land

MDPI

Article

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

Yan Zhang [1], Shuhan Liu [2], Peiheng Yu [3], Yanchi Lu [2], Yang Zhang [4], Jinting Zhang [2] and Yiyun Chen [2,5,6,*]

[1] Land Consolidation and Rehabilitation Center, Ministry of Natural Resources, Beijing 100035, China; zhyan92@126.com
[2] School of Resource and Environment Sciences, Wuhan University, Wuhan 430079, China; 18227065255@163.com (S.L.); yanchilu@whu.edu.cn (Y.L.); whuzjt@whu.edu.cn (J.Z.)
[3] Department of Building and Real Estate, Research Institute of Sustainable Urban Development, The Hong Kong Polytechnic University, Hong Kong 999077, China; peiheng.yu@connect.polyu.hk
[4] School of Architecture, Southeast University, Nanjing 210096, China; zhangyang2021@seu.edu.cn
[5] Key Laboratory of Digital Cartography and Land Information Application Engineering, Ministry of Natural Resources, Wuhan 430079, China
[6] Hubei Luojia Laboratory, Wuhan University, Wuhan 430079, China
* Correspondence: chenyy@whu.edu.cn

Abstract: Integrating ecosystem services (ESs) to delineate ecological functional zones (EFZs) is fundamental 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 a self-organizing feature mapping method to delineate EFZs at a township scale, and then applying a hotspot overlay analysis to refine the resulting EFZs by designating them with different grades at the village scale. The proposed method was applied in Wuhan City, dividing it into five types of EFZs with different ES combinations and land use compositions. Furthermore, 5.23% of villages were identified as level I areas 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

check for updates

Citation: Zhang, Y.; Liu, S.; Yu, P.; Lu, Y.; Zhang, Y.; Zhang, J.; Chen, Y. Delineating Ecological Functional Zones and Grades for Multi-Scale Ecosystem Management. *Land* **2024**, *13*, 1624. https://doi.org/10.3390/land13101624

Academic Editor: Yongsheng Wang

Received: 9 September 2024
Revised: 25 September 2024
Accepted: 30 September 2024
Published: 6 October 2024

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 [1,2]. Rapid urban expansion, which is accompanied by the encroachment of natural habitats into semi-natural and artificial landscapes, impacts ecological elements, structure, and function, causing the widespread degradation of ESs [3,4]. 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 [5]. Meanwhile, land expansion is also faster than population urbanization [6]. Given this, from the perspective of ESs, conducting research on their planning, management and utilization 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 [7], spatial mapping [8] and identification of the driving mechanisms [9] of ESs, interactions and trade-offs between different ESs [10], and the balance of supply and demand of ESs and ESs flows [11], forming a wealth of theoretical research. In the application aspects, researchers have implemented ES theory and methods into the construction of regional ecological security patterns [12], the proposal of ecological protection strategies [13], ecological compensation, and territorial spatial planning [14]. 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 [15]. Nevertheless, compared to theoretical research, the application of ES 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 applying ES theory in territorial spatial planning [16]. This is developed based on traditional ecological zoning, combining ecological elements and ecological functions and services, to identify the major ecological characteristics of different geographic zones, so as to formulate precise protection, restoration and control measures [17]. Schneider [18] drew a map of the global urban ecological zones based on MODIS data. Chen [19] 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 [20] and regional [21,22] to watershed and ecological engineering zones [23,24]. Earlier studies mainly utilized a single indicator, such as ecological functional importance or ecosystem health to determine zones. For example, Zhao [25] used the ecosystem health index to delineate the ecological management zones of the Yangmei River basin. However, using a single indicator cannot fully capture the comprehensive ecological functions and services that ecosystems provide. To address this limitation, scholars adopted more sophisticated indicators that represent the comprehensive ability of ecosystems to provide ESs and functions during the zoning process. For example, Zeng [26] used the ES indicator to delineate ecological management zones in China. However, they overlooked the different combinations of multiple ESs that ecosystems provide at various EFZs. In contrast, Sun [27] and Zhang [28] linked ES bundles to establish landscape functional zones that reflect the clustered spatial pattern of various ESs that ecosystems provide at distinct EFZs. While these studies integrated multiple ES indicators in determining EFZs, they were usually conducted at a single scale, overlooking the nested hierarchical structure of ecosystems. In reality, ESs management should consider such hierarchical structures and take measures at multiple scales, making it necessary to refine EFZs at a finer scale.

In the methodological aspects, 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 [29] used a multi-criteria decision analysis technique to delineate the ecological red lines in Hangzhou Bay. Bailey [30] 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 [31] 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 [32] 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 and the methods of big data, machine learning methods 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 [17,19]. Zhang [28] and Fei [33] 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. Although previous studies have developed various models to determine EFZs, there is still a gap in integrating the existing methods to refine the EFZs at a finer scale on the basis of determining EFZs.

In this context, this study proposed a "two-step refinement zoning method" to further determine ecological functional grades (EFGs) nested in the EFZs at a finer scale. First, a SOFM model was used to determine EFZs at the township scale based on an assessment of six ES indicators. Subsequently, a hotspot overlay analysis was applied to refine the resulting EFZs by designating them with different EFGs at the village scale. According to the results of ecological functional zoning and grading, multi-scale management and conservation strategies in Wuhan were proposed.

2. Data and Methods

2.1. Study Area

Wuhan City (29°58′–31°22′ N, 113°41′–115°05′ 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 8569.15 km^2 (Figure 1). It is situated in the transition zone from the Jianghan 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 km^2, 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 [34]. Meanwhile, ecological degradation, such as severe soil erosion and the diversity (e.g., aquatic species) decline of the Yangtze River, is becoming more and more prominent. Integrating ES theory and methods to determine EFZs and their grades would provide guidance to ecological security patterns and ecological protection and management in Wuhan.

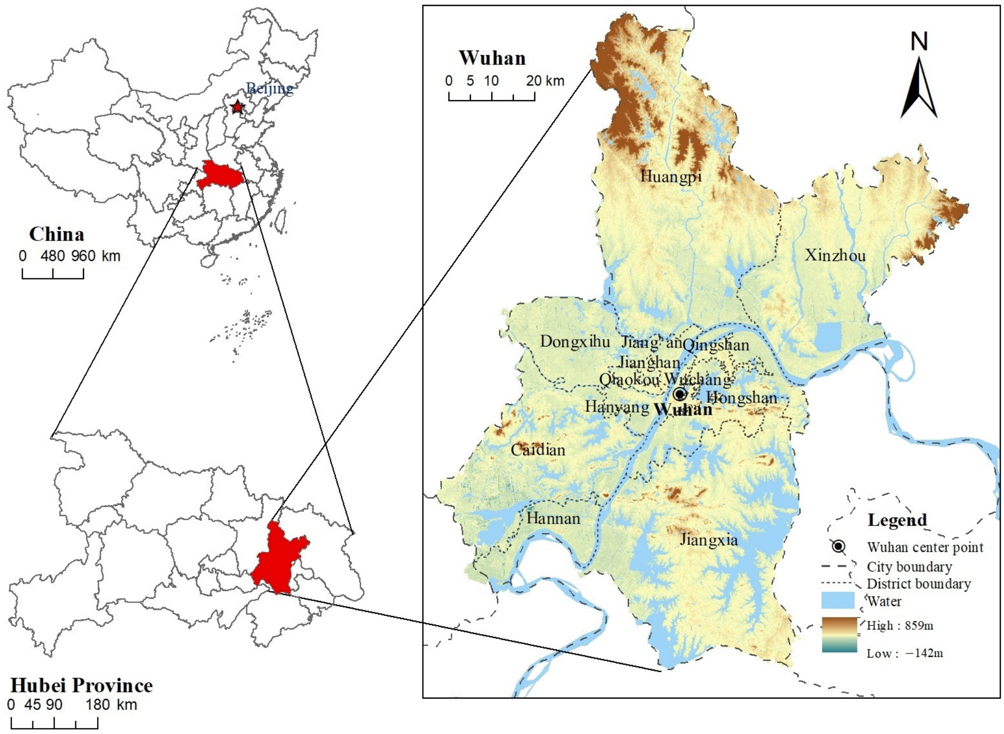

Figure 1. Geographic location and elevation of Wuhan City.

2.2. Data Description

Multisource and heterogeneous data from natural, socioeconomic, and LULC aspects were integrated to conduct this research. Specifically, (1) DEM with a resolution of 30 m was extracted from the ASTER GDEM V2 dataset, provided by the Geospatial Data Cloud (http://www.giscloud.cn) (accessed on 18 March 2018). (2) Meteorological data, including average monthly temperature and rainfall, were downloaded from the China Integrated Meteorological Information Service System. Radiation-related data were sourced from the National Climatic Data Center in the United States (accessed on 24 December 2021). (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) (accessed on 2 September 2020). These data were classified according to the FAO-90 classification system. (4) Vegetation coverage data, including leaf area index data, were downloaded from the National Earth System Science Data Center, and NDVI data were extracted from the Geospatial Data Cloud's Landsat-8 images (accessed on 8 March 2024). (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 were classified into 6 primary and 25 secondary categories, and they were reclassified into 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, were provided by the Wuhan Planning & Design Institute. (7) Grain production data were extracted from the 2020 Statistical Yearbook.

2.3. Methods

2.3.1. Model Framework

A two-step refinement zoning method was developed to determine the EFGs nested in EFZs in Wuhan (Figure 2). Initially, trade-offs or synergies among six ES indicators were identified based on an evaluation of them. Subsequently, the SOFM model was utilized to identify ES bundles, which formed the basis for delineating EFZs at the township scale. Then, a hotspot analysis was performed to identify ES hotspots, which formed the basis for determining EFGs at the village level. Finally, a spatial overlay analysis was conducted to refine the EFZs by stratifying them into two EFGs. Villages exhibiting hotspots of dominant ESs were assigned to level I EFZs, while those lacking such hotspots were assigned to level II EFZs.

2.3.2. Ecosystem Service Selection, Evaluation and Correlation Identification

Grain production, water yield, carbon storage, biodiversity conservation, erosion prevention, and outdoor recreation 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 the Millennium Ecosystem Assessment [35]. Among them, grain production and water yield belong to supply services, while carbon storage, biodiversity conservation, and erosion prevention belong to regulating services, and outdoor recreation belongs to cultural services; (2) they are easily affected by various human activities; (3) they can be conveniently assessed using existing models and methods, and the necessary data are readily available in the study area.

This study utilized various ecological models to assess the selected six ES indicators, with the assessment timeframe set in 2020. The detailed assessment method refers to Zhang's study [36]. Based on the assessment results, the 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.

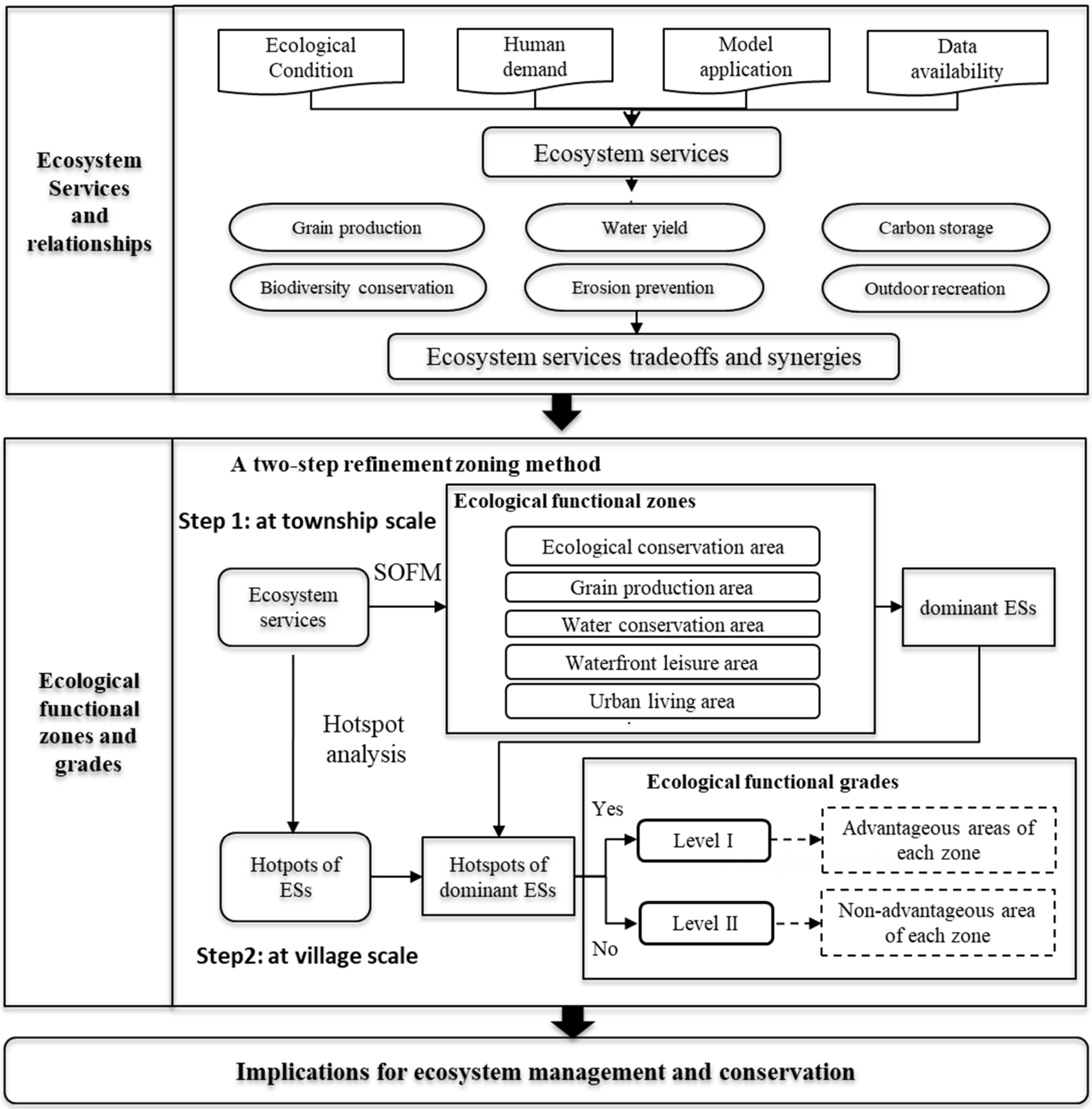

Figure 2. Framework of the method.

2.3.3. Determination of Ecosystem Service Bundles at Township Level

This study employed the SOFM algorithm to determine ES bundles [37], 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 [38]. 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 cth node at the time point t. $\theta(\mu, c, s)$ represents the neighborhood function between μ and s during the sth 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 the Kohonen package in RStudio. The number of clusters is a determinant parameter of the result of SOFM and the following ecological functional zoning, which was determined based on the sum of squared errors (SSEs) using the "elbow method" in this research.

2.3.4. Identification of Ecosystem Service Hotspots at Village Level

The global Moran's Index can reveal overall correlations but cannot pinpoint specific clustered areas [39]. The introduction of Getis-Ord Gi* enables the identification of statistically significant spatial clusters of high values (hotspots) and low values (coldspots) [40], understanding the local heterogeneity characteristics of an attribute's spatial aggregation. It is a method of local autocorrelation analysis. In this study, Getis-Ord Gi* was used to identify hotspot areas of ESs at the village level [41].

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

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.

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

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

3. Results

3.1. Spatial Distributions and Correlations of Ecosystem Services

The spatial distributions of ESs in Wuhan are shown in Figure 3. Generally, except for erosion prevention service, other services displayed a spatial characteristic of "lower values in the central region and higher values in the city's periphery". The values of grain production service ranged from 0 to 3.74 × 10^7 kg, which were generally higher in the northern region than in the southern region, but lower in the southwestern and western parts of the city. 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 water yield service ranged between 0 and 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 the carbon storage service showed a pattern of lower values in the city center and higher values in the surrounding areas, in which the high values of carbon storage service arose in the northwestern Mulan Mountain area, the northeastern General Mountain area, and the southeastern region, and the low values of carbon storage service were widely distributed within the central city. The value range of erosion prevention 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 erosion prevention service. The biodiversity conservation 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. The value of outdoor recreation service ranged between 0 and 1, with high values centered in the mountainous area in the north of Huangpi District and Xinzhou District, and water areas (e.g., rivers and lakes) in the south of Jiangxia District, and scattered in the southwestern and central parts of the city.

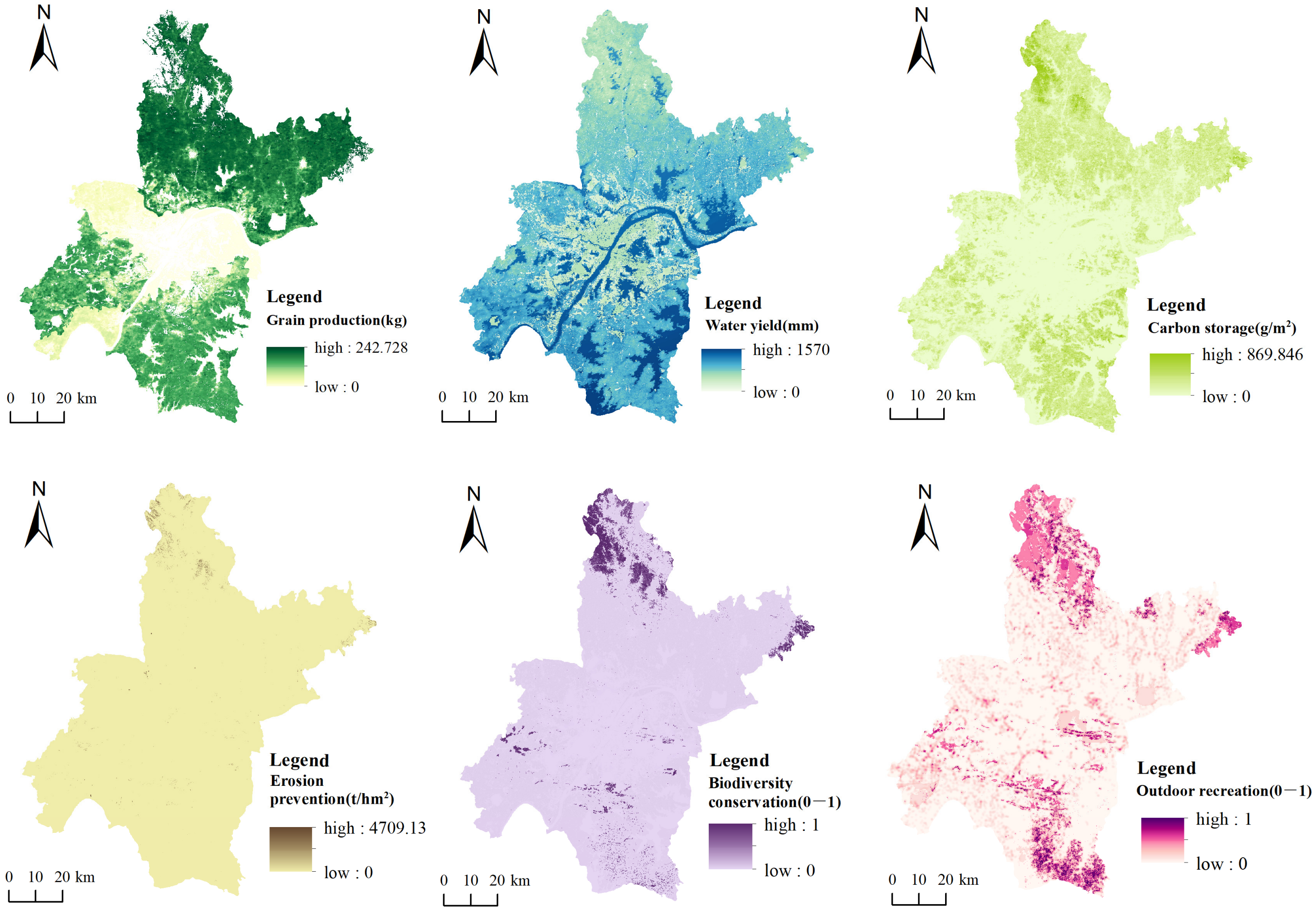

Figure 3. Spatial patterns of ecosystem services in Wuhan.

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 carbon storage and grain production services, with a correlation coefficient of 0.73, while the weakest arose between carbon storage and water yield services, marked by a coefficient of −0.07. Specifically, grain production service exhibited a synergistic relationship with carbon storage, erosion prevention, biodiversity conservation, and outdoor recreation services, with the most pronounced synergy with carbon storage service. Conversely, water yield displayed trade-off relationships with carbon storage, erosion prevention, and outdoor recreation services, showing the strongest tradeoff relationship with erosion prevention service with a correlation coefficient of −0.43. Carbon storage also aligned synergistically with erosion prevention, biodiversity conservation, and outdoor recreation services, with the strongest correlation, notably, with biodiversity conservation service. Additionally, erosion prevention showed strong synergy with biodiversity conservation service and even stronger synergy with outdoor recreation service. Although the biodiversity conservation and outdoor recreation services were synergistically correlated, the strength of this relationship was comparatively weak.

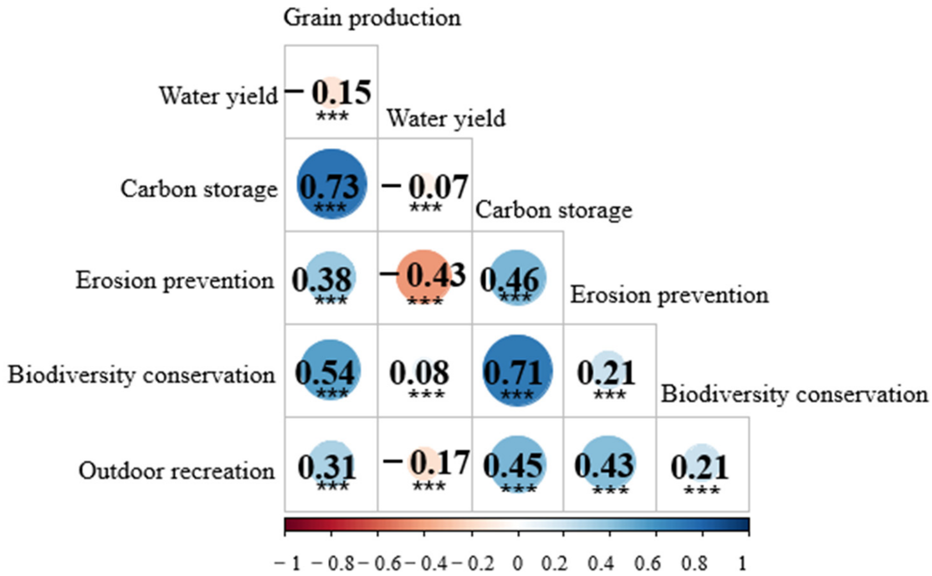

Figure 4. Tradeoff or synergy between each pair of ecosystem services in Wuhan. (*** denotes significant at level $p < 0.01$).

3.2. Ecological Functional Zones at Township Level

The graph of the sum of squared errors (SSEs) 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.

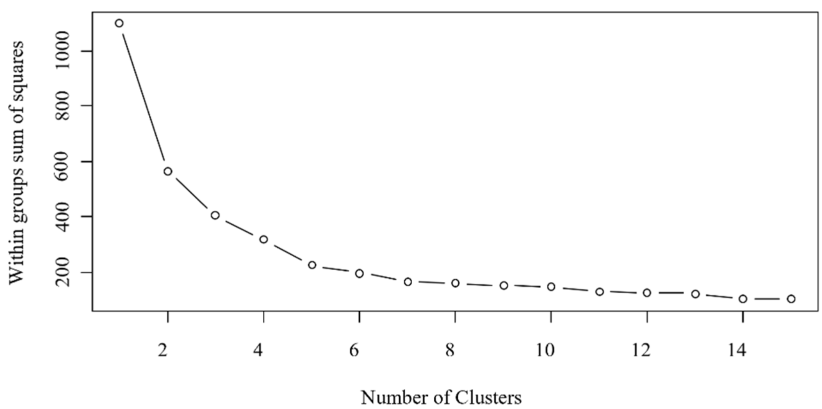

Figure 5. Change in within-group sum of squared errors with number of clusters in self-organized mapping network process.

The mean values of ESs and the land use compositions within each ecological functional zone are shown in Figures 6 and 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 area (GPA), water conservation area (WCA), waterfront leisure area (WLA) and urban living area (ULA).

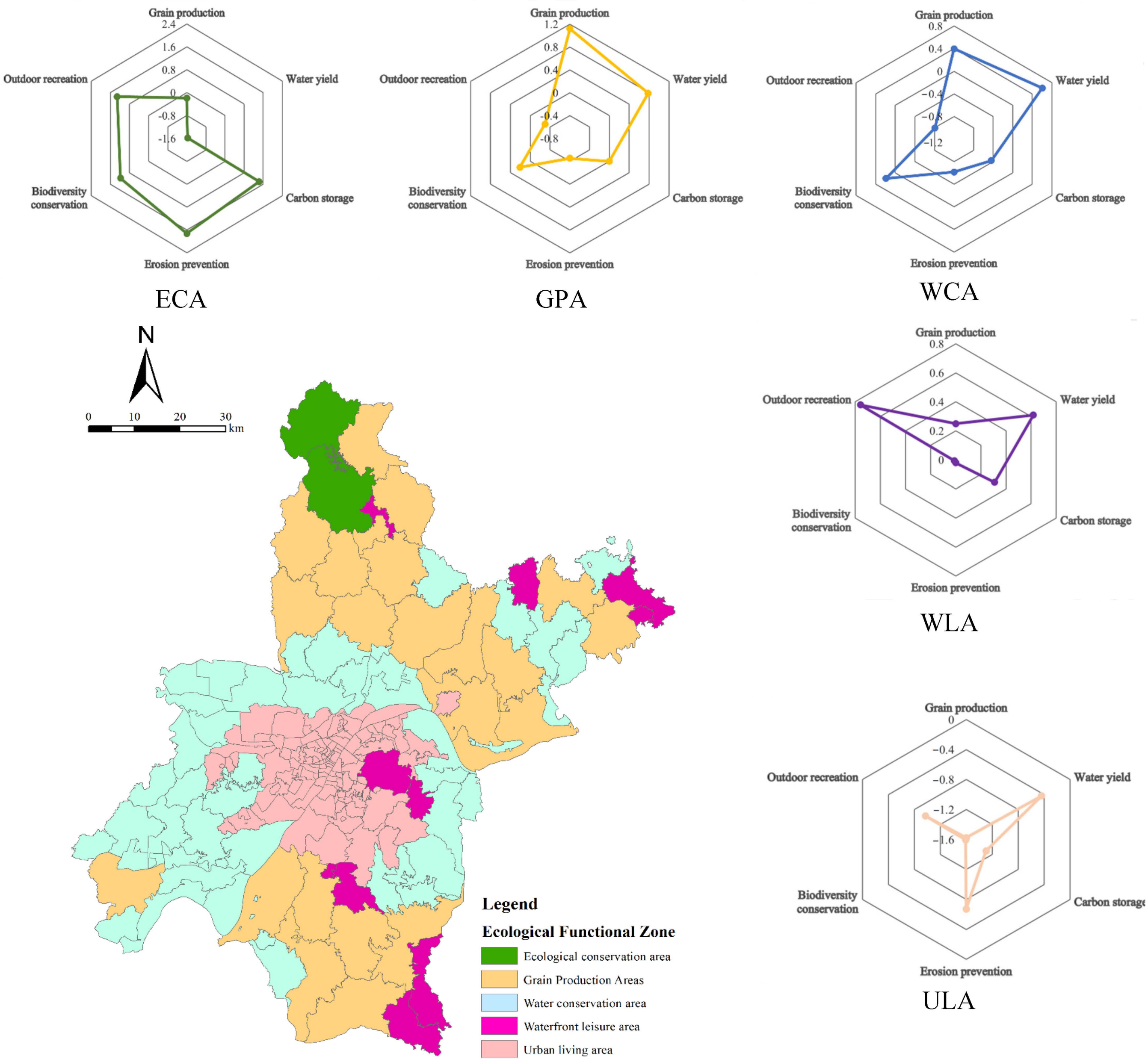

Figure 6. Spatial distribution and ecosystem service composition of each ecological functional zone (ECA: ecological conservation area; GPA: grain production area, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

The ECA was mainly located on Changxuanling Street and Caidian Street in Huangpi District, with an area of 393.56 km^2. 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 grain production and water yield services, other services were maintained relatively high. This may be due to this zone having high vegetation cover with a high capacity to provide erosion prevention service; in addition, Mulan Tianchi, Qingliangzhai, Jinli Gou and other scenic spots were gathered here, which also provide this zone with a high capacity to supply outdoor recreation service. Meanwhile, this zone could provide a high level of carbon storage service and suitable quality habitats. On the whole, the ecological environment was good.

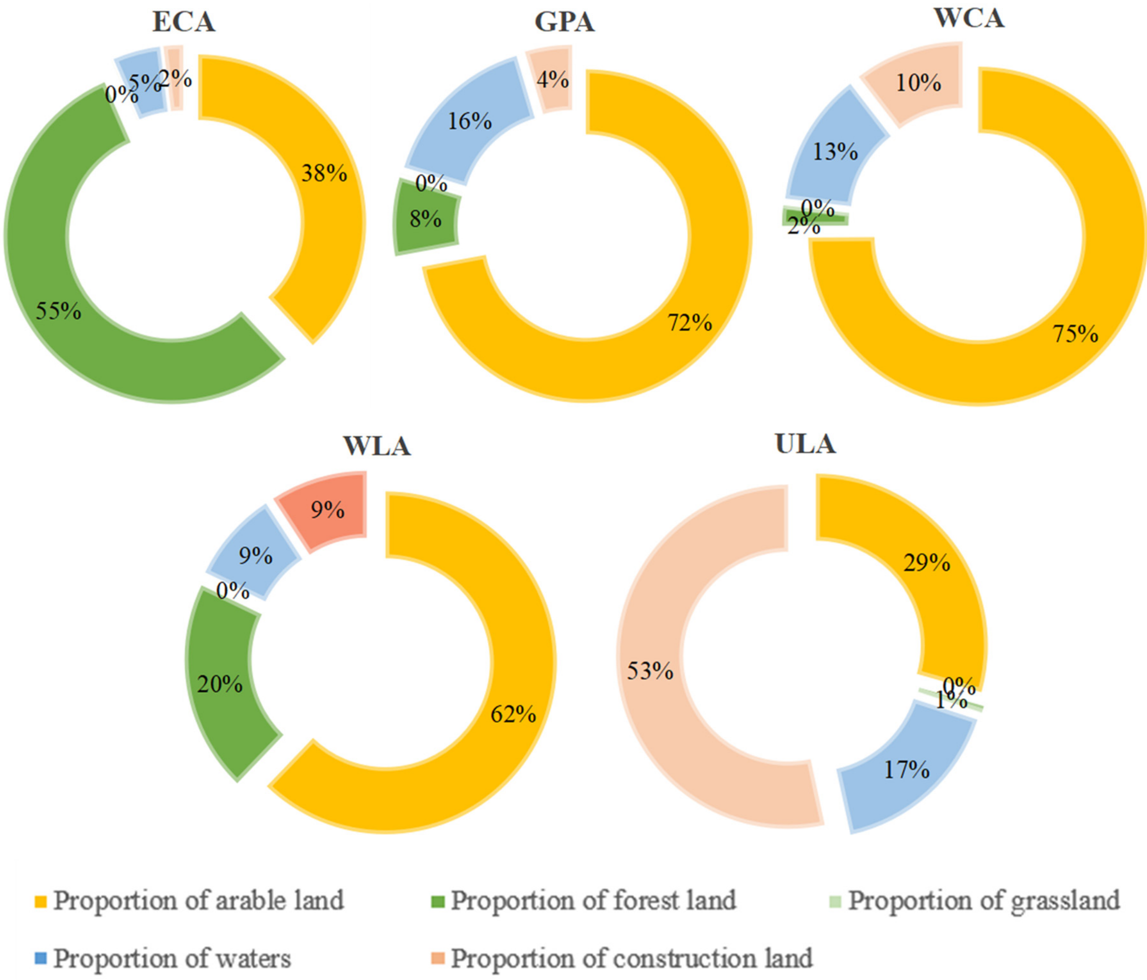

Figure 7. Land use composition within each ecological functional zone (ECA: ecological conservation area; GPA: grain production area, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

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 km^2, accounting for 39.98% of the total area of Wuhan City. It was one of the most widely distributed ecological functional zones. The land use type of this zone was dominated by arable land, accounting for about 71.94%, followed by water, accounting for 15.7%. Grain production and water yield services, which showed a strong synergistic relationship, were the dominant services of this zone, followed by biodiversity conservation service, with carbon storage, erosion prevention and outdoor recreation 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 the urban center to the rural areas. This zone covered an area of 2969.90 km^2, 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 water and construction land, accounting for 12.65% and 10.41%, respectively. The zone was dominated by water yield service, followed by grain production and biodiversity conservation services, with the rest of the services below average.

The WLA was relatively scattered, involving 10 towns, located in the Mulan Mountain Scenic Area in Huangpi District, the Daoguan River Scenic Tourism Area and Xugu Street in Xinzhou District, Husi Street and Shu'an Street in Jiangxia District, and Shidong Street and the 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 outdoor recreation service was relatively high, and the water yield and carbon storage 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 water 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 the East and West Lake District, Xinzhou District and Caidian District, totaling 107 towns over a total area of 1232.53 km^2, 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 ES composition, all ESs in the zone were below average, especially biodiversity conservation, grain production and carbon storage services, and only water yield and erosion prevention services showed a slightly higher value than those in other zones, reflecting that the ecosystem in this zone was more fragile and should be paid more attention.

3.3. Ecosystem Service 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. The coldspot areas for grain production and biodiversity conservation services were the largest in spatial distribution, and the coldspot areas of the water yield and erosion prevention services were relatively small. The notable hotspot areas of the grain production 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 the water yield 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 the carbon storage and outdoor recreation hotspots were very similar, with hotspots concentrated in the north and south of Wuhan, where extensive forests exist, scattered in the northeast and southwest. The distribution of hotspot areas for the erosion prevention 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 the biodiversity conservation service exhibited the widest distribution, showing a clear spatial characteristic of "low in the center and high in the surrounding".

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 the carbon storage, erosion prevention, biodiversity conservation and outdoor recreation services. The dominant ESs in the GPA area were the grain production and water yield services. The dominant ESs in the WCA were the water yield, grain production and biodiversity conservation services. The dominant ESs in the WLA were the outdoor recreation and water yield services. 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 the water yield and erosion prevention 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 resulting EFZs with the corresponding hotspots of dominant ESs in each ecological functional zone, 10 types of sub-EFZs were obtained, as shown in Figure 9. Overall, level I EFZs contained 823 villages, occupying 5.23% of the total village number in the region. The specific characteristics of five EFZs are elaborated below.

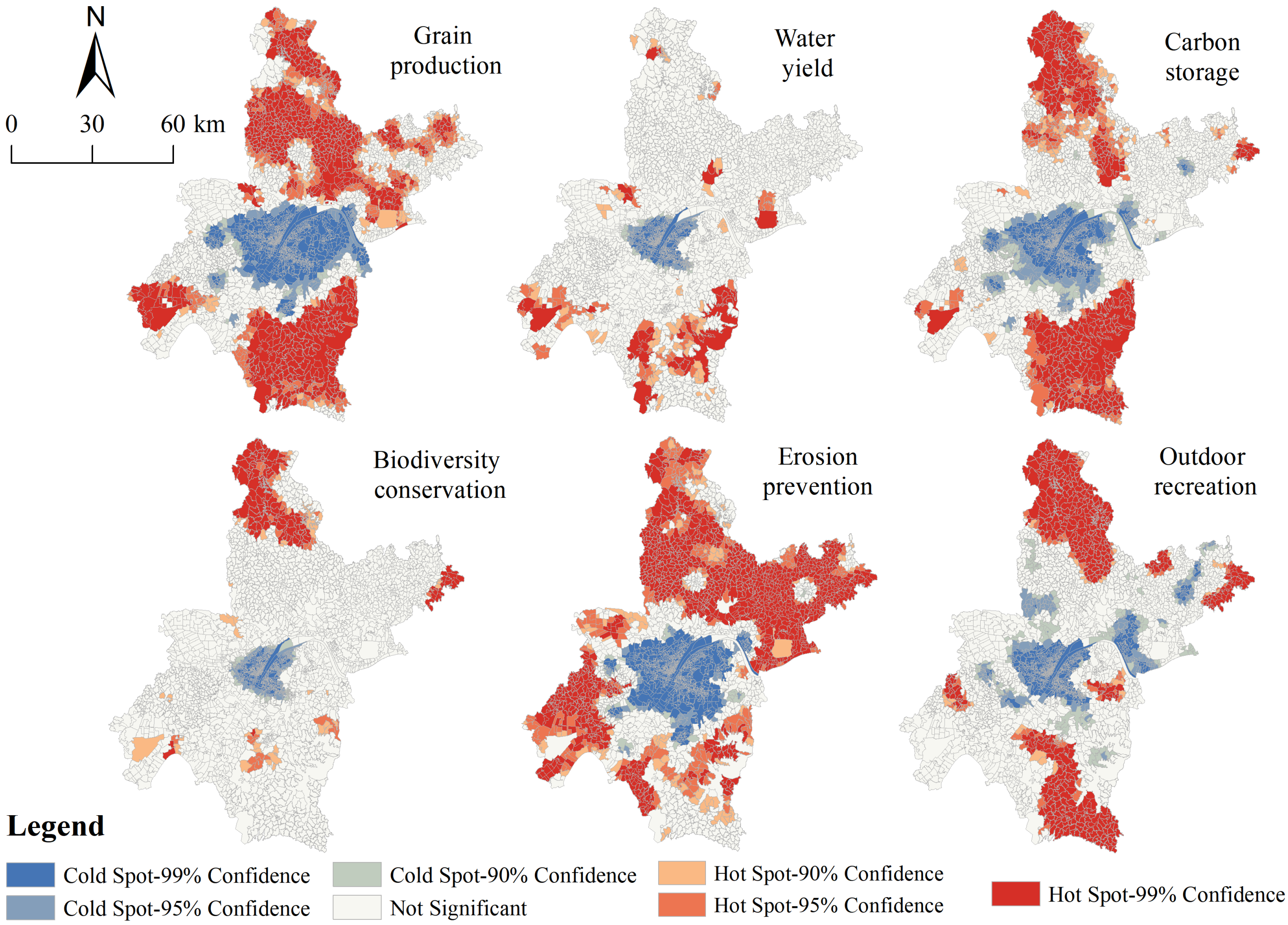

Figure 8. Hotspots and coldspots of ecosystem services at village level in Wuhan.

The ECA level I area contained 60 villages, with all of them 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 biodiversity conservation and erosion prevention services was lower compared to those in the ECA level I area.

The GPA level I area contained 75 villages, mainly concentrated on the 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 the 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 zones. These areas were hotspots areas for water yield, grain production and biodiversity conservation services.

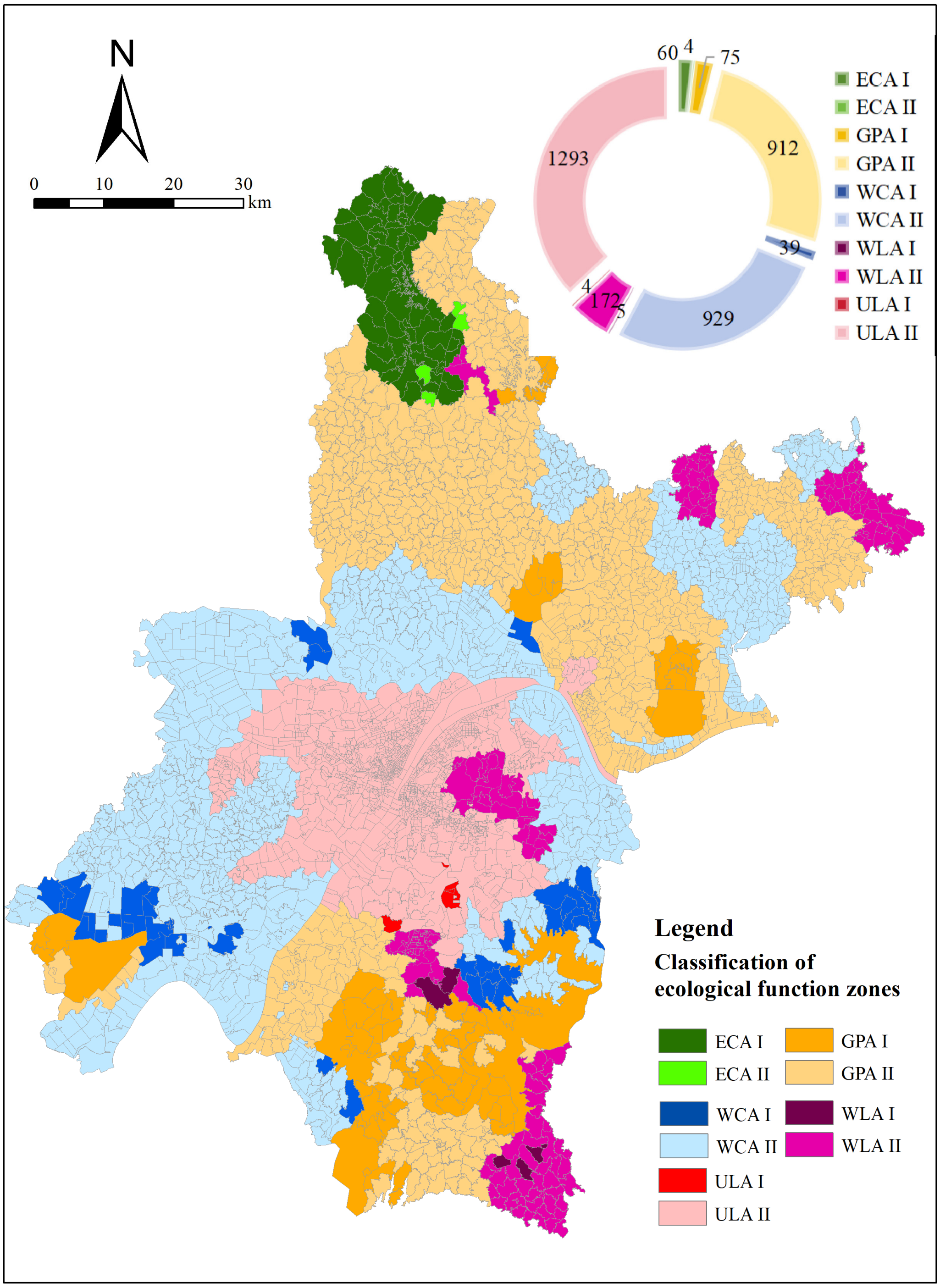

Figure 9. Results of ecological functional zones and grades at township and village scales (ECA: ecological conservation area; GPA: grain production area, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

The WLA level I area contained five villages, all of which were located in Jiangxia District, namely, Linhang Village and Zhaoyao Village on Yifang Street, Heili Village on Zhengdian Street, Fushan Village on Husi Street, and Guandizhou Village on 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 a high capacity to supply outdoor recreation and water yield services. The WLA level II area, which was classified as such due to its high capacity to supply outdoor recreation or water yield services, contained 172 villages.

The ULA level I area contained four 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 water yield or erosion prevention services, 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 needed to enhance the capacity to provide ESs in these 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 [42]. Numerous studies have utilized ESs as indicators for ecological functional zoning [43,44], 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 [45,46]. Moreover, ecosystems benefit human societal development by offering a multitude of services, and these services are frequently interconnected [47,48]. 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. In spatial planning practice, it would be best to promote the simultaneous improvement of multiple ESs while preventing the tradeoffs among them.

ES 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 ES interrelationships [49]. It is instrumental in guiding ecological functional zoning, balancing multifunctional land use, and offering strategic insights that can be leveraged to optimize ecological benefits [50]. Researchers have employed diverse techniques to identify ES bundles, such as K-means clustering analysis [51], principal component analysis [52], and self-organizing map networks [45]. In the context of this study, the area under investigation was delineated into five distinct EFZs based on the SOFM technique, 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. The dominant ESs in each ecological functional zone should be continuously maintained and conserved, while the non-dominant ESs could be promoted during management. Taking the GPA as an example, it is highly beneficial in terms of providing grain production and water yield services, but lacks in terms of supplying erosion prevention service (see Figure 6). Therefore, conservation and restoration measures could be undertaken to maintain the grain production and water yield services in this zone. At the same time, ecological restoration measures could be implemented to promote erosion prevention service.

ES hotspots are defined as spatially clustered areas with high-value ESs. Identifying ES hotspots could assist in scientifically delineating conservation boundaries and setting a protection priority area, so as to inform the arrangement of limited resources [53,54]. Two types of methods are commonly used in ES hotspot identification: threshold or quantiles-based methods and spatial clustering methods [55]. 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 the fragmentation of hotspot areas. To address the fragmentary hotspots, a spatial clustering method was developed by integrating neighborhood factors into the model to identify the high-value and low-value clustering areas [56]. This study used a kind of spatial clustering method (i.e., Getis-Ord Gi*) to identify the hotspots of dominant ESs within each ecological functional zone. This information was used to determine the various EFGs nested in EFZs. The hotspot areas of dominant ESs were considered as the level I areas of each EFZ, indicating the first priority conservation areas that require the most conservation measures and financial resource inputs.

4.2. Implications of Ecological Functional Zones and Grades for Multi-Scale Ecosystem Management

The delineation of ecological functional zones and grades based on ESs provides vital support to natural resource users and decision-makers for ecosystem management and conservation [48]. The resulting EFZs 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, EFGs nested in the EFZs indicate the relative importance of each ecological functional zone in providing ESs, which provides a reference for setting conservation priorities. The following section describes the specific implications of this study for management and conservation.

Firstly, 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 (erosion prevention in this example) within a zone are not worth 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 as an example, the ecosystem in this zone exhibited a strong capacity to provide grain production and water yield services, but had a weak capacity to provide erosion prevention. Possible measures, including enhancing the construction of high-standard farmland, and strictly controlling the conversion of farmlands to other land use types, are encouraged to maintain the grain production service in this zone. Additionally, strengthening water-saving irrigation and other engineering constructions could leverage the region's capacity to provide a high-level water yield 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 an erosion prevention service. Due to the limited space, the policy guidance for implementing management strategies in five types of EFZs was summarized in Figure 10.

Secondly, tradeoffs and synergies among ESs should be paid attention to when measures are undertaken to address multiple services. One principle that should be followed is that it would be best to 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 ES trade-offs and synergies: common drivers and the inherent correlations between services [57]. Common drivers are elements that impact multiple services simultaneously, such as land use patterns, climatic conditions like precipitation, and vegetation conditions [47,58]. Conversely, factors that uniquely affect a single service are termed independent factors [59]. 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, biodiversity conservation and carbon storage 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.

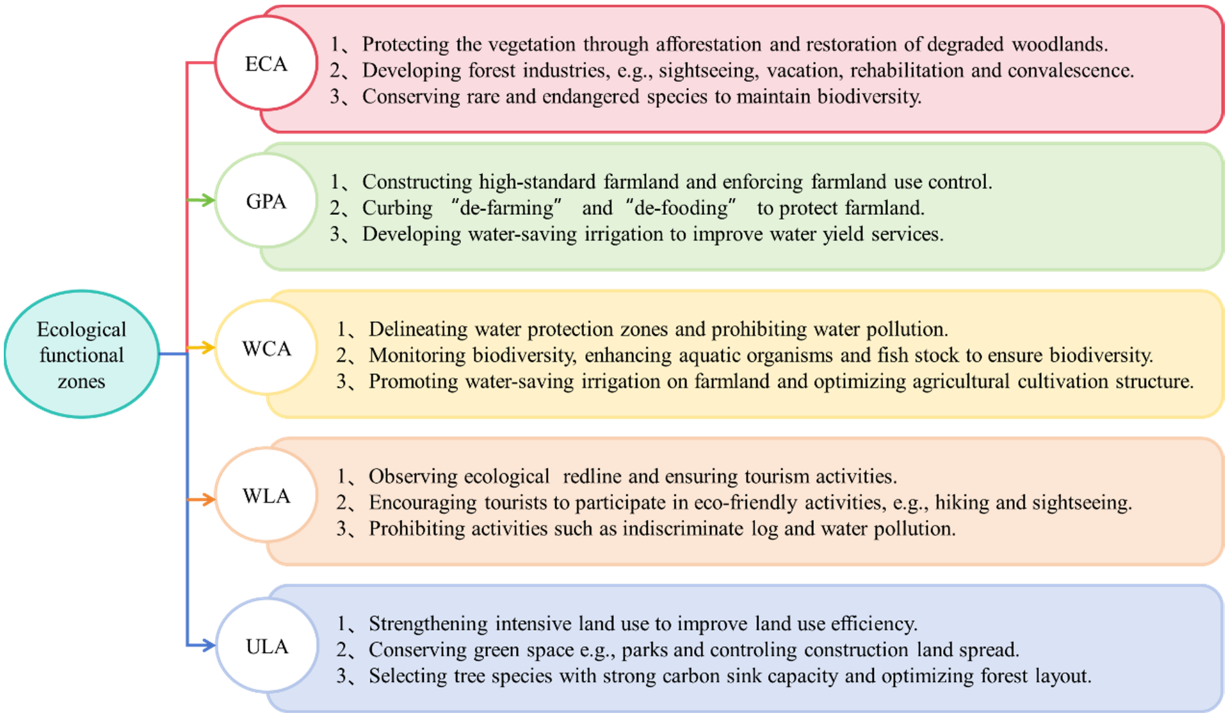

Figure 10. Policy guidance for implementing ecosystem management strategies in different ecological functional zones of Wuhan City (ECA: ecological conservation area; GPA: grain production area, WCA: water conservation area, WLA: waterfront leisure area; ULA: urban living area).

Finally, different conservation priorities could be set according to the EFGs nested within EFZs. The level I areas of EFZs, which represent the hotspot areas of dominant ESs, signify the advantageous and priority areas for ecological preservation and restoration. The areas should take more targeted measures in conjunction with their dominant function position, and increase the intensity of conservation and restoration in these areas. As for the level II areas of EFZs, they 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 utilize the ecological benefits and promote the grade transformation from level II to level I.

4.3. Advances and Limitations

This paper presents a new two-step refinement method to identify EFGs after delineating EFZs at a finer scale. Unlike previous studies conducted at a single scale [46,60], this method is performed at two district scales: it first delineates EFZs at the township scale and then determines the EFGs nested in EFZs at the village scale. This approach considers the nested hierarchical structure of ecosystems and provides more detailed information at the local level, informing multi-scale ecosystem management. The SOFM used in the identification of EFZs is advantageous in automatically recognizing the spatial clustering characteristics of ES bundles in each zone, providing accurate guidance on ecosystem management. In addition, the hotspot analysis applied in the determination of EFGs can identify areas with high ES values, providing information on the identification of first priority areas in each zone where conservation measures are most urgently needed [45]. This method represents a significant advancement in the identification and management of EFZs and EFGs.

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 integrated the SOFM model with hotspot analysis to determine EFZs and EFDs at two district 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 multi-scale 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 grain production and water yield 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 water yield, followed by grain production and biodiversity conservation. All ESs within the ULA were below average. Hotspot analysis revealed that clustered areas with lower ES provision were predominantly located in the central urban regions, while areas with higher provision were more dispersed throughout the city. An overlay analysis further stretched the EFZs into two EFGs: level I and level II. The level I zones, which included 823 villages and represented 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 the level I zones of other EFZs were 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, multi-scale ecosystem management strategies have been proposed for Wuhan, which are intended to ensure the long-term health of the ecosystem and to promote sustainable regional development.

Author Contributions: Conceptualization, Y.Z. (Yan Zhang) and Y.C.; methodology, S.L.; software, S.L.; validation, P.Y. and Y.C.; formal analysis, S.L.; investigation, Y.Z. (Yan Zhang); resources, Y.Z. (Yan Zhang) and Y.C.; data curation, S.L., Y.L. and Y.Z. (Yang Zhang); writing—original draft preparation, Y.Z. (Yan Zhang) and S.L.; writing—review and editing, P.Y. and Y.C.; visualization, S.L.; supervision, J.Z. and Y.C.; project administration, Y.Z. (Yan Zhang) and Y.C.; funding acquisition, Y.Z. (Yan Zhang) and Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 42101284) and Development projects in Hubei Province (No. 2021BCA220).

Data Availability Statement: The data presented in this study are available on request from the corresponding author on reasonable request. The data are not publicly available due to privacy policies.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Costanza, R.; d'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; Oneill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
2. Nápoles-Vértiz, S.; Caro-Borrero, A. Conceptual diversity and application of ecosystem services and disservices: A systematic review. *Ecosyst. Serv.* **2024**, *67*, 101627. [CrossRef]
3. Zhai, Y.; Zhai, G.; Yu, Z.; Lu, Z.; Chen, Y.; Liu, J. Coupling coordination between urbanization and ecosystem services value in the Beijing-Tianjin-Hebei urban agglomeration. *Sustain. Cities Soc.* **2024**, *113*, 105715. [CrossRef]
4. Zhang, Y.; Chang, X.; Liu, Y.F.; Lu, Y.C.; Wang, Y.H.; Liu, Y.L. Urban expansion simulation under constraint of multiple ecosystem services (MESs) based on cellular automata (CA)-Markov model: Scenario analysis and policy implications. *Land Use Policy* **2021**, *108*, 105667. [CrossRef]
5. Yuan, Y.J.; Wu, S.H.; Yu, Y.N.; Tong, G.J.; Mo, L.J.; Yan, D.H.; Li, F.F. Spatiotemporal interaction between ecosystem services and urbanization: Case study of Nanjing City, China. *Ecol. Indic.* **2018**, *95*, 917–929. [CrossRef]

6. Sun, Y.; Jiao, L.; Guo, Y.; Xu, Z. Recognizing urban shrinkage and growth patterns from a global perspective. *Appl. Geogr.* **2024**, *166*, 103247. [CrossRef]
7. Halperin, S.; Castro, A.J.; Quintas-Soriano, C.; Brandt, J.S. Assessing high quality agricultural lands through the ecosystem services lens: Insights from a rapidly urbanizing agricultural region in the western United States. *Agric. Ecosyst. Environ.* **2023**, *349*, 108435. [CrossRef]
8. Nyelele, C.; Keske, C.; Chung, M.G.; Guo, H.; Egoh, B.N. Using social media data and machine learning to map recreational ecosystem services. *Ecol. Indic.* **2023**, *154*, 110606. [CrossRef]
9. Luis Valença, P.; Miguel, I.; Katažyna, B.; Marius, K.; Eduardo, G.; Paulo, P. Factors affecting cultural ecosystem services use in Vilnius (Lithuania): A participatory mapping survey approach. *Heliyon* **2023**, *9*, e15384. [CrossRef]
10. Frizzle, C.; Fournier, R.A.; Trudel, M.; Luther, J.E. Towards sustainable forestry: Using a spatial Bayesian belief network to quantify trade-offs among forest-related ecosystem services. *J. Environ. Manag.* **2022**, *301*, 113817. [CrossRef]
11. Molla Sitotaw, T.; Willemen, L.; Tsegaye Meshesha, D.; Nelson, A. Empirical assessments of small-scale ecosystem service flows in rural mosaic landscapes in the Ethiopian highlands. *Ecosyst. Serv.* **2024**, *67*, 101622. [CrossRef]
12. Kim, J.; Song, Y. Integrating ecosystem services and ecological connectivity to prioritize spatial conservation on Jeju Island, South Korea. *Landsc. Urban Plan* **2023**, *239*, 104865. [CrossRef]
13. Zhang, Y.; Liu, Y.F.; Wang, Y.H.; Liu, D.F.; Xia, C.; Wang, Z.Y.; Wang, H.F.; Liu, Y.L. Urban expansion simulation towards low-carbon development: A case study of Wuhan, China. *Sustain. Cities Soc.* **2020**, *63*, 102455. [CrossRef]
14. Cole, S.; Moksnes, P.-O.; Söderqvist, T.; Wikström, S.A.; Sundblad, G.; Hasselström, L.; Bergström, U.; Kraufvelin, P.; Bergström, L. Environmental compensation for biodiversity and ecosystem services: A flexible framework that addresses human wellbeing. *Ecosyst. Serv.* **2021**, *50*, 101319. [CrossRef]
15. Deng, H.; Zhou, X.; Liao, Z. Ecological redline delineation based on the supply and demand of ecosystem services. *Land Use Policy* **2024**, *140*, 107109. [CrossRef]
16. Yu, P.; Wei, Y.; Ma, L.; Wang, B.; Yung, E.H.K.; Chen, Y. Urbanization and the urban critical zone. *Earth Crit. Zone* **2024**, *1*, 100011. [CrossRef]
17. Zhao, H.; He, J.; Liu, D.; Han, Y.; Zhou, Z.; Niu, J. Incorporating ecological connectivity into ecological functional zoning: A case study in the middle reaches of Yangtze River urban agglomeration. *Ecol. Inform.* **2023**, *75*, 102098. [CrossRef]
18. Schneider, A.; Friedl, M.A.; Potere, D. Mapping global urban areas using MODIS 500-m data: New methods and datasets based on 'urban ecoregions'. *Remote Sens. Environ.* **2010**, *114*, 1733–1746. [CrossRef]
19. Chen, W.; Gu, T.; Xiang, J.; Luo, T.; Zeng, J.; Yuan, Y. Ecological restoration zoning of territorial space in China: An ecosystem health perspective. *J. Environ. Manag.* **2024**, *364*, 121371. [CrossRef]
20. Du, W.; Yan, H.; Feng, Z.; Liu, G.; Li, K.; Peng, L.; Xiang, X.; Yang, Y. Zoning for the sustainable development mode of global social-ecological systems: From the supply-production-demand perspective. *Resour. Conserv. Recycl.* **2024**, *203*, 107447. [CrossRef]
21. Liao, Q.; Li, T.; Wang, Q.; Liu, D. Exploring the ecosystem services bundles and influencing drivers at different scales in southern Jiangxi, China. *Ecol. Indic.* **2023**, *148*, 110089. [CrossRef]
22. Shen, J.; Li, S.; Liu, L.; Liang, Z.; Wang, Y.; Wang, H.; Wu, S. Uncovering the relationships between ecosystem services and social-ecological drivers at different spatial scales in the Beijing-Tianjin-Hebei region. *J. Clean. Prod.* **2021**, *290*, 125193. [CrossRef]
23. He, L.; Xie, Z.; Wu, H.; Liu, Z.; Zheng, B.; Wan, W. Exploring the interrelations and driving factors among typical ecosystem services in the Yangtze river economic Belt, China. *J. Environ. Manag.* **2024**, *351*, 119794. [CrossRef]
24. Sadeghi, S.H.; Chamani, R.; Silabi, M.Z.; Tavosi, M.; Katebikord, A.; Darvishan, A.K.; Moosavi, V.; Sadeghi, P.S.; Vafakhah, M.; Rekabdarkolaei, H.M. Watershed health and ecological security zoning throughout Iran. *Sci. Total Environ.* **2023**, *905*, 167123. [CrossRef]
25. Zhao, X.; Huang, G. Urban watershed ecosystem health assessment and ecological management zoning based on landscape pattern and SWMM simulation: A case study of Yangmei River Basin. *Environ. Impact Assess. Rev.* **2022**, *95*, 106794. [CrossRef]
26. Zeng, J.; Cui, X.; Chen, W.; Yao, X. Ecological management zoning based on the supply-demand relationship of ecosystem services in China. *Appl. Geogr.* **2023**, *155*, 102959. [CrossRef]
27. Sun, X.; Yang, P.; Tao, Y.; Bian, H. Improving ecosystem services supply provides insights for sustainable landscape planning: A case study in Beijing, China. *Sci. Total Environ.* **2022**, *802*, 149849. [CrossRef]
28. Zhang, L.; Shi, L.; Yang, F. Assessing ecosystem service dynamics in China's coastal shelterbelt: Implications for ecosystem restoration. *Environ. Impact Assess. Rev.* **2024**, *106*, 107515. [CrossRef]
29. Chunye, W.; Delu, P. Zoning of Hangzhou Bay ecological red line using GIS-based multi-criteria decision analysis. *Ocean Coast. Manag.* **2017**, *139*, 42–50. [CrossRef]
30. Bailey, R.G. Delineation of ecosystem regions. *Environ. Manag.* **1983**, *7*, 365–373. [CrossRef]
31. Mamat, K.; Du, P.; Ding, J. Ecological function regionalization of cultural heritage sites in Turpan, China, based on GIS. *Arab. J. Geosci.* **2017**, *10*, 1–12. [CrossRef]
32. Cao, Y.; Li, G.; Tian, Y.; Fang, X.; Li, Y.; Tan, Y. Linking ecosystem services trade-offs, bundles and hotspot identification with cropland management in the coastal Hangzhou Bay area of China. *Land Use Policy* **2020**, *97*, 104689. [CrossRef]

33. Fei, D.Q.; Cheng, Q.; Mao, X.; Liu, F.; Zhou, Q. Land use zoning using a coupled gridding-self-organizing feature maps method: A case study in China. *J. Clean. Prod.* **2017**, *161*, 1162–1170. [CrossRef]
34. Zhu, J.; Ke, X.; Zhou, T.; He, L. Evaluation of ecological security of natural resources in Wuhan based on "contribution-vitality-organization-strength-resilience". *Bull. Soil Water Conserv.* **2023**, *43*, 248–255+306.
35. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: General Synthesis*; Island Press: Washington, DC, USA, 2005; pp. 77–101.
36. Zhang, Y.; Liu, Y.F.; Zhang, Y.; Liu, Y.; Zhang, G.X.; Chen, Y.Y. On the spatial relationship between ecosystem services and urbanization: A case study in Wuhan, China. *Sci. Total Environ.* **2018**, *637*, 780–790. [CrossRef]
37. Li, S.; Zhao, Y.; Xiao, W.; Yellishetty, M.; Yang, D. Identifying ecosystem service bundles and the spatiotemporal characteristics of trade-offs and synergies in coal mining areas with a high groundwater table. *Sci. Total Environ.* **2022**, *807*, 151036. [CrossRef] [PubMed]
38. Xu, G.; Xiong, K.; Shu, T.; Shi, Y.; Chen, L.; Zheng, L.; Fan, H.; Zhao, Z.; Yang, Z. Bundling evaluating changes in ecosystem service under karst rocky desertification restoration: Projects a case study of Huajiang-Guanling, Guizhou province, Southwest China. *Environ. Earth Sci.* **2022**, *81*, 302. [CrossRef]
39. Bivand, R.S.; Wong, D.W. Comparing implementations of global and local indicators of spatial association. *Test* **2018**, *27*, 716–748. [CrossRef]
40. Getis, A.; Ord, J.K. The analysis of spatial association by use of distance statistics. *Geogr. Anal.* **1992**, *24*, 189–206. [CrossRef]
41. Roces-Diaz, J.V.; Vayreda, J.; Banque-Casanovas, M.; Diaz-Varela, E.; Bonet, J.A.; Brotons, L.; de-Miguel, S.; Herrando, S.; Martinez-Vilalta, J. The spatial level of analysis affects the patterns of forest ecosystem services supply and their relationships. *Sci. Total Environ.* **2018**, *626*, 1270–1283. [CrossRef]
42. Gong, J.; Jin, T.; Liu, D.; Zhu, Y.; Yan, L. Are ecosystem service bundles useful for mountainous landscape function zoning and management? A case study of Bailongjiang watershed in western China. *Ecol. Indic.* **2022**, *134*, 108495. [CrossRef]
43. Li, J.; Hu, D.; Wang, Y.; Chu, J.; Yin, H.; Ma, M. Study of identification and simulation of ecological zoning through integration of landscape ecological risk and ecosystem service value. *Sustain. Cities Soc.* **2024**, *107*, 105442. [CrossRef]
44. Peng, J.; Wang, A.; Luo, L.; Liu, Y.; Li, H.; Hu, Y.n.; Meersmans, J.; Wu, J. Spatial identification of conservation priority areas for urban ecological land: An approach based on water ecosystem services. *Land Degrad. Dev.* **2019**, *30*, 683–694. [CrossRef]
45. Li, Z.G.; Yang, F.; Zhong, J.L.; Zhao, J.J. Self-Organizing Feature Zoning and Multiple Hotspots Identification of Ecosystem Services: How to Promote Ecological Refined Management of Chengdu-Chongqing Urban Agglomeration. *J. Urban Plan. Dev.* **2023**, *149*, 04022049. [CrossRef]
46. Liu, Y.X.; Li, T.; Zhao, W.W.; Wang, S.; Fu, B.J. Landscape functional zoning at a county level based on ecosystem services bundle: Methods comparison and management indication. *J. Environ. Manag.* **2019**, *249*, 109315. [CrossRef]
47. Zhang, Y.; Yu, P.H.; Tian, Y.S.; Chen, H.T.; Chen, Y.Y. Exploring the impact of integrated spatial function zones on land use dynamics and ecosystem services tradeoffs based on a future land use simulation (FLUS) model. *Ecol. Indic.* **2023**, *150*, 110246. [CrossRef]
48. Turkelboom, F.; Leone, M.; Jacobs, S.; Kelemen, E.; García-Llorente, M.; Baró, F.; Termansen, M.; Barton, D.N.; Berry, P.; Stange, E.; et al. When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. *Ecosyst. Serv.* **2018**, *29*, 566–578. [CrossRef]
49. Zoderer, B.M.; Tasser, E.; Carver, S.; Tappeiner, U. Stakeholder perspectives on ecosystem service supply and ecosystem service demand bundles. *Ecosyst. Serv.* **2019**, *37*, 100938. [CrossRef]
50. Dittrich, A.; Seppelt, R.; Václavík, T.; Cord, A.F. Integrating ecosystem service bundles and socio-environmental conditions—A national scale analysis from Germany. *Ecosyst. Serv.* **2017**, *28*, 273–282. [CrossRef]
51. Huang, F.X.; Zuo, L.Y.; Gao, J.B.; Jiang, Y.; Du, F.J.; Zhang, Y.B. Exploring the driving factors of trade-offs and synergies among ecological functional zones based on ecosystem service bundles. *Ecol. Indic.* **2023**, *146*, 109827. [CrossRef]
52. Chen, D.D.; Jin, G.; Zhang, Q.; Arowolo, A.O.; Li, Y.F. Water ecological function zoning in Heihe River Basin, Northwest China. *Phys. Chem. Earth* **2016**, *96*, 74–83. [CrossRef]
53. Mo, W.B.; Zhao, Y.L.; Yang, N.; Xu, Z.G. Ecological function zoning based on ecosystem service bundles and trade-offs: A study of Dongjiang Lake Basin, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 40388–40404. [CrossRef]
54. De Vreesea, R.; Leys, M.; Fontaine, C.M.; Dendoncker, N. Social mapping of perceived ecosystem services supply—The role of social landscape metrics and social hotspots for integrated ecosystem services assessment, landscape planning and management. *Ecol. Indic.* **2016**, *66*, 517–533. [CrossRef]
55. Li, Y.; Zhang, L.; Yan, J.; Wang, P.; Hu, N.; Cheng, W.; Fu, B. Mapping the hotspots and coldspots of ecosystem services in conservation priority setting. *J. Geogr. Sci.* **2017**, *27*, 681–696. [CrossRef]
56. Moilanen, A.; Meller, L.; Leppänen, J.; Montesino Pouzols, F.; Arponen, A.; Kujala, H. *Zonation Spatial Conservation Planning Framework and Software V. 3.1: User Manual*; Helsingin Yliopisto: Helsinki, Finland, 2012.
57. Bennett, E.M.; Peterson, G.D.; Gordon, L.J. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* **2009**, *12*, 1394–1404. [CrossRef]
58. Berry, Z.C.; Jones, K.W.; Aguilar, L.R.G.; Congalton, R.G.; Holwerda, F.; Kolka, R.; Looker, N.; Ramirez, S.M.L.; Manson, R.; Mayer, A.; et al. Evaluating ecosystem service trade-offs along a land-use intensification gradient in central Veracruz, Mexico. *Ecosyst. Serv.* **2020**, *45*, 101181. [CrossRef]

59. Feng, Q.; Zhao, W.W.; Hu, X.P.; Liu, Y.; Daryanto, S.; Cherubini, F. Trading-off ecosystem services for better ecological restoration: A case study in the Loess Plateau of China. *J. Clean. Prod.* **2020**, *257*, 120469. [CrossRef]
60. Temirbayeva, R.K.; Akiyanova, F.Z.; Orazbekova, K.S.; Veysov, S.K. Socio-economic aspects of nature management in the kazakhstan's caspian sea region based on functional zoning of the territory. *Ser. Geol. Tech. Sci.* **2020**, *1*, 131–137. [CrossRef]