 million km². The YREB is located in the first-level development axis area in the “T” spatial structure of China’s territorial spatial development (Lu, 2018). In the past 30 years, the YREB has accounted for about 21% of China’s territory and supported more than 40% of the population and the GDP (Wang et al., 2020). During this period, it also undertook at least 30% of food production and nearly 45% of water resource conservation tasks. The YREB plays a very important role in China’s economic–social–ecological development. In general, urban expansion and population growth have become typical geographical features of the YREB, especially in the Yangtze River Delta (Liu et al., 2018; Luo et al., 2018). However, ecosystems are severely degraded in some areas because of overexploitation and the indiscriminate use of natural resources (Xu et al., 2018). These ecological and environmental problems pose a huge threat to the sustainable development of the YREB. In response, the Chinese central government published the “Outline of the Development Plan for the Yangtze River Economic Belt” and pointed out that the YREB area should pursue high-quality development. It is necessary to carry out multilevel zoning management of LUFs to achieve this goal. In this paper, all 130 cities in the YREB are selected as the research objects. The goal of this study is to carry out multilevel zoning of LUFs, and propose corresponding land use strategies (Fig. 1).

Fig. 1. Location of the YREB, China.

2.2. Data source and processing

In this study, multisource data, such as land use/land cover data, geographic data, meteorological data, and socioeconomic data, were used to evaluate each land use function (Table 1). The types of land use were divided into arable land, orchard land, forestland, grassland, urban and rural construction land, transportation land, water area, and unused land. The annual net primary productivity (NPP) and normalized difference vegetation index
(NDVI) from 1990 to 2015 were calculated using the ArcGIS 10.6 spatial analysis tool. The kriging interpolation method was used to obtain a map of total solar radiation, sunshine duration, temperature, and precipitation. We used the inference tool of the linear regression method to fill in missing data. Finally, the panel data of 130 cities from 1990 to 2018 were compiled to calculate the corresponding LUF metrics.

Table 1

<table>
<thead>
<tr>
<th>Data category</th>
<th>Data description</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use/Land cover data</td>
<td>Land use/Land cover database (1990-2018); Raster; 1 km×1 km</td>
<td>Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<a href="http://www.resdc.cn">http://www.resdc.cn</a>)</td>
</tr>
<tr>
<td>Geographic data</td>
<td>NPP (1985-2015); Raster; 1 km×1 km</td>
<td>Monthly NPP 1 km Raster Dataset of China’s Terrestrial Ecosystems (1985-2015) (<a href="https://doi.org/10.3974/gedb.2019.03.02.V1">https://doi.org/10.3974/gedb.2019.03.02.V1</a>)</td>
</tr>
<tr>
<td></td>
<td>NDVI (1981-2015); Raster; 1 km×1 km</td>
<td>Global GIMMS NDVI3g v1 dataset (1981-2015) (<a href="http://data.tpdc.ac.cn">http://data.tpdc.ac.cn</a>)</td>
</tr>
<tr>
<td>Meteorological data</td>
<td>Total solar radiation, sunshine duration, temperature, and precipitation (1985-2019); Sites</td>
<td>National Meteorological Information Center (<a href="http://data.cma.cn/">http://data.cma.cn/</a>), and Local Meteorological Administration</td>
</tr>
</tbody>
</table>

3. Research framework and methods

3.1. Research framework

The study procedure was divided into three steps (Fig. 2): (1) A evaluation system was established for economic function (ENF), social function (SCF), and ecological function (ELF); LUFs in the YREB from 1990 to 2018 were assessed. (2) The least square error model (LSE) was adopted to identify the morphologies of LUFs in 1990, 2000, 2010, and 2018. A two-dimensional discriminant matrix of the dynamic degree of LUF change and terrain niche index from 1990 to 2018 was constructed and divided into different spaces. The trade-offs between ELF and ENF, ELF and SCF in 2018 were detected by Bivariate local spatial autocorrelation. (3) Finally, a multilevel zoning scheme for LUFs was proposed. (4) According to the YREB development requirements, the land use policies and recommendations of each zoning were matched.
3.2. Identification and evaluation of LUFs

With the continuous development of LUFs, scholars tended to choose the widely evaluated framework of LUFs proposed by the European Union SENSOR project (Pérez-Soba et al., 2008) and have achieved convincing results (Pérez-Soba et al., 2018). This study follows this framework and highlights the YREB requirements for ecological protection. It divides LUFs into ENF, SCF, and ELF.

ENF supports human existence through material supply and economic activities. The YREB covers all types of agricultural production, and has developed secondary and tertiary industries. So, we choose the two sub-functions of agricultural production and non-agricultural production to represent the economic value of land use.

SCF refers to the food and locations provided by land use to meet the basic demands of human survival and development. Ensuring food security and providing comfortable venues are the keys to improving living conditions in the YREB. Therefore, the two sub-functions of residence support and food supply are selected to represent the guaranteed services of land use to space load and food security. ELF is the foundation of supporting human production and living activities by providing ecological products and services, including gas regulation, water regulation, and ecological nursery functions. Abundant ecological resources are the advantages of the YREB and the focus of its protection. We choose three sub-functions of gas regulation, water regulation and ecological conservation to represent the ecological services provided by land use in the YREB (Cai et al., 2017; Lyu et al.,...
Based on the above analysis, we built an indicator system for LUFs, with three primary functions and seven sub-functions (Table 2) and produced the calculation formula and key references for each indicator. We obtained the weight of each indicator through the entropy weight method (Table 2). Considering the urgent need for ecological protection in the YREB, we increased the weight of the ecological function when calculating land use comprehensive function, and assigned the weights of economic, social, and ecological functions of 0.35, 0.25, and 0.40, respectively. The purpose is to support the determination of the morphology types of LUFs in different regions. The indicators were normalized by min–max normalization so that the value range of each indicator was from zero to one. Then, the comprehensive evaluation method was adopted. The formulas are as follows:

\[
ENF = \sum_{j=1}^{7} I_{ij} \times W_j
\]

(1)

\[
SCF = \sum_{j=1}^{7} I_{ij} \times W_j
\]

(2)

\[
ELF = \sum_{j=1}^{7} I_{ij} \times W_j
\]

(3)

where \(ENF\), \(SCF\), and \(ELF\) represent economic function, social function, and ecological function, respectively. \(I_{ij}\) is the value of indicator \(j\) within city \(i\), and \(W_j\) is the weight of indicator \(j\).

### Table 2
Evaluation index system and calculation method of LUFs.

<table>
<thead>
<tr>
<th>Primary functions (Weight)</th>
<th>Sub-functions (Weight)</th>
<th>Indicators</th>
<th>Formula</th>
<th>Key references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic function (ENF)</td>
<td>Agriculture production (0.34)</td>
<td>Output value of agricultural, animal husbandry, forestry, fishery</td>
<td>(G1_i = \sum G1_{ij})</td>
<td>Li et al. (2021)</td>
</tr>
<tr>
<td></td>
<td>Non-agriculture production (0.66)</td>
<td>Output value of secondary industry, tertiary industry</td>
<td>(G23_i = G2_i + G3_i)</td>
<td>Zhang et al. (2019)</td>
</tr>
<tr>
<td>Social function (SCF)</td>
<td>Residence support (0.55)</td>
<td>Population density</td>
<td>(PD_i = P_i/S_i)</td>
<td>Lu et al. (2008)</td>
</tr>
<tr>
<td></td>
<td>Food supply (0.45)</td>
<td>Grain yield</td>
<td>(GY_i = \sum GY_{ij})</td>
<td>Zhang et al. (2022)</td>
</tr>
<tr>
<td>Ecological function (ELF)</td>
<td>Gas regulation (0.29)</td>
<td>Carbon sequestration</td>
<td>(CS = N \times \beta \sum NPP)</td>
<td>Jiang et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>Water regulation (0.33)</td>
<td>Water yield</td>
<td>(Y(i) = \sum Y(x)) (\frac{Y(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)})</td>
<td>Zhang et al. (2001); Zhang et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Ecological conservation (0.38)</td>
<td>Vegetation coverage index</td>
<td>(C_i = \frac{NDVI - NDVI_s}{NDVI_v - NDVI_s})</td>
<td>Hou and Li (2021)</td>
</tr>
</tbody>
</table>

### 3.3. Multilevel zoning of LUFs

#### 3.3.1. Identification of the morphology types of LUFs
The LSE was adopted to analyze LUF morphological types and their changes in different evaluation units in the YREB. The LSE model, also known as the Weave Combination Index, was widely used in land space division (Liu et al., 2019). The principle is to identify the value with the smallest deviation between the actual distribution of the sample and the theoretical distribution according to the characteristics of “the number of samples gradually increases, and the variance first becomes larger and then smaller” and then judge the closest type of sample. The formula is as follows:

\[ S_L^2 = \frac{1}{n} \sum_{i=1}^{n} (k_i - y_i)^2 \]  

where \( S_L^2 \) is variance; \( k_i \) is the degree of contribution of the \( i \)-th position after ranking the unit’s LUF contribution from largest to smallest; \( y_i \) is the dimensional contribution of the \( i \)-th position after ranking the dimension LUF contribution to the theoretical model from largest to smallest.

The calculation process of the LSE is as follows:

The LUF morphological types in the YREB are divided into: single-morphological dominant type, double-morphological combination type, and triple-morphological combination type. According to the hypothesis of the LSE, if there are \( A \) factors leading to the LUF morphological type, then the contribution of each factor leading to the LUF morphological type is \( 1/A \). For example, if there is a single-morphological dominant type, its contribution degree is 1; The LUF morphological type caused by two factors has a contribution of 0.5 each, and so on. Based on the above assumptions, first, the actual contribution of each dimension of each evaluation unit to the LUF morphological type is calculated, and sorted from large to small; Second, the variance of the actual dimension and the theoretical dimension is obtained, and the theoretical model with the smallest variance of the contribution distribution of the actual dimension is determined, that is, the dominant LUF morphological type of the evaluation unit. According to the theoretical model and variance results of the multi-dimensional morphological representation of LUFs in the YREB, LUF types in the evaluation units can be divided into single function dominance, double functions combination, and triple functions combination.

### 3.3.2. Terrain gradient analysis of LUF changes

The terrain gradient includes factors such as elevation, slope, and aspect that affect land use change, and the analysis of changes in basic influencing factors. In this study, the terrain niche index (\( T \)) was adopted to analyze the terrain gradient effect of the YREB. The terrain niche index can comprehensively reflect the influence of terrain factors, such as elevation and slope on the land use pattern (Ma et al., 2021). The formula is as follows:

\[ T = \ln[(E/E_0 + 1) \times (S/S_0 + 1)] \]  

where \( T \) represents the terrain niche index; \( E \) and \( S \) represent the elevation (m) and slope (°) of a point,
respectively; $E_0$ and $S_0$ represent the average elevation (m) and slope (°) of the area where the point is located; The higher the elevation and the higher the slope, the larger the terrain niche index, and vice versa.

3.3.3. Trade-off analysis among LUFs

Bivariate local spatial autocorrelation is the comparison of the observed value of a variable in a spatial unit with the observed value of another variable in an adjacent spatial unit, which can reveal the spatial correlation of the two variables (Li et al., 2022). In this study, bivariate local Moran’s I modules are used to quantify the spatial heterogeneity of the trade-off relationship between ELF and ENF, and ELF and SCF, and at the same time as the basis for the subsequent comprehensive zoning of LUFs. The formula is as follows:

$$I_i = \frac{x_i - \bar{x}}{S_x^2} \sum_{j=1, j \neq i}^n w_{i,j} (y_i - \bar{y})$$

(7)

where $I_i$ represents bivariate local Moran’s $I$; $x_i$ and $y_i$ represent the different functional values of evaluation units $i$ and $j$, respectively; $\bar{x}$ and $\bar{y}$ represent the mean values of the different functional values of all $i$ and $j$ locations, respectively; $S_x^2$ represents the variance of the functional value of the evaluation unit $i$; $n$ represents the number of all evaluation units; $w_{i,j}$ is the spatial adjacent weight matrix between each evaluation unit $i$ and $j$ within the research scope. In this study, the queen adjacency method is used to construct the spatial weight matrix, and the confidence interval is 95%; that is, the significance level is $p < 0.05$.

4. Results

4.1. Spatial-temporal changes of LUFs in the YREB from 1990 to 2018

There were significant spatial and temporal differences in the three main LUFs of the YREB from 1990 to 2018 (Fig. 3). For ENF, the high-value areas were mainly concentrated in economically developed areas, including the eastern coastal areas and some provincial capital cities. ENF of cities along the Yangtze River improved rapidly, while that of the eastern coastal areas declined. The location and resource advantages promoted the rapid economic development of cities along the Yangtze River. The overall level of SCF was in decline, while increased in the eastern coastal, southwest, and central and eastern fringe areas. These regions have natural environment and policy advantages and attracted a large amount of investment and population. Also, the improvement of science and technology has enhanced food production capacity. ELF in the south of the Yangtze River was better than that in the north. Over time, ELF in the western part of the YREB have improved, while the central and eastern parts have experienced a slight decline. The main reason is that the south of the Yangtze River had more favorable climatic conditions, such as abundant rainfall, higher temperature, and humidity. Moreover, there were high-intensity human activities in the east, while the west had a good natural ecological environment.
Fig. 3. Spatial-temporal changes of LUFs in the YREB during 1990–2018.
4.2. Morphological changes zoning of LUFs

The LSE model was used to identify the morphologies of LUFs in each city in 1990, 2000, 2010, and 2018, including ENF-SCF combination, ENF-ELF combination, SCF-ELF combination, ENF-SCF-ELF combination, and ELF dominance. Four combination types were obtained according to the morphological changes of the LUFs and the combination rule (Table 3). Each evaluation unit was classified according to the rule in Table 3, and there were 18 classifications in total (Fig. 4 (a)). The first-level zoning of LUFs was obtained by merging similar items (Fig. 4 (b)). The ENF-SCF combination areas were mainly distributed in the provincial capital cities, accounting for 9.45% of the total area. These areas had a high socioeconomic development level. The ENF-ELF combination areas were concentrated in the eastern part of Zhejiang Province, the smallest area, accounting for only 3.38%, while the SCF-ELF combination areas were the largest, accounting for 48.17%. The ENF-SCF-ELF combination areas were mainly distributed in the eastern part of Jiangsu Province, accounting for 4.52% of the total area, due to the radiation effect of Shanghai and the background natural conditions. The ELF dominance areas were concentrated in the western part of the YREB and around Chongqing and Hangzhou, accounting for 34.48% of the total area. Their social and economic development level was relatively backward, and the ecological environment remained good.

Table 3

<table>
<thead>
<tr>
<th>Combination number</th>
<th>Combination type in four years (1990, 2000, 2010, 2018)</th>
<th>Combination rule</th>
<th>Combination result</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Four same combinations</td>
<td>Quantity advantage</td>
<td>Combination of any year</td>
</tr>
<tr>
<td>II</td>
<td>Three same combinations and one other different combination</td>
<td>Quantity advantage</td>
<td>A member of the three same combinations</td>
</tr>
<tr>
<td>III</td>
<td>Two same combinations, and the other two combinations are also the same</td>
<td>Combination of the last year</td>
<td>Combination in 2018</td>
</tr>
<tr>
<td>IV</td>
<td>Three different combinations, and fourth combination is the same as one of the former three combinations</td>
<td>Quantity advantage</td>
<td>A member of the two same combinations</td>
</tr>
</tbody>
</table>

(a) Combination types of LUF morphology

(b) First-level zoning
4.3. Terrain gradient analysis zoning of LUF changes

A two-dimensional discriminant matrix of dynamic degree of LUF changes from 1990 to 2018 and a terrain
niche index were constructed. We split the horizontal axis at the third-quarter quantile ($T = 1.27$) of the terrain
niche index and the vertical axis at $-0.4\%$ and $0.4\%$, dividing the two-dimensional space into six regions (Fig. 5).
We defined them as rising area, rapidly rising area, rapidly rising area, declining area, rapidly declining area, and
rapidly declining area. Based on the spatial distribution of the three main dynamic degrees of LUF changes of
each evaluation unit in Fig. 5, the first-level zoning was corrected according to the rules in Table 4. The results
were shown in Fig. 7 (a). Then, the second-level zoning was obtained (Fig. 7 (b)) according to the functional
zoning scheme of Fig. 6. The results mainly subdivided SCF-ELF combination areas and ELF dominance areas.
The spatial distribution of socioeconomic key development zone (SEKDZ), eco-economic enhancement zone
(EEEZ), and comprehensive development zone (CDZ) were consistent with the first-level zoning. Socio-
ecological advantage zone (SEAZ) was mainly distributed in the southwest and northeast of the YREB, and
depended on the superior natural climatic conditions and the relatively developed socioeconomic level,
respectively. Socio-ecological coordinated development zone (SECDZ) mainly included key cities, such as
Nanjing, Wuhan, Changsha, and Chongqing. Their SCF has been improved as a result of the radiation effect of
key cities. Socio-ecological enhancement zone (SEEZ) was distributed along the middle and lower reaches of the
Yangtze River and the southern part of Jiangxi, Hunan, and Guizhou; their SCF or ELF have declined to varying
degrees. There was ecological advantage zone (EAZ) in the western mountainous areas where the natural
environment conditions were favorable, and the forest coverage rate and water resource conservation were very
rich. The ecological enhancement zone (EEZ) existed in the middle and lower reaches of the YREB, close to
Hangzhou and Shanghai. The process of urbanization had taken over a large amount of ecological land in these
zones.
Fig. 5. Terrain gradient division of LUFs changes.

Table 4
Second-level zoning process rule.

<table>
<thead>
<tr>
<th>Combination name</th>
<th>Process</th>
<th>Combination components and LUF area result</th>
<th>LUF area result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single function</td>
<td>$d_{LUF}$</td>
<td>I, III</td>
<td>I</td>
</tr>
<tr>
<td>dominance</td>
<td>LUF area result</td>
<td>Rapidly rising area</td>
<td>Rising area</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double functions</td>
<td>First $d_{LUF}$</td>
<td>II, III</td>
<td>I</td>
</tr>
<tr>
<td>combination</td>
<td>Second $d_{LUF}$</td>
<td>II, III</td>
<td>I, II, III</td>
</tr>
<tr>
<td></td>
<td>LUF area result</td>
<td>Rapidly rising area</td>
<td>Rising area</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triple functions</td>
<td>First $d_{LUF}$</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>combination</td>
<td>Second $d_{LUF}$</td>
<td>I</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td>Third $d_{LUF}$</td>
<td>IV, V, VI</td>
<td>IV, V, VI</td>
</tr>
<tr>
<td></td>
<td>LUF area result</td>
<td>Fluctuating area</td>
<td>Fluctuating area</td>
</tr>
</tbody>
</table>

Note: I, II, III, IV, V, and VI denote LUF change areas divided by $d_{LUF}$ and terrain gradient.
4.4. Trade-off analysis zoning of LUFs

Ecological protection is one of the most important tasks in the YREB at present. Therefore, we strengthened the areas with weak ecological function to highlight the concept of ecological priority and green development. The zoning of some cities was corrected if they satisfied the conditions of that “ENF or SCF were at an advantage, and ELF was at a disadvantage” and “∆ELF<0” Appendix A shows the results; a total of ten cities in the east of the YREB were corrected. We adjusted CDZs to socioeconomic optimization zones (SEOZs), and SECDZs and
SEEZs to EEZs. These zones were all located in Jiangsu Province, and they belonged to the developed eastern coastal areas. In the process of rapid urbanization, construction land continued to expand, and ecological land such as cultivated land, grassland, and water areas continued to be occupied, resulting in a continuous decline in ELF. The zones were named according to the “geographical location/city level and trade-off correction results” rule. Finally, we achieved third-level zoning, with a total of nine zones (Fig. 9 (a)). They were SEKDZ in the central cities (CC), SEOZ in the CC, CDZ in the CC, EEEEZ in the lower reaches (LR), SEAZ in the upper and lower reaches (ULR), SECDZ in the middle and lower reaches (MLR), SEEZ in the MLR, EAZ in the middle and upper reaches (MUR), and EEZ in the LR. In addition, the third-level zoning was processed by “merging similar items” to obtain six major functional zonings. They were SEKDZ, SEOZ, CDZ, EEEEZ, SECDZ, and ecological conservation zone (ECZ) (Fig. 9 (b)), accounting for 9.45%, 2.05%, 2.47%, 3.38%, 46.51%, and 36.14%. They showed the focus and direction of land use management in the YREB.

**Fig. 9.** Third-level zoning of LUFs.

5. Discussion

5.1. Insights into the spatial heterogeneity and multilevel zoning of LUFs

The uncoordinated development of LUFs has brought challenges to the sustainable use of territory space (Zhang et al., 2014). The rapid decline of economic and social functions in the eastern coastal areas, as in Shanghai and Jiangsu, indicates that a large amount of cultivated land in these areas has been sacrificed for urban expansion, and the total agricultural output value has continued to decline. These indications are consistent with the research results of other scholars (Chen et al., 2020; Chen et al., 2022). The ecological function has changed significantly in the areas south and north of the Yangtze River, the former being clearly better than the latter. The analysis showed that compared with the area north of the Yangtze River, the south had more precipitation, higher humidity, and higher temperature. These conditions are conducive to the growth of plants, the activity of microorganisms, and the production of organic matter, thereby improving the service capacity of the ecosystem.
(Luo et al., 2020). The changes in ecological function over time showed obvious differences in the eastern and western regions. The ecological function in the western region increased rapidly, while that in the central and eastern regions decreased slightly. The intensity of human activities and regional natural conditions were the main determining factors.

A single or multiple schemes involving a simple comparison of zoning could not meet the needs of large-scale land use (Fan et al., 2018; Meng et al., 2022). The multilevel zoning scheme of LUFs proposed in this study solves this dilemma. Compared with traditional spatial zoning schemes that considered dominance and difference among LUFs, the biggest feature of the multilevel zoning scheme was that it considered the process of regional land use functional change and involved a systematic and comprehensive concept. In the identification of the morphology of LUFs, the morphological changes in four years were considered, rather than the high-value aggregation areas of LUFs (Liu et al., 2012), or only the dominant function of one year (Cheng et al., 2021). Some scholars also noticed the systematic importance of LUF zoning and proposed a zoning scheme combining the dominant function and trade-off analysis of LUFs (Zhang et al., 2022). However, they ignored the importance to zoning of LUF change, which directly reflected the development trend of LUFs. Our study not only considered the effect of LUF change on zoning, but also analyzed the role of the terrain gradient effect on a large regional scale. What is more, this study explored the trade-off effect between ecological function and economic function, and ecological function and social function in line with the requirements of ecological protection in the YREB. Therefore, the systematic zoning scheme proposed in this study can help policymakers accurately identify regional land use problems and formulate corresponding policies. Finally, compared with the grid as the evaluation unit (Liu et al., 2021), which involved dividing the study area into regular grids, this research selected the basic unit at city level, which could completely retain the original economic and social information in the administrative unit, thereby reducing errors caused by data segmentation.

5.2. Policy allocation and recommendations for sustainable regional management

Sustainable zoning management of LUFs must match the corresponding land use policies. We divide land use policies into three aspects: economic development, social development, and ecological protection represented by red circles, blue squares, and green triangles respectively. The number of graphs represents the corresponding policy intensity. When the graph quantity is one, it means that the land use policy intensity is the lowest, and when the graph quantity is 5, it means it is the highest. Based on the above rules, we formulated land use policies for different functional zones (Fig. 10).

SEKDZs include seven provincial capital cities, and Shanghai and Chongqing. They are the core cities of the
socioeconomic development of the YREB, and bear the responsibility for driving the development of the surrounding economically backward areas. These cities should explore low-consumption, sustainable economic development patterns. Therefore, the economic development and social development intensity of these zones are grade five, and the ecological protection intensity is grade one. SEOZs are concentrated around Shanghai and Nanjing. Rapid urbanization has occupied a large amount of ecological land, resulting in a decline in ecological service capacity (Luo et al., 2019). So, we reduce the intensity of economic development and social development to grade four, and increase the intensity of ecological protection to grade two. CDZs need to coordinate economic, social, and ecological functions (Liu et al., 2021). We further increase ecological protection to grade three, while maintaining the grade four advantages of economic and social development. EEEZs are concentrated in the eastern coastal areas of Zhejiang Province. Economic conditions and ecological environment are their advantages, but the coordination between the two is low. The development direction of these zones is to take into account economic growth and ecological services, and the intensity of economic development and ecological protection is set as grade three, while the intensity of social development is grade two. In SECDZs, SEAZs in the ULR should maintain the advantages of food production, extend the food processing industry chain, and develop rural tourism and characteristic agricultural products. At the same time, they need to explore ways to convert rich ecological resources into economic output value, so as to increase the number of people earning an income (Shen and Chou, 2022). Thus, we set the intensity of social development and ecological protection as grade four and economic development as grade one. The social and ecological functions of SECDZs in the MLR are in a state of fluctuation. The intensity of social development and ecological protection should be appropriately reduced to grade three, and the intensity of economic development should be increased to grade two. There is a mismatch between the population and the carrying capacity of the ecological environment in SEEZs in the MLR. The government should organize free professional skills training for the unemployed, and send them to the surrounding core cities to increase the employment rate. We set the intensity of economic development and social development as grade two, and the intensity of ecological protection as grade three. The ECZs, and EAZs in the MUR are concentrated in the western mountainous areas of the YREB, the basis for the maintaining the ecological environment. These areas should give priority to ecological protection, improving it to grade five, reduce economic development and social development to grade one. They should also build ecological product brands (Li et al., 2021), such as pure nutrient-rich honey, and develop the health care industry using negative oxygen ions. The ecological environment of the EEZs in the LR is in an advantageous position. However, it faces the challenge of indiscriminate urban expansion. These zones should classify the concentrated and contiguous ecological advantage areas as nature reserves (Wu et al., 2022). Conversely, government managers should carry out reasonable urban planning and
explore the path of green development. We also set the intensity of ecological protection to grade five, and
adjusted the intensity of economic development and social development to grade two. Differentiated policy
allocation for land use functional zoning can help to give full play to the advantages of different regions of the
YREB and make up for the corresponding disadvantages, thereby achieving sustainable development.
Fig. 10. The policy allocation of LUF zoning.

5.3. Limitation and further directions
The multilevel LUF zoning scheme proposed in this paper has significant theoretical implications for the sustainable development strategies of different regions of the YREB. However, there are some problems in this research. This study selected seven indicators that can best reflect the LUFs in the YREB for the index system. However, these indicators cannot cover all LUFs, such as the cultural service function, due to the lack of long-term survey data (Paracchini et al., 2014). The limitations of the length of this paper allowed for the analysis of the spatial and temporal characteristics of LUFs in the YREB, and the proposal of multilevel LUF zoning, but not for the exploration of the influencing factors of land use functional zoning.

Two important directions for future research are worth exploring. It is necessary to build a comprehensive and quantifiable evaluation index system of LUFs using multisource data, various spatial analysis methods, remote sensing images, and point of interest data. Field surveys could be used to evaluate the cultural service function. An exploration of the influencing factors and driving mechanisms of land use functional zoning from the perspective of regional background and external environment will be the focus and hotspot of future research.

6. Conclusion

Over the past three decades, the improvement in cultivated land utilization efficiency and the rapid expansion of construction land have promoted rapid social and economic development. It is of value to analyze the evolution law of LUFs in the different regions of the YREB and to reasonably divide different functional zoning for a sustainable regional development that prioritizes ecological concerns and socioeconomic development. This study not only deepens the understanding of LUFs, but also provides a systematic and comprehensive zoning scheme for LUFs.

This study built a quantitative evaluation index system to evaluate LUFs at the city scale in the YREB. It included three primary functions and seven sub-functions. The improvement of economic function and the overall decline of social function of cities along the Yangtze River showed the importance of natural resources and location advantages for urban development and the extensiveness of urban development. There were significant differences in ecological function in the areas south and north of the Yangtze River, and in east, middle, and west of the YREB from 1990 to 2018. The reasons included internal natural conditions and external human activity intensity. A series of spatial analysis methods were adopted to build a systematic and comprehensive multilevel zoning framework. We analyzed fully the morphological changes in LUFs, the terrain gradient effect of LUF change, and the trade-off effect between ecological function and economic function, and ecological function and social function. We designed a three-level zoning scheme, which resulted in nine LUF zonings and six major functional zonings. The zoning results reflect the change process of LUFs under the influence of the basic
morphological characteristics of LUFs and the terrain gradient effect. Simultaneously, the protection of areas with weak ecological function has been strengthened, reflecting the concept of ecological protection in the YREB.

This study also formulated land use policies for each zoning from three aspects: economic development, social development, and ecological protection. The tasks of SEKDZs, SEOZs, and CDZs should focus on improving social and economic benefits, providing an economic foundation for urban development, and gradually strengthening ecological protection. EEEZs need to reduce the intensity of social development based on the intensity of economic development and ecological protection. For SEAZs in the ULR, SECDZs in the MLR, and SEEZs in the MLR, it is necessary to ensure the dominant position of social development and ecological protection and moderately increase the intensity of economic development. Ecological protection is the development focus for EAZs in the MUR, EEZs in the LR. The land use policy allocation scheme proposed in this study is effective in accurately supporting the zoning management of LUFs and promoting the sustainable development of territorial space.

### Appendix A

#### Table A1

The rule of third-level zoning correction.

<table>
<thead>
<tr>
<th>Number</th>
<th>Zoning unit</th>
<th>High trade-off function</th>
<th>ELF trade-off (H/L)</th>
<th>( \Delta ) ELF (1990–2018)</th>
<th>Zoning correction (Y/N)</th>
<th>Zoning result</th>
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<td>1</td>
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</table>

Note: ENF denotes economic function, SCF denotes social function, ELF denotes ecological function. H denotes that ELF has high trade-off. L denotes that ELF has low trade-off. Y denotes that LUF zoning needs to be corrected. N denotes that LUF zoning doesn’t need to be corrected.

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Data availability The data and materials used to support the findings of this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to Participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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