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Article

Delineating Ecological Functional Zones and Grades for Multi-Scale Ecosystem Management

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Abstract: Integrating ecosystem services (ESs) to delineate ecological functional zones (EFZs) is a fundamental work in terrestrial spatial planning and ecosystem management. However, existing studies have largely overlooked the refinement of EFZs at local scales, which hinders targeted and multi-scale ecosystem management. This study introduced a “two-step refinement zoning method” to address this gap, first using the self-organizing feature mapping method to delineate EFZs based on ESs at a township scale, and then applying hotspot overlay analysis to identify hotspots of dominant ESs within EFZs at a village scale. By overlaying the outcomes of these two steps, EFZs can be further graded by designating villages with hotspots of dominant ESs as level I and those without as level II. The proposed method was applied in Wuhan City, dividing it into five types of EFZs with different ESs combinations and land use compositions. Furthermore, 5.23% of villages were identified as Level I of EFZs, serving as advantageous areas of dominant ESs in the study area. On this basis, diversified management strategies and conservation priorities were proposed. This study provides a theoretical and methodological reference for terrestrial spatial planning and sustainable ecosystem management.

Keywords: ecosystem services; ecological functional zones; tradeoffs and synergies; self-organizing feature mapping; multi-scale management

1. Introduction

Ecosystem services (ESs) are “the goods and services that humans derive from ecosystems”, which provide a bridge between ecosystems and human well-being (Costanza et al., 1997; Nápoles-Vértiz et al., 2024). Rapid urban expansion, which is accompanied by the encroachment of natural habitats into semi-natural and artificial landscapes, poses impacts on ecosystem elements, structure, and function, causing widespread degradation of ESs (Zhai et al., 2024; Zhang et al., 2021). According to the report, urban population and built-up land are still growing in China, and the urbanization rate is expected to reach 66.4% by 2050 (Yuan et al., 2018). Meanwhile, land expansion is also faster than population urbanization (Sun et al., 2024). Given this, from the perspective of ESs, conducting research on their planning, managing and utilizing is of great significance for the sustainable development of human society and ecosystem management in China.

In recent years, scholars have conducted extensive research on the assessment (Halperin et al., 2023), spatial mapping (Nyelele et al., 2023) and driving mechanisms identification (Pinto et al., 2023) of ESs, interactions and trade-offs between different ESs (Frizzle et al., 2022; Teng et al., 2022), the balance of supply and demand of ESs and ESs flows (Molla Sitotaw et al., 2024), forming a wealth of theoretical research. In the application aspects, researchers have implemented ESs theory and methods to the construction of regional ecological security patterns (Kim et al., 2023), the proposal of ecological protection strategies (Zhang, et al. 2020), ecological compensation, and territorial spatial

planning (Cole et al., 2021). The ecological red line, as the most important spatial plan for ecosystem protection in China, is delineated based on the importance of ecosystem functions and services as well as ecological sensitivity (Deng et al., 2024). Nevertheless, compared to theoretical research, the application of ESs theory and methods in practice is still relatively immature.

Delineating ecological functional zones (EFZs) is a fundamental part of ecosystem management in territorial spatial planning, which is also the first step of application ESs theory in territorial spatial planning. It is developed based on traditional ecological zoning, combining ecological elements and ecological functions and services, to identify major ecological characteristics of different geographic zones, so as to formulate precise protection, restoration and control measures (Zhao et al., 2023). Schneider et al. (2010) drew a map of the global urban ecological zones based on MODIS data. Chen et al. (2024) divided mainland China into ecological reshaping zones, ecological correction zones, ecological buffer zones, ecological enhancement zones and ecological restoration zones based on ecosystem health indicators. The spatial scales on which EFZs are performed range from global (Du et al., 2024), regional (Liao et al., 2023; Shen et al., 2021; Wang et al., 2024), and to watershed and ecological engineering zones (He et al., 2024; Sadeghi et al., 2023). Earlier studies mainly utilized a single indicator such as ecological functional importance or ecosystem health to determine zones. For example, Zhao et al. (2022) used the ecosystem health index to delineate the ecological management zones of the Yangmei River basin. To fill in this gap, scholars adopted more sophisticated indicators that represent the comprehensive ability of ecosystems to provide ESs and functions during the zoning process. For example, Zeng et al. (2023) used the ESs indicator to delineate ecological management zones in China. However, most of the studies paid less attention to the combination of multiple ESs in each ecological functional zone. In addition, they overlook the refinement of zones at local space, which is not conducive to the precise and targeted ecological protection and restoration measures.

In addition, scholars have developed many quantitative methods to carry out ecological functional zoning, and the relevant methods have evolved from the qualitative methods by a priori knowledge to quantitative methods such as simple overlay analysis, regression analysis and principal component analysis. Wang et al. (2017) used a multi-criteria decision analysis technique to delineate the ecological red lines in Hangzhou Bay. Bailey et al. (2004) drew a block map for the ecological environment in a region, analyzed the ecological problems and evaluated the whole ecosystem, providing a holistic spatial cognition on ecological management. Mamat et al. (2017) adopted the sensitivity analysis method to zone the cultural heritage sites in the Turpan region according to the condition and spatial variability characteristics of ecosystems based on the theory of nature reserve zoning. Cao et al. (2020) utilized an integrated approach of trade-off analysis, hotspot identification and clustering algorithm to identify the priority zones for cropland protection and propose corresponding policy guidelines. With the development of computer technology, the methods of big data and machine learning are also increasingly applied to ecological functional zoning. Neural networks, especially self-organized mapping network (SOFM) algorithms, have attracted much attention due to their accuracy, intelligence, and efficiency in processing data (Chen et al., 2024; Zhao et al., 2023). Zhang et al. (2024) and Xia et al. (2023) applied SOFM models to identify the functional zones of ESs in China's coastal protection forest areas and the Qiantang River Basin respectively, aiming to provide sustainable spatial planning and management strategies. However, in general, there is still room for the optimization of zoning methods, especially, developing an innovative method or adopting an appropriate technique to refine the EFZs on the basis of delineating them.

In this context, this study proposed a "two-step refinement zoning method" to delineate ecological functional zones and grades at two district scales. First, based on an assessment result of six ESs indicators, the SOFM model was used to identify ESs bundles to inform EFZs at the township scale. Subsequently, hotspot overlay analysis was applied to identify ESs hotspots at the village scale. Finally, a spatial overlay method by coupling the results of the two steps was performed to refine EFZs by designating them with different grades. According to the results of ecological functional zoning and grading, management strategies and conservation priorities in Wuhan were proposed, which are intended to provide a basis for the sustainable development of the region.

2. Data and Methods

2.1. Study Area

Wuhan City ($29^{\circ}58' - 31^{\circ}22' \text{ N}$, $113^{\circ}41' - 115^{\circ}05' \text{ E}$) is located in the eastern part of Hubei Province, at the confluence of the Yangtze River and the Han River, covering an area of about 8,569.15 km² (**Figure 1**). It is situated in the transition zone from the Jiangnan Plain to the Dabie Mountains, with flat terrain in the center, and hilly landscapes in the north and south. Low hills, ridge plains and plains occupy 5.8%, 12.3%, 42.6% and 39.3% of the total area, respectively. Wuhan has 166 large and small lakes, known as the “City of a Hundred Lakes”, and lakes cover 803.17 km², ranking the first among Chinese cities. As an ecological barrier city of the central plains, Wuhan has a strategic position in the ecological protection of the region and even the country. However, with the rapid urban land expansion and infrastructure construction occupying a large amount of ecological land, the ecosystem has suffered damage and its capacity to provide ESs has declined in Wuhan. The area of lakes has shrunk by nearly 60% compared with that in the 1980s (Zhu et al., 2023). Meanwhile, ecological degradation such as serious soil erosion and diversity (e.g., aquatic species) decline of the Yangtze River are becoming more and more prominent. Integrating ESs theory and methods to determine EFZs and their grades would provide guidance to ecological security pattern and ecological protection and management in Wuhan.

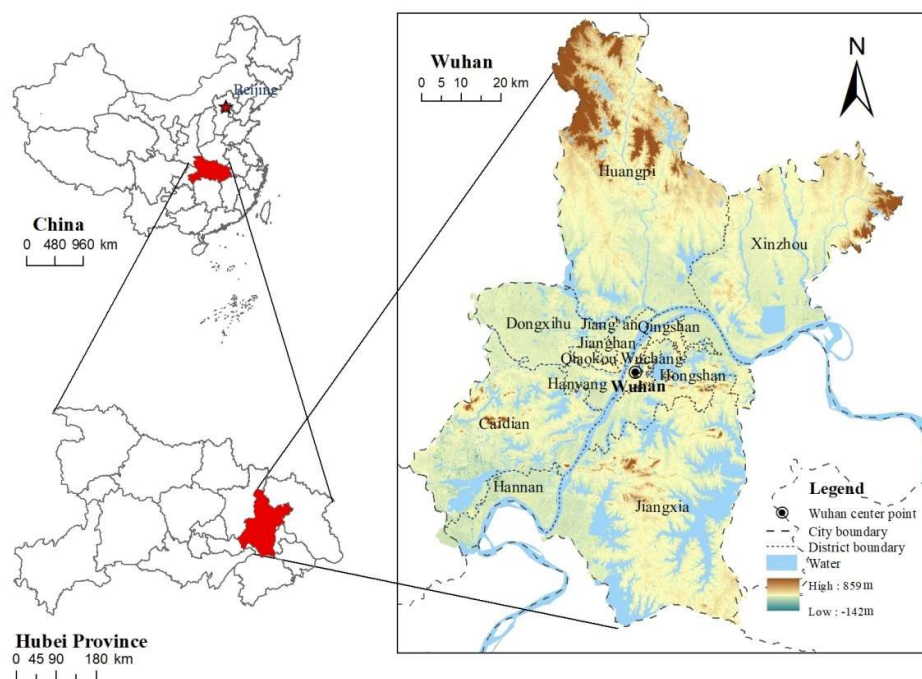


Figure 1. Geographic location and elevation of Wuhan city.

2.2. Data Description

Multisource and heterogeneous data from natural, socioeconomic, and LULC aspects was integrated to conduct this research. Specifically, (1) DEM with a resolution of 30m was extracted from the ASTER GDEM V2 dataset, provided by the Geospatial Data Cloud (<http://www.giscloud.cn>). (2) Meteorological data, including average monthly temperature and rainfall, was downloaded from the China Integrated Meteorological Information Service System. Radiation-related data was sourced from the National Climatic Data Center in the United States. (3) Soil data including soil organic matter content and soil types (clay, sand and silt content) at a resolution of 1 km, were extracted from the

Harmonized World Soil Database version 1.1 provided by the Big Data Center of Sciences in Cold and Arid Regions (<http://westdc.westgis.ac.cn>). This data was classified according to the FAO-90 classification system. (4) Vegetation coverage data, including leaf area index data was downloaded from the National Earth System Science Data Center and NDVI data was extracted from the Geospatial Data Cloud's Landsat-8 images. (5) Land use data and vegetation type maps were provided by the Chinese Academy of Sciences Resource and Environmental Sciences Data Platform. The original land use data was classified into six primary categories and 25 secondary categories, and it was reclassified six major categories in our study, including arable land, forests, grassland, waters, construction land, and unused land. (6) Administrative division data including maps of township and village-level administrative boundaries was provided by the Wuhan Planning & Design Institute. (7) Grain production data was extracted from the 2020 Statistical Yearbook.

2.3. *Methods*

2.3.1. Model Framework

A two-step refinement zoning method was developed to determine ecological functional zones and grades at two distinct scales in Wuhan (**Figure 2**). Initially, based on an evaluation of six ESs indicators, trade-offs or synergies among ESs were identified. Moreover, the SOFM model was utilized to identify ESs bundles, serving as the basis to determine EFZs, at a township scale. Subsequently, a hotspot analysis was adopted to identify ESs hotspots at a village level. Ultimately, a spatial overlay analysis was performed to refine the EFZs at the township level by stratifying them into two grades according to the presence or absence of hotspots of dominant ESs at the village level. Specifically, villages exhibiting hotspots of dominant ESs were designated as level I, while those lacking such hotspots were categorized as level II.

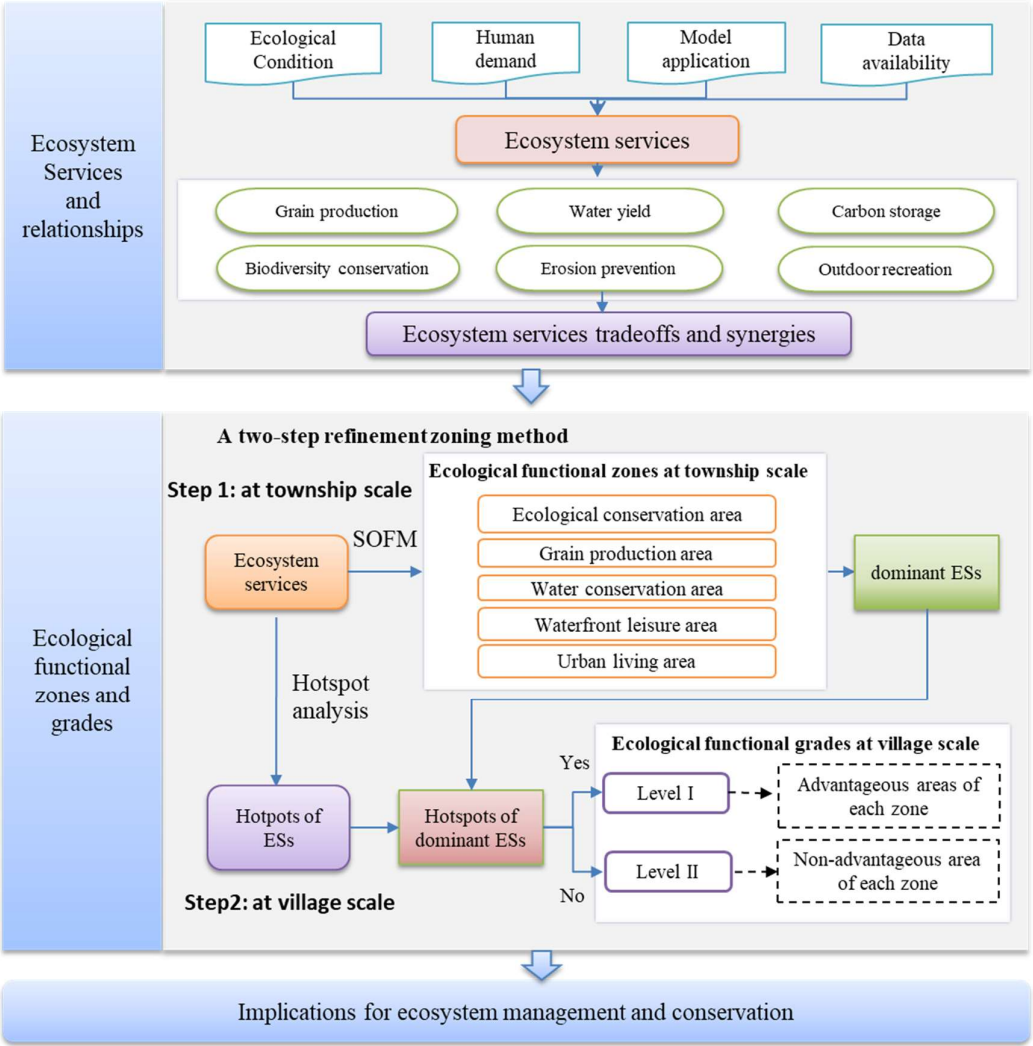


Figure 2. Framework of the method.

2.3.2. Ecosystem Services Selection, Evaluation and Correlation Identification

Grain production (GP), water yield (WY), carbon storage (CS), biodiversity conservation (BC), soil conservation (SC), and outdoor recreation (OR) were selected as indicators of ESs. These services were chosen because (1) they cover the supply services, regulating services, and cultural services categories listed by MA (2005). Among them, GP and WY belong to supply services, while CS, BC, and SC belong to regulating services, and OR belongs to cultural services; (2) they are closely related to urbanization and other human activities and are easily affected by various human activities; (3) using existing models and methods, these services can be conveniently assessed, and the necessary data is readily available in the study area.

This study uses various ecological models to assess six ESs, with the assessment timeframe set in 2020. The detailed assessment method refers to Zhang, et al. (2018). Based on the assessment results, Spearman correlation coefficient was used to quantitatively characterize the trade-off or synergy relationship between each pair of ESs, providing a basis for subsequent ecological functional zoning and management. Before the correlation analysis, the raw assessment results were dimensionlessly normalized using the maximum-minimum method.

2.3.3. Determination of Ecosystem Services Bundles at Township Level

This study employed the SOFM algorithm to determine ESs bundles (S. Li et al., 2022), which aids in guiding ecological functional zoning. Compared to the K-means clustering algorithm, SOFM enhances neural networks through a competitive learning strategy, offering higher visualization and interpretability. The SOFM was first proposed by Finnish scholar Kohonen and is a network model that maps high-dimensional datasets to low-dimensional spaces to determine the similarities between data (Xu et al., 2022). It is an unsupervised competitive neural network, characterized by adaptability, self-organization, and self-learning. The model consists of an input layer and an output layer (competition layer), with input nodes connected to output nodes through weights. The initial weights are continuously adjusted through learning, gradually aligning the output nodes closer to the topological characteristics of the input vectors. The weight update formula for the output node c is as follows:

$$W_c(t+1) = W_c(t) + \theta(\mu, c, s)a(t)(D(t) - W_c(t)) \quad (1)$$

$W_c(t)$ denotes the current weight of c^{th} node at the time point t . $\theta(\mu, c, s)$ represents the neighborhood function between μ and s during the s^{th} iteration, i.e., the update magnitude. $a(t)$ denotes the learning rate. $D(t)$ indicates the winning node of the current input sample. The SOFM algorithm was conducted by Kohonen package in RStudio. Number of clusters is a determinant parameter to the result of SOFM and the following ecological functional zoning, which was determined based on the sum of squared errors (SSE) using the “elbow method” in this research.

2.3.4. Identification of Ecosystem Services Hotspots at Village Level

The global Moran's Index can reveal overall correlations but cannot pinpoint specific clustered areas (Bivand & Wong, 2018). The introduction of Getis-Ord G_i^* enables the identification of statistically significant spatial clusters of high values (hotspots) and low values (coldspots) (Getis & Ord, 1992), understanding the local heterogeneity characteristics of attribute's spatial aggregation. It is a method of local autocorrelation analysis. In this study, Getis-Ord G_i^* was used to identify hotspot areas of ESs at the village level (Roces-Díaz et al., 2018).

$$G_i^* = \frac{\sum_{j=1}^n w_{i,j}x_j - \bar{X} \sum_{j=1}^n w_{i,j}}{S \sqrt{\frac{[n \sum_{j=1}^n w_{i,j}^2 - (\sum_{j=1}^n w_{i,j})^2]}{n-1}}} \quad (2)$$

x_j represents the attribute value of element j , $w_{i,j}$ represents the spatial weight between elements i and j , and n is the total number of elements.

$$\bar{X} = \frac{\sum_{j=1}^n x_j}{n} \quad (3)$$

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

3. Results

3.1. Spatial Distributions and Correlations of Ecosystem Services

The spatial distribution of ESs in Wuhan is shown in the **Figure 3**. Generally, except for EP service, other services displayed a trend of lower values in the central region and higher values in the city's periphery. The value of GP service ranged from 0-3.74×10⁷ kg, which was generally higher in the northern region than in the southern region, and the GP in the region southwest of the western part of the city was also relatively low. This is mainly because the northern part of Wuhan is richer in arable land resources than the southern part, and there is more concentrated and continuous basic

arable land, while there is less arable land distributed in the city center. The WY service ranged between 0-1570 mm, which was generally higher in the south than in the north, higher in the east than in the west, and higher in the surrounding area than in the center, especially in the areas where water is concentrated. The distributions of CS showed a pattern of lower in the city center and higher in the surrounding areas, in which the high values of CS arose in the northwestern Mulan Mountain area, the northeastern General Mountain area, and the southeastern region, and the low values of CS were widely distributed within the central city. The value range of SC service was 0-333.02 t/ha, with high-values mainly concentrated in the mountainous area in the northern part of Huangpi District and the area of the Dabie Mountain remnants in the northeastern part of Xinzhou District, and sporadically distributed in the southern and southwestern parts of the city. The rest of the area had a relatively low level of SC service. The BC service was in the range of [0,1], with high values occupying a small area proportion centered in the northwest, northeast, and south where forests are largely distributed, and low values concentrated in the rest of the area. OR value is ranged between 0 and 1, with high values centered in the mountainous area in the north of Huangpi District, the area around General Mountain in the northwest and northeast of Xinzhou District, and the concentrated area of rivers and lakes in the south of Jiangxia District, and scattered in the southwestern and central parts of the city.

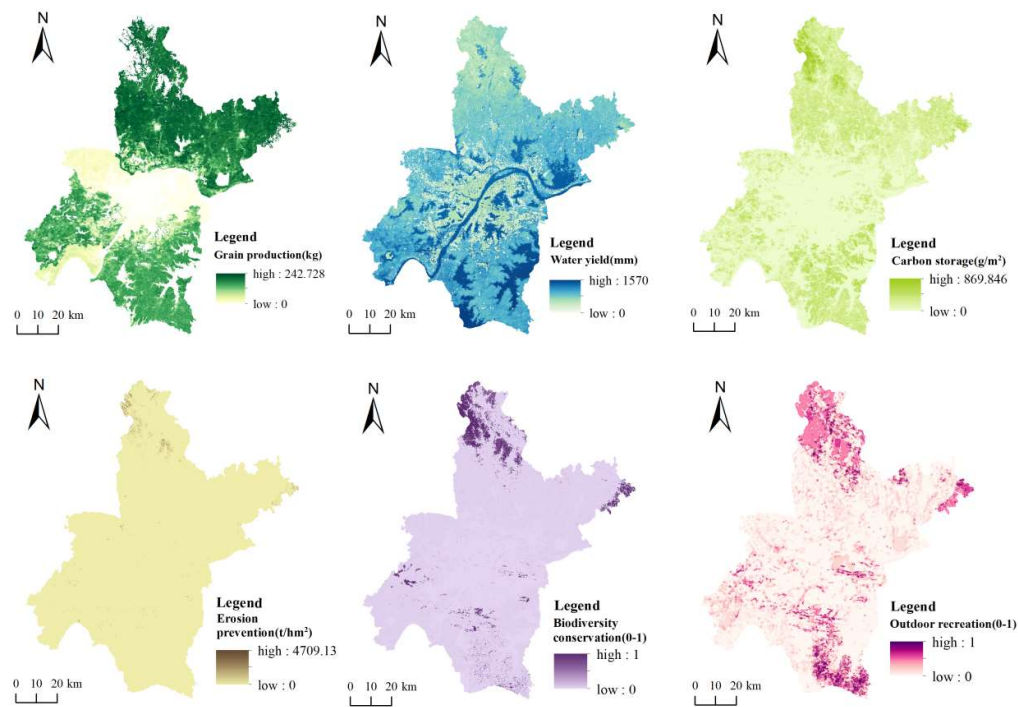


Figure 3. Spatial patterns of ecosystem services in Wuhan.

Figure 4 illustrates the correlation between each pair of ESs, revealing significant relationships between all pairs of ESs, among which four pairs showed negative correlations and eleven pairs showed positive correlations. The strongest relationship occurred between CS and GP, with a correlation coefficient of 0.73, while the weakest arose between CS and WY, marked by a coefficient of -0.07. Specifically, GP service exhibited a synergistic relationship with CS, EP, BC, and OR services, with the most pronounced synergy with CS service. Conversely, WY displayed trade-off relationships with CS, EP, and OR services, showing the strongest tradeoff relationship with EP service with a correlation coefficient of -0.43. CS also aligned synergistically with EP, BC, and OR, with a notably strongest correlation with BC. Additionally, EP showed strong synergy with BC and

even stronger synergy with OR. Although BC and OR were synergistically correlated, the strength of this relationship was comparatively weak.

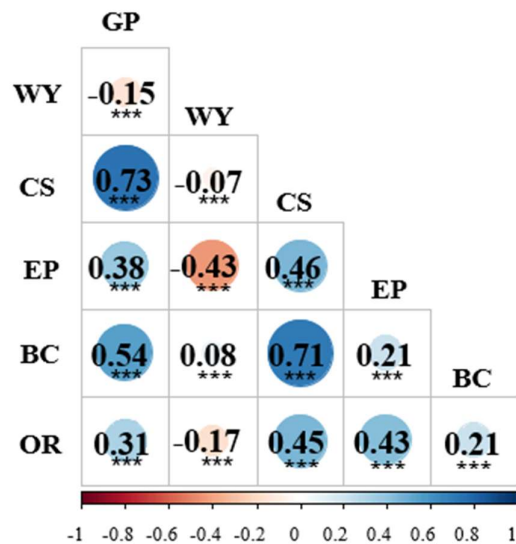


Figure 4. Tradeoff or synergy between each pair of ecosystem services in Wuhan (GP: grain production; WY: water yield; CS: carbon storage, BC: biodiversity conservation, SC: soil conservation; OR: outdoor recreation).

3.2. Ecological Functional Zones at Township Level

The graph of the sum of squared errors (SSE) with the number of clusters during the SOFM process is shown in **Figure 5**. It can be seen that the curve inflection point effect is obvious when the number of clusters equals 5, so the optimal number of clusters was set to 5. At the same time, the number of model training times was set to 10,000 times, and the initial learning rate and the end learning rate were 0.1 and 0.01, respectively.

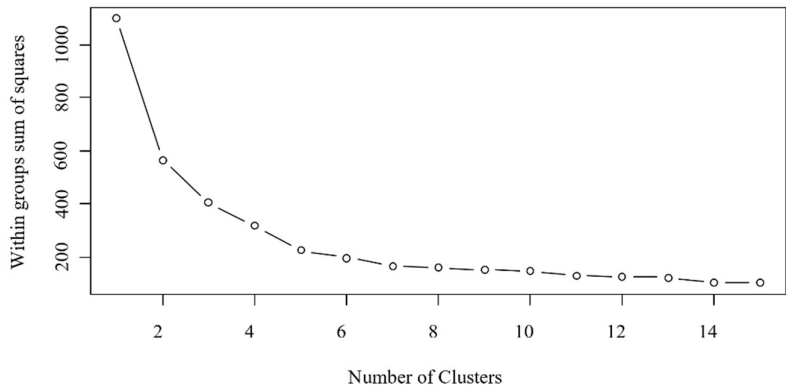


Figure 5. Change of within-group sum of squared errors with number of clusters in self-organized mapping network process.

The mean values of ESs and the land use compositions within each ecological functional zone are shown in **Figures 6-7**. According to the characteristics of ESs and land use composition in each zone, the five types of EFZs were named ecological conservation area (ECA), grain production areas (GPA), water conservation area (WCA), waterfront leisure area (WLA) and urban living area (ULA).

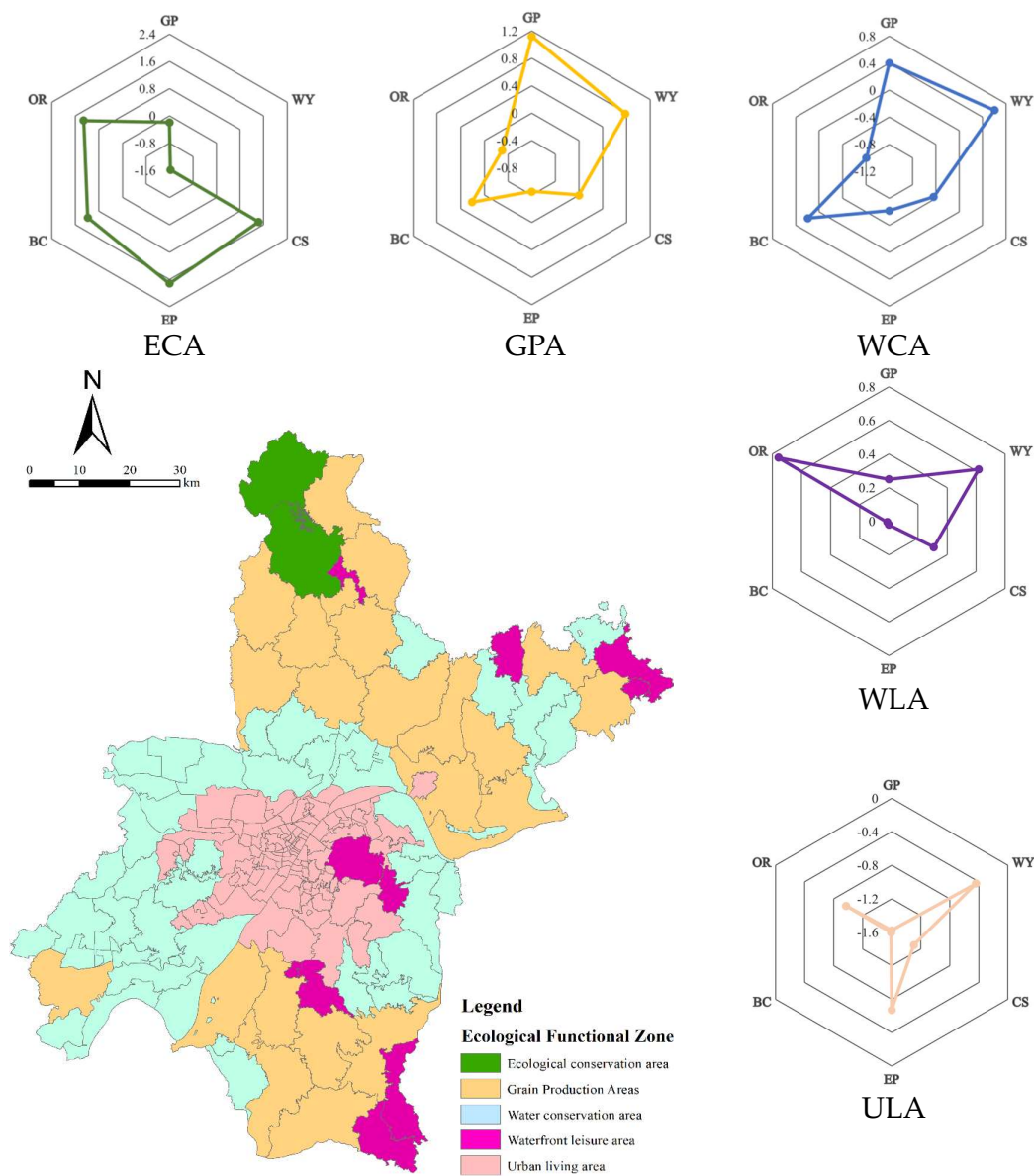


Figure 6. Spatial distribution and ecosystem services composition of each ecological functional zone (GP: grain production; WY: water yield; CS: carbon storage, BC: biodiversity conservation, SC: soil conservation; OR: outdoor recreation; ECA: ecological conservation area; GPA: grain production areas, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

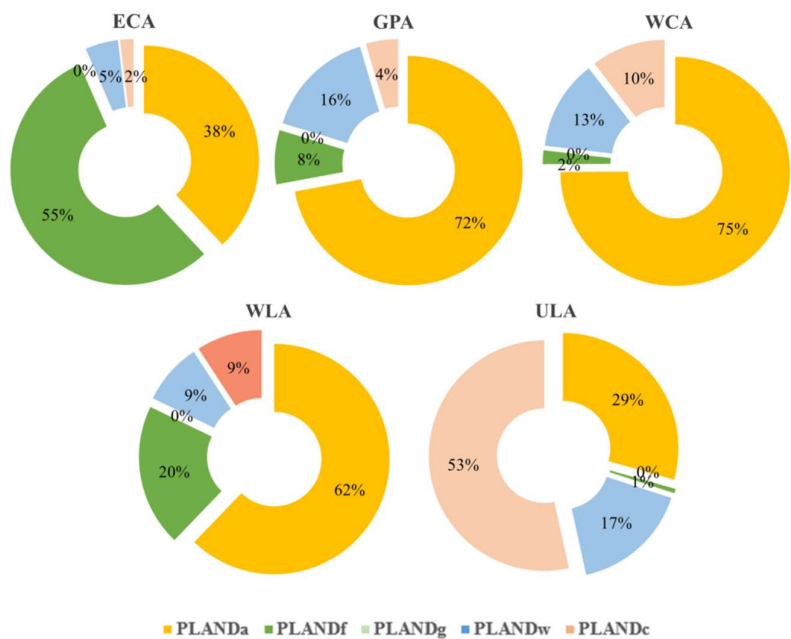


Figure 7. Land use composition within each ecological functional zone (ECA: ecological conservation area; GPA: grain production areas, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area; PLANDa: proportion of arable land; PLANDf: proportion of forest land; PLANDg: proportion of grassland; PLANDw: proportion of waters; PLANDc: proportion of construction land).

The ECA was mainly located in the towns of Changxuanling Street and Caidian Street in Huangpi District, with an area of 393.56 km². The land use type of this zone was dominated by forests, followed by arable land, which accounts for 55.26% and 37.92% of the total area respectively, and the proportion of construction land was relatively small. Except for GP and WY services, other services maintained relatively high. This may be due to this zone having high vegetation cover with a high capacity to provide EP, in addition, Mulan Tianchi, Qingliangzhai, Jinli Gou and other scenic spots were gathered here, which also makes this zone a high capacity to supply OR service. Meanwhile, this zone could provide a high level of CS service and good quality habitats. On the whole, the ecological environment was good.

The GPA was mainly located in the northern, northeastern and southern parts of Wuhan City, involving a total of 21 township-level administrative districts in Huangpi, Xinzhou, Jiangxia and Caidian districts, with an area of 3429.73 km², accounting for 39.98% of the total area of Wuhan City. It was one of the most widely distributed ecological functional zone. The land use type of this zone was dominated by arable land, accounting for about 71.94%, followed by waters, accounting for 15.7%. GP and WY services, which showed a strong synergistic relationship, were the dominant services of this zone, followed by BC service, with CS, EP and OR services below average.

The WCA was mainly distributed in the periphery of the main city as well as the central and northern parts of Xinzhou District with a total of 44 towns, which belongs to the transitional area from urban center to rural areas. This zone covered an area of 2,969.90 km², accounting for 34.62% of the total area of Wuhan, and was the second-largest functional zone. Arable land was the dominant land use type in the zone, accounting for about 74.66%, followed by waters and construction land, accounting for 12.65% and 10.41% respectively. The zone was dominated by WY service, followed by GP and BC services, with the rest services below average.

The WLA was relatively scattered, involving 10 towns, located in the Mulan Mountain Scenic Area in Huangpi District, Daoguan River Scenic Tourism Area and Xugu Street in Xinzhou District, Husi Street and Shu'an Street in Jiangxia District, and Shidong Street and Donghu Scenic Area in Wuchang District. This zone basically consisted of scenic areas and was close to rivers, most of which

were far away from the cities, so the OR service was relatively high, and the WY and CS services were also relatively high. The zone was dominated by arable land, which accounts for 61.7% of the zone area, followed by forests, which accounts for about 20%, while waters and construction land occupied less than 10%.

The ULA was mainly located in the central part of Wuhan, involving seven main urban areas of Wuhan and individual towns in East and West Lake District, Xinzhou District and Caidian District, totaling 107 towns, with 107 towns of total area of 1232.53 km², accounting for 14.37% of the total area of Wuhan. The region was dominated by construction land and arable land, accounting for 53.41% and 29.39% respectively, with a high level of urbanization and intensive human activities. In terms of ESs composition, all ESs in the zone were below average, especially BC, GP and CS services, and only WY and EP services showed a slightly higher value than those in other zones, reflecting that the ecosystem in this zone was more fragile and should to be paid more attention.

3.3. Ecosystem Services Hotspots at Village Level

The results of the hotspot analysis of ESs are shown in **Figure 8**. It can be seen that each ecosystem service showed a spatial differentiation, in which the coldspot areas were all concentrated within the main urban areas. Coldspot areas for GP and BC services were the largest in spatial distribution, and the coldspot areas of WY and EP services were relatively small. The notable hotspot areas of GP service were concentrated in the villages of Huangpi and Jiangxia Districts, the southern part of Xinzhou District and the southern villages of Caidian District. The hotspots of WY service were mainly located in the south of Caidian and Jiangxia Districts, and there were also small-scale block distributions throughout the city. The spatial distributions of CS and OR hotspots were very similar, with hotspots concentrated in the north and south of Wuhan where extensive forests exist and scattered in the northeast and southwest. The distribution of hotspot areas for EP service was the smallest, mainly concentrated in villages in the northern part of Huangpi District, followed by villages in the central part of Jiangxia District and the northeastern part of Xinzhou District. The hotspot for BC service exhibited the widest distribution, showing a clear spatial characteristic of “low in the center and high in the surrounding”.

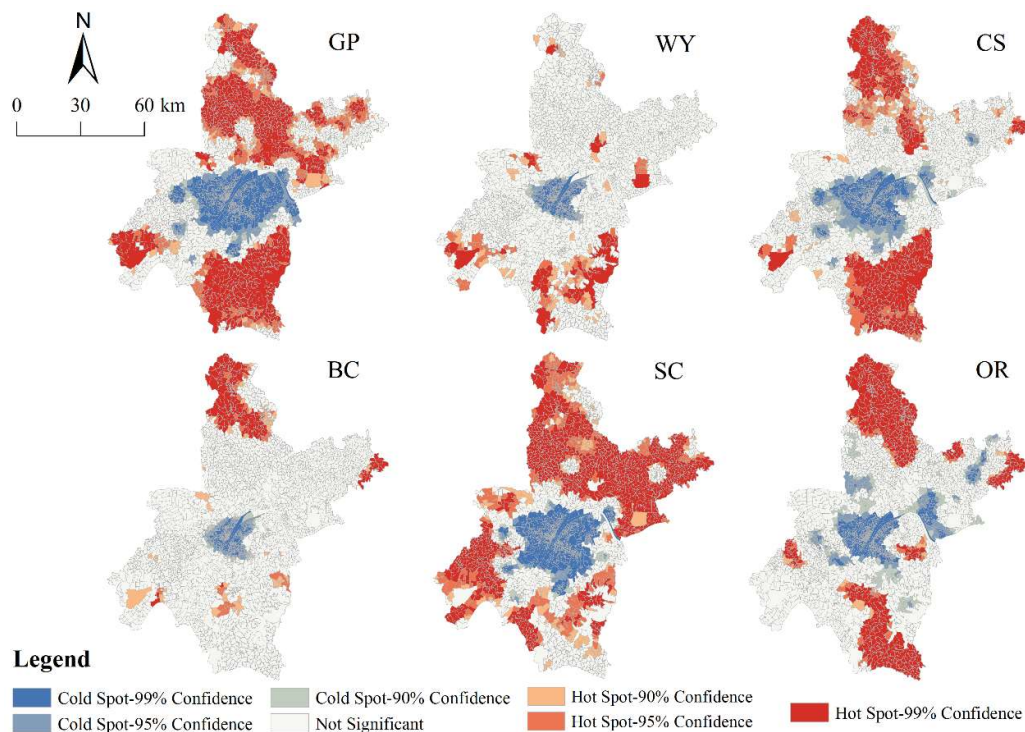


Figure 8. Hotspots and coldspots of ecosystem services at village level in Wuhan (GP: grain production; WY: water yield; CS: carbon storage; BC: biodiversity conservation, SC: soil conservation; OR: outdoor recreation).

3.4. Ecological Functional Zones and Grades at Two District Levels

As shown in **Figure 6**, dominant ESs in different EFZs were distinctly different. Specifically, the dominant ESs in the ECA were CS, SC, BC and OR. The dominant ESs in the GPA area were GP and WR. The dominant ESs in the WCA were WR, GP and BC. The dominant ESs in the WLA were OR and WR. Therefore, the hotspot areas of the dominant ESs within each ecological functional zone were superimposed. Since all services in the ULA were below average, and only WR and SC services showed relatively high values, the place where any of the two service hotspots were located was identified as ULA level I zones. By overlaying the resulted EFZs with the corresponding hotspots of dominant ESs in each EFZ, 10 types of sub-EFZs were obtained, as shown in **Figure 9**. Overall, level I of EFZs contained 823 villages, occupying 5.23% of the total village number in the region. The specific characteristics of five EFZs are elaborated below.

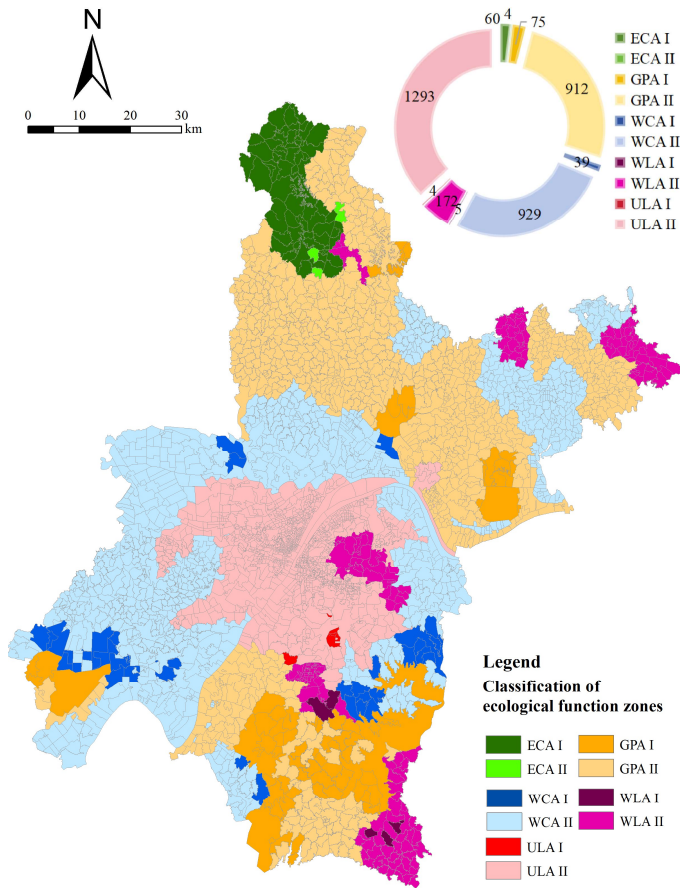


Figure 9. Results of ecological functional zones and grades at township and village scales (ECA: ecological conservation area; GPA: grain production areas, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

The ECA level I area contained 60 villages, with all located in the mountainous area in the northwestern part of Huangpi District. This area had a high forest cover and was less affected by human activities, thus it had a strong capacity for supplying advantageous services, which contributed to the further development of dominant functions in ECA. On the other hand, the ECA level II area was located in the southern and western parts of Changxuanling Street, where the terrain

was higher and the capacity to supply BC and SC services was lower compared to those in the ECA level I area.

The GPA level I area contained 75 villages, mainly concentrated in Wangji and Shuangliu Streets in Xinzhou District, villages in Xiashi Towns in Caidian District, and the central part of Jiangxia District. These places had low topography, high-quality arable land, and easy proximity to water sources, making them advantageous areas to ensure food security. The remaining areas were the GPA level II areas, which were heavily distributed in Huangpi and Xinzhou districts.

The WCA level I area contained a total of 39 villages, mainly located in the eastern part of Baiquan Street in East-West Lake District, the southwestern part of Caidian District, the southwestern part of Jiangxia District and the central-eastern part of Jiangxia District. It also exhibited a small centralized distribution in the Caidian and Jiangxia districts, and a more sporadic distribution in the rest of the WCA zone. These areas were hotspots areas for WY, GP and BC services, which need to continuously maintain the advantages to supply these services.

The WLA level I area contained 5 villages, all of which were located in Jiangxia District, namely, Linhang Village and Zhaoyao Village in Yifang Street, Heili Village in Zhengdian Street, Fushan Village in Husi Street, and Guandizhou Village in Guandizhou Street. These areas were close to rivers, lakes and some scenic spots, which had high forest coverage and good ecological environment. These areas had high capacity to supply OR and WY services. The WLA level II area which was classified due to the high capacity to supply OR or WY service contained 172 villages.

The ULA level I area contained 4 villages, namely, Townsend Lake Village in Hongshan District, Miaoshan Village in Jiangxia District, Wuhan University of Science and Technology (WUST) Zhongnan Campus Community and October Village. These areas were located in the urban fringe and were hotspot areas for WY or SC service, which were more conducive to the utilization of the corresponding advantageous services. However, the ecological environment in these areas was still critical, and measures were urgently to enhance the capacity to provide ESs in the areas.

4. Discussion

4.1. Understanding the Mechanism of Determining Ecological Functional Zones and Grades Based on Ecosystem Services

Linking specific ecological indicators with spatial planning to manage ecosystems has been a significant challenge for scientists and policymakers (Gong, et al. 2022). Numerous studies have utilized ESs as indicators for ecological functional zoning (J. Li et al., 2024; Peng et al., 2019), recognizing that these services reflect the importance of ecological processes and functions which are formulated based on the combined effects of geographical conditions, climate, environmental characteristics, and human activities (Li, et al. 2023; Liu, et al. 2019). Moreover, ecosystems benefit human societal development by offering a multitude of services and these services are frequently interconnected (Turkelboom, et al. 2018; Zhang, et al. 2023). For instance, in our study area, significant correlations were identified between 15 pairs of services, with 4 pairs exhibiting trade-off relationships and 11 pairs demonstrating synergistic relationships. Identifying ESs tradeoffs and synergies enlightens the formulation of management measures (Wang et al., 2024), particularly the formulation of land use policies, in the scenario that we should address the various services provided by ecosystems simultaneously.

ESs bundles serve as a strategic framework to identify the combination of distinct ESs in space, which is predicated not only on the spatial distribution of ESs but also on the dynamics of ESs interrelationships (Zoderer, et al. 2019). It is instrumental in guiding ecological functional zoning, balancing multifunctional land use, and offering strategic insights that can be leveraged to optimize ecological and societal benefits (Dittrich, et al. 2017). Researchers have employed diverse techniques to discern ESs bundles, such as K-means clustering analysis (Huang, et al. 2023), principal component analysis (Chen, et al. 2016), and self-organizing map networks (Li, et al. 2023). In the context of this study, the area under investigation was delineated into five distinct EFZs by utilizing the SOFM technique based on ESs bundles, i.e., ECA, GPA, WCA, WLA, and ULA (see **Figure 7**). Each zone is

characterized by a unique constellation of ESs with some services being more dominant than others. Taking the GPA for example, it is particularly robust in providing GP and WY services but lags in supplying SC service (see **Figure 6**). GP and WY were then recognized as the dominant ESs, which are advantageous services that an ecological functional zone can provide. Identifying ESs bundles was the prerequisite for the delineation of EFZs and the identification of dominant functions of EFZs.

ESs hotspots are defined as spatially clustered areas with high-value ESs. Identifying ESs hotspots could assist in scientifically delineating conservation boundaries and setting protection priority area so as to inform the arrangement of limited resources (De Vreesea, et al. 2016; Mo, et al. 2023). Two types of methods are commonly used in ESs hotspot identification: threshold or quantiles-based methods and spatial clustering methods (Li, et al. 2017). The former identifies areas with ESs above a certain threshold or above the regional average value as hotspots. However, such a method ignores landscape connectivity and may cause fragmentation of hotspot areas. To address the fragmentary hotspot, spatial clustering method was developed by integrating neighborhood factors into the model to identify the clustering areas of high-value and low value (Moilanen et al., 2014). This study used a kind of spatial clustering method (i.e., Getis Ord Gi*) to identify the hotspots of dominant ESs within EFZs so as to designate level I zones of EFZs. The resulted zones could be considered as conservation priority areas which are worth priority conservation measures and financial resources.

4.2. Implications of Ecological Functional Zones and Grades for Ecosystem Management and Conservation

Delineation of ecological functional zones and grades based on ES provides vital support to natural resource users and decision-makers for ecosystem management and conservation (Turkelboom, et al. 2018). The resulted ecological functional zones in this study manifest the different combinations of ESs that ecosystems provide in space, which provides a basis for the determination of spatially heterogeneous management strategies. Furthermore, ecological functional grades indicate the relative importance of dominant ESs within each ecological functional zone, which provides a reference for the setting of conservation priorities. The following section describes the specific implications of this study for management and conservation.

First, our study delineated five types of EFZs with varied combinations of ESs and compositions of land use types. We could implement differentiated management strategies to leverage dominant ESs and improve non-dominant ESs in different zones. The dominant ESs play a fundamental role in maintaining the sustainability and functionality of an ecosystem, which should be emphatically protected and restored so as to promote the sustainable development of the ecosystem. However, this does not mean that the non-dominant ESs (SC in this example) within a zone are not worthy of attention. We could also implement some management and engineering measures to improve the capacity of ecosystems to provide non-dominant ESs, but in most cases, this improvement is limited. Taking the GPA for example, the ecosystem in this zone exhibited strong capacity to provide GP and WY services, but had weak capacity to provide SC. Possible measures, including enhancing the construction of high-standard farmland, and strictly controlling conversion of farmlands to other land use types are encouraged to maintain the GP service in this zone. Additionally, strengthening water-saving irrigation and other engineering constructions could leverage the region's capacity to provide high-level WY service. Moreover, measures like slope protection and terracing, and forests and grasses planting, could reduce the zone's soil erosion risk so as to enhance the capacity to provide SC service. Due to the limited space, policy guidance for implementing management strategies in five types of EFZs was summarized in **Figure 10**.

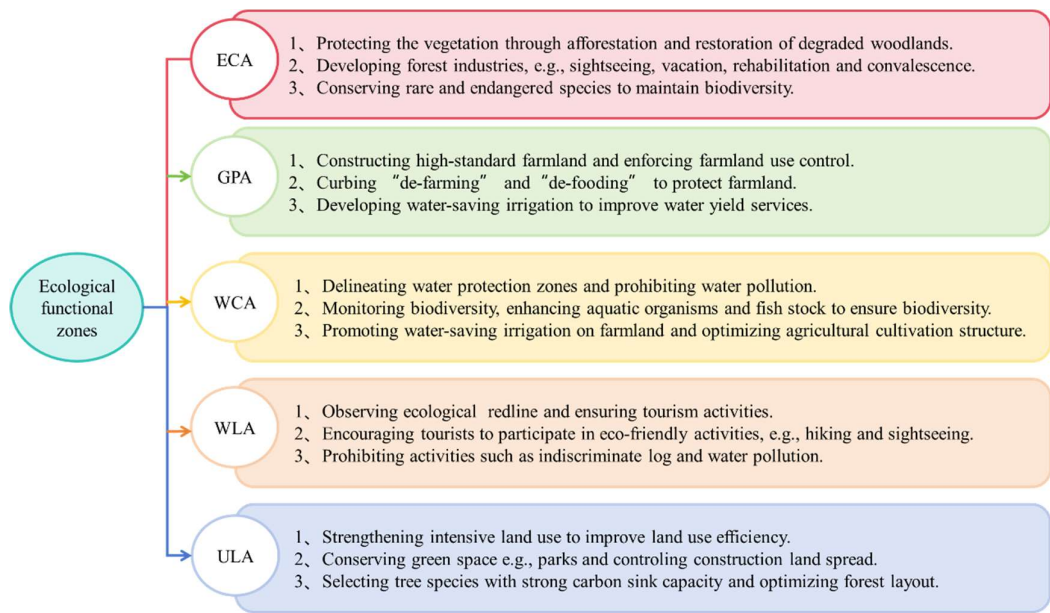


Figure 10. Policy guidance for implementing ecosystem management strategies in different ecological functional zones of Wuhan City (ECA: ecological conservation area; GPA: grain production areas, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

Second, tradeoffs and synergies among ESs should be paid attention to when measures are undertaken to address multiple services. One principle that should follow is that we’d better promote the simultaneous improvement of multiple ESs while preventing the tradeoffs among them. This involves a thorough evaluation of the determinants that influence ESs relationships, either through empirical studies or literature review. Generally, two principal factors influence the dynamics of ESs trade-offs and synergies: common drivers and the inherent correlations between services (Bennett, et al. 2009). Common drivers are elements that impact multiple services simultaneously, such as land use patterns, climatic conditions like precipitation, and vegetation condition (Berry, et al. 2020; Zhang, et al. 2023). Conversely, factors that uniquely affect a single service are termed independent factors (Feng, et al. 2020). In scenarios where services exhibit synergistic relationships, enhancing a common driver may facilitate a concurrent improvement of multiple ESs. However, for ESs that are in a trade-off relationship, it is crucial to focus on optimizing independent variables to carefully prevent the inadvertent degradation of one service when we attempt to improve another. For example, as illustrated in **Figure 4** that BC and CS exhibited a synergic relationship, when we implement measures in ULA where the two services are both relatively low, an improvement in common drivers of these two services would be encouraged. Accordingly, measures that revitalize underutilized lands, conserving green space and developing low-carbon industries would be advocated.

Finally, different conservation priorities could be set according to ecological functional grades within EFZs. The level I area is the advantageous area as well as the priority area for ecological conservation and restoration. It should take more targeted measures in conjunction with its dominant function position, and increase the intensity of conservation and restoration. As for the level II area, it should focus on developing the advantages of dominant functions and promoting the improvement of ecological quality. The corresponding management measures could be more comprehensive to better play the ecological benefits and promote the grade transformation from level II to level I.

4.3. *Advances and Limitations*

Existing studies mostly determined EFZs at a single scale, which is prone to neglecting the cross-scale variability of EFZs, thereby failing to provide accurate information at local space (Liu, et al. 2019; Temirbayeva, et al. 2020). This paper introduced a novel two-step refinement method to further

grade the EFZs after delineating them. The SOFM was employed for identifying EFZs at township scale, leveraging its capability to automatically recognize the spatial clustering characteristics of ESs bundles. Subsequently, hotspot analysis was applied to identify ESs hotspot areas at village scale, offering more granular guidance for the refined grading of EFZs. Hotspot areas, in contrast to areas with high-value ESs, focus more on the aggregation of these high-value services, effectively identifying key regions where dominant ESs necessitate conservation priority (Li, et al. 2023).

Despite the above-mentioned innovative advances, this study has limitations that merit further exploration. For instance, the delineation of EFZs in this study was based solely on data from 2020, neglecting the dynamic nature of ESs, which might influence the stability of the zoning outcomes. Furthermore, the determination of EFZs ideally should be conducted following a comprehensive evaluation of the regional ecosystem conditions and ecological functions. The selection of six services in this study was predicated on data and model availability, which may not encompass the full spectrum of services that regional ecosystems can offer.

5. Conclusions

This study presented a novel “two-step refinement zoning method” that integrates the SOFM model with hotspot analysis to delineate and grade EFZs across multiple scales. This innovative approach enables the zoning of ecological functions at the township level and their precise grading at the village level, thus providing a more nuanced framework for ecosystem management and conservation.

The application of the SOFM model divided Wuhan into five distinct EFZs: ECA, GPA, WCA, WLA and ULA. Among them, the GPA exhibited the widest distribution, accounting for approximately 40% of Wuhan's total area, with GP and WY services as the dominant ESs. WCA was the second largest functional area, accounting for about 35% of the total area, and the area was dominated by WY, followed by GP and BC. All ESs within the ULA were below average. Hotspot analysis revealed that clustered areas with lower ESs provision were predominantly located in the central urban regions, while areas with higher provision were more dispersed throughout the city. An overlay analysis further categorized the EFZs into two levels of ecological importance: Level I and Level II zones. The Level I zones, which include 823 villages and represent 5.23% of the total number of villages in the region, were found to be crucial for ecosystem management. Except for the ECA, the number of villages in Level I zones of other EFZs was smaller than in Level II zones. Spatially, the GPA's Level I zone was observed to be clustered in large patches, whereas Level I zones of the other EFZs were more scattered. Based on these results, ecosystem management strategies and conservation priorities have been proposed for Wuhan, which are intended to ensure the long-term health of the ecosystem and to promote sustainable regional development.

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