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Ecological Functional Zoning in Urban Fringe Areas Based on the Trade-Offs Between Ecological–Social Values in Ecosystem Services: A Case Study of Jiangning District, Nanjing

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Abstract: Amid the rapid socio-economic development of urban fringe areas, promoting the multi-functional supply of ecosystems and sustainable development is essential. Taking Jiangning District in Nanjing as a case study, this study explores the relationships and spatial clustering characteristics among various ecosystem service values in urban fringe areas, focusing on the trade-offs between ecological and social values. Ecological functional zones were delineated based on the ecosystem service clustering results and regional conjugation principles, followed by an analysis of the trade-offs and synergies among the values within each zone. The findings reveal the following: (1) trade-offs between ecological and social ecosystem service values are prevalent across the entire region, as well as within sub-regions in urban fringe areas; (2) Jiangning District can be divided into five key ecological functional zones—the Vibrant Industry-Urbanization Integration Zone, Important Habitat Conservation Zone, Livable Organic Renewal Zone, Characteristic Rural Landscape Development Zone, and Riparian Recreation and Ecological Conservation Zone. Each zone exhibits significant differences in the types and features of the services provided; and (3) understanding the relationships among ecological and social values within each zone may help to resolve trade-offs between them. This progressive trade-off analysis, from the regional to sub-regional level, enables more precise identification of ecosystem functions, providing reference for decision-making to enhance the overall regional value and guide sustainable planning and management practices in urban fringe areas.

Keywords: ecosystem service value trade-offs; ecological value; social value; urban fringe areas; ecological functional zoning

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1. Introduction

Since the 1950s, rapid urban expansion has become an irreversible global trend. In this context, the emergence of urban fringe areas has become a defining feature in the evolution of urban spatial structures. Urban fringe areas are a crucial part of urban regional structures, serving as both a hub for the exchange of material and energy between urban and rural settings. It also serves as a zone where the natural environment integrates with human living spaces. As urbanization accelerates, these areas have experienced significant economic growth and faced challenges related to the degradation of both natural and cultural ecosystems. Urban fringe areas can be viewed as complex ecosystems that encompass the relationships among people, nature, and society [1]. The ecological and social values of ecosystem services reflect both the natural ecological characteristics and the socio-cultural attributes of these ecosystems. Their interactions manifest as either synergistic cooperation, conflicting trade-offs, or independent relationships. A synergistic or trade-off relationship occurs when an increase in the value of one ecosystem service corresponds to an increase or decrease in the value of another, respectively [2]. Due to limited resources and the existence of trade-off relationships, reliance on a single type of ecosystem service can hinder the maximization of overall ecological benefits. Compared to typical rural areas, urban fringe zones stand at the forefront of urbanization, balancing the needs of ecological protection and economic development for both the urban core and the fringe itself. As such, these areas face significant environmental pressures, and their ecosystems are characterized by high complexity, dynamic changes, and limited protection. The population and land uses are diverse, with complex demands from both urban and rural residents. Rapid changes in spatial forms and industrial structures make ecological spaces, settlement patterns, and traditional cultures highly susceptible to disruption. If the coordinative relationship between the ecological and social values of ecosystem services in urban fringe areas is disrupted, it can lead to the degradation and simplification of ecosystem functions. For example, the intense competition between large-scale crop production and natural or semi-natural land use often limits the enhancement of multiple ecosystem service values [3]. While programs such as returning farmland to forests may help to address this issue, farmland abandonment can sometimes result in loss of biodiversity, damage to cultural heritage, and even increase the risks of natural disasters and human–wildlife conflicts. Moreover, in suburban areas near densely populated regions, the rapid development of non-agricultural industries has led to fragmented agricultural and natural landscapes in urban fringe areas. This fragmentation, coupled with the diverse spatial demands of urban and rural residents for esthetics, recreation, and education [4], seriously threatens food security and habitat conservation. Given the complexities surrounding the interconnections of ecosystem service values in urban fringe areas, addressing key issues in ecological conservation is essential. This can be achieved through tailored spatial planning and ecological management strategies, with the goal of enhancing the comprehensive value of ecosystem services.

In existing studies on the trade-offs in ecosystem service values, carbon storage, food provision, biodiversity, water resource protection, and water conservation are the most-frequently mentioned factors. These studies place the greatest emphasis on regulating services, followed by provisioning and supporting services, with the least attention given to social values [5]. However, in recent years, an increasing number of scholars have begun to focus on the intangible values of ecosystem services, and incorporating socio-ecological variables into the assessment of trade-offs in ecosystem service values has become an emerging trend. For example, Alessa et al. [6] proposed the concept of and a mapping method for socio-ecological spatial hotspots, using landscape indices to explore the spatial structure characteristics of the hotspots. Bryan et al. [7] used the Analytic Hierarchy Process to determine the weights of ecological and social values and identified socio-ecological value hotspots through the local Moran's I index. Karimi et al. [8] evaluated social and ecological values through public participatory geographic information systems and software for species distribution and conservation priority, identifying socio-ecological value hotspots using multiple importance thresholds. In their subsequent study, they established the relationships between biodiversity, the social values of ecosystem services, and land management preferences. Bagstad et al. [9] used hotspot analysis tools to identify socio-ecological value hotspots and cold spots in the San Isabel National Forest, USA. Chi et al. [10] analyzed changes in ecosystem service values in karst areas through land use change assessments using quantitative methods, highlighting their role in understanding ecosystem service supply and demand, trade-offs, and implications for sustainable development and land resource planning. Lourdes et al. [11] examined the social values of ecosystem services in rapidly urbanizing Greater Kuala Lumpur, Malaysia, using the SolVES tool and a public participatory GIS survey to reveal distinct resident preferences for green versus gray development and identifying potential areas of land use conflict.

During the dynamic evolution of urban fringe areas, complex mechanisms of interaction occur among various ecosystem service values, presenting both trade-offs and synergies. Cueva et al. [12] quantified the provisioning, regulating, and supporting ecosystem services of urban and peri-urban forests, identifying a trade-off effect between supporting and provisioning services, as well as between supporting and regulating services. This suggests that planning for suburban forests should consider these trade-off patterns. Zhang et al. [13] examined the interactions and relationships among the ecological values of five ecosystem services—carbon storage, water yield, soil conservation, biodiversity protection, and food production—in urban–rural transitional areas of southwestern China. They noted that interactions among ecosystem services in urban fringe areas are stronger than those in urban and rural areas. Chen et al. [14] highlighted the complex relationships among ecosystem services in peri-urban areas, mainly characterized by agricultural landscapes, observing that provisioning services trade-off, to some extent, with regulating and cultural services.

Nevertheless, existing research on the interaction patterns of ecosystem service values in urban fringe areas has revealed notable gaps: regarding their research focus, many studies mainly examine relationships centered on ecological values, such as food supply and habitat quality [12]. As such, they often overlook social values that capture the non-material benefits of ecosystems, limiting the applicability of their methods and findings to the complex ecological and socio-cultural contexts of urban fringe areas. In terms of research content, the majority of studies are based on correlation analyses to quantify trade-offs between pairs of values [13], neglecting clustering analyses of multiple values. This limits the ability to identify dominant value types and regions with concentrated synergistic effects. As for outcomes, a few studies have delineated ecological functional zones based on the trade-off relationships between ecosystem service values [14]. However, they often fail to investigate the internal value relationships within these zones, leading to the oversight of critical ecological control points. In addition, compared to urban and rural areas, research on the application of ecosystem service values in spatial planning for urban fringe areas remains relatively lacking. Most practices are carried out based on different goal-oriented approaches, with spatial planning and management methods being determined through the definition of ecosystem types and value assessments. The focus is mainly on identifying key areas for ecological restoration [15], constructing habitat conservation patterns [16], and optimizing ecosystem service spaces based on public perceptions and preferences [17]. Moreover, its application in ecological functional zoning is particularly scarce, which, to some extent, limits the management level of regional ecosystems.

Ecological functional zoning emphasizes the spatial heterogeneity resulting from differences in environmental resources, ecological succession, and human interventions. This makes region-specific functional zoning a vital approach for managing and regulating ecological environments. Kareiva et al. [18] first introduced the concept of ecosystem service bundles, which later evolved into a significant research method guiding ecological functional zoning. Ecosystem service bundles are groups of ecosystem services that consistently occur across time and space [19], representing clusters of interacting ecosystem services within a given region. Identifying these bundles can help to reveal the dominant ecosystem service values in a region and their clustering patterns, offering insights that can help to prevent the negative consequences of poorly informed decision-making. This approach has broad prospects for application in ecological spatial zoning, landscape planning, management, optimizing ecosystem services, and other related fields. For example, Karimi et al. [20] used the K-means clustering algorithm to identify ecosystem service bundles in urban areas at a 2 m resolution. On the other hand, Cheng et al. [3] applied hierarchical clustering at the grid scale to identify four types of ecosystem service bundles and their key landscape features within a park. However, existing research on the trade-offs among ecosystem service bundles remains limited, which somewhat restricts their practical application in ecological functional zoning management. Moreover, most research on trade-offs among ecosystem service values for ecological functional zoning has focused on urban or rural areas, with relatively little attention paid to urban fringe areas.

Since the 1990s, China's cities have increasingly adopted a growth-oriented development model. Spatial planning has mainly focused on utilizing rural resources, supporting urban expansion, and promoting economic growth. In this "growth-oriented planning" [21] paradigm, urban fringe areas have become key zones for urban sprawl. However, with issues such as ecological degradation and resource depletion arising from uncontrolled urban sprawl and extensive rural development, the traditional growth model has become unsustainable. China's urban development has now entered an era of stock, and landscape planning urgently needs to shift toward the more efficient allocation and use of internal spatial resources. In response, urban fringe areas must adopt refined zoning and management strategies which are tailored to actual development needs. This approach should avoid the negative impacts of uniform development constraints and management approaches while preserving the natural and cultural beauty with minimal intervention. Furthermore, ecological landscape planning in these areas should not focus solely on environmental conservation; it must also adopt an integrated approach that thoroughly assesses multiple values. This includes ensuring the continued provision of ecological benefits at the natural level while minimizing social disruptions and addressing the legitimate demands of residents for non-material benefits. Therefore, to facilitate differentiated and refined ecosystem management in urban fringe areas, it is important to expand the scope of research on the trade-off relationships between ecosystem service values and strengthen the synchronized assessment of social values. Additionally, accurately identifying homogeneous regions with similar trade-off characteristics is essential for ecological functional zoning, as this enables a clearer analysis of the complex relationships among multiple values across different zones.

This study examines the Jiangning District in Nanjing, analyzing the trade-off relationships between the ecological and social values of ecosystem services. Using clustering methods, the functional and structural characteristics of various regions are identified and ecological functional zones are delineated. Additionally, the interaction patterns of values within each zone at a refined spatial scale are explored. The aim of this study is to provide scientific support for comprehensive value enhancement and sustainable planning and management practices of urban fringe areas oriented towards collaborative development. The structure of the remainder of this study is as follows: Section 2 provides an overview of the study area. Section 3 outlines the methodology and data sources used in the research. Section 4 presents the spatial patterns of both individual and comprehensive ecological–social values in the study area; the trade-offs between the ecological–social values of its ecosystem services are also analyzed. Section 5 presents the ecological functional zoning of Jiangning District based on the ecosystem service cluster identification results, followed by an in-depth analysis of the trade-offs within the district. Finally, Section 6 concludes the study with a summary of the main findings and their implications.

2. Overview of the Study Area

Jiangning District is located in southwestern Jiangsu Province, China (Figure 1). It boasts a favorable natural ecological environment along with distinct social, economic, and transportation positioning advantages. Since 2000, Jiangning has transformed from a suburban county into a vital hub for external communications in Nanjing. It serves as a pivotal growth pole in the city's strategic metropolitan expansion. As a result, it has emerged as a model for ecological civilization initiatives at both national and local levels, encompassing rural revitalization, technological innovation, comprehensive tourism, and historical resource preservation, making it a region of significant importance. By the end of 2023, Jiangning District comprised 10 sub-districts, 136 communities, and 71 administrative villages, spanning a total area of 1560.82 km^2 [22]. Of this area, 335.20 km^2 is arable land, 34.42 km^2 is garden land, 434.53 km^2 is forest land, 29.96 km^2 is grassland, and 2.79 km^2 is wetland. The remaining land includes 381.91 km^2 for urban, rural, industrial, and mining purposes; 86.00 km^2 for transportation; and 256.01 km^2 covered by water bodies and water conservancy infrastructure [23]. In terms of its natural environment, Jiangning District is characterized by low mountain ranges and hills to the north and south, with extensive plains in the central region. It is situated in the northern subtropical monsoon climate zone, characterized by abundant rainfall. The district boasts rich water resources, including the Yangtze River, Qinhuai River, and Tangshan Hot Springs. Economically, Jiangning District is the largest logistics hub for agricultural and side-line products in East China. The local economy and technology sector have grown rapidly, with the per capita income of residents increasing severalfold over the past decade. In addition, Jiangning District boasts a rich cultural and historical heritage, with more than 100 historical sites. Furthermore, its tourism resources are abundant, earning it more than 20 accolades, including recognition as a National Demonstration County for Leisure Agriculture and Rural Tourism, among other honors.

Jiangning District boasts a favorable natural ecological environment and distinctive social, economic, and transportation advantages. Since the 1990s, it has experienced rapid economic growth driven by significant industrialization and urbanization, with its built-up area and population growth among the highest in Nanjing's administrative districts. However, this rapid urbanization has led to "urban maladies," including the fragmentation of ecological spaces, landscape homogenization, and severe environmental pollution. Additionally, as public demands diversify, the conflict between land redevelopment in the stock development phase and ecological protection has intensified. This conflict hinders the healthy development of ecosystems and the living environment. In conclusion, this region serves as an exemplary case for examining the critical contradictions between environmental protection and social development in urban fringe areas. It also provides valuable insights for conducting research on ecological functional zoning, which can inform the management of ecosystems in other urban fringe regions.

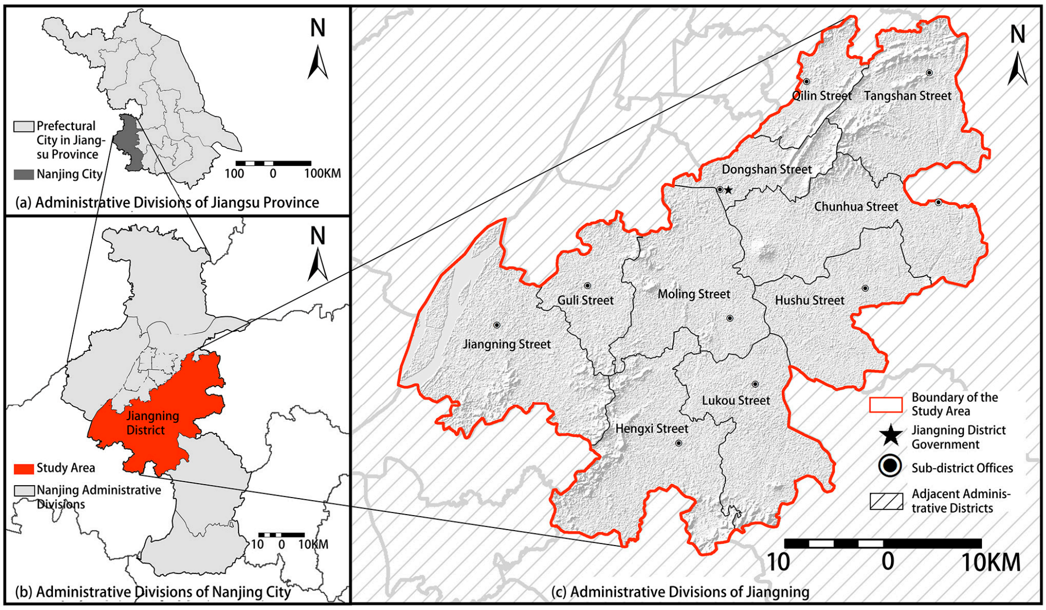


Figure 1. Location map of Jiangning District.

3. Research Methods and Data Sources

This research employs a three-step approach involving the assessment of ecosystem service values, the analysis of spatial trade-offs, and ecological functional zoning along with intra-zonal trade-off analysis (Figure 2). This workflow covers the complete process from database construction to spatial decision-making, establishing a comprehensive research methodology for ecological functional zoning. It transitions from a regional to a more localized level within urban fringe areas, facilitating ecological management and spatial optimization.

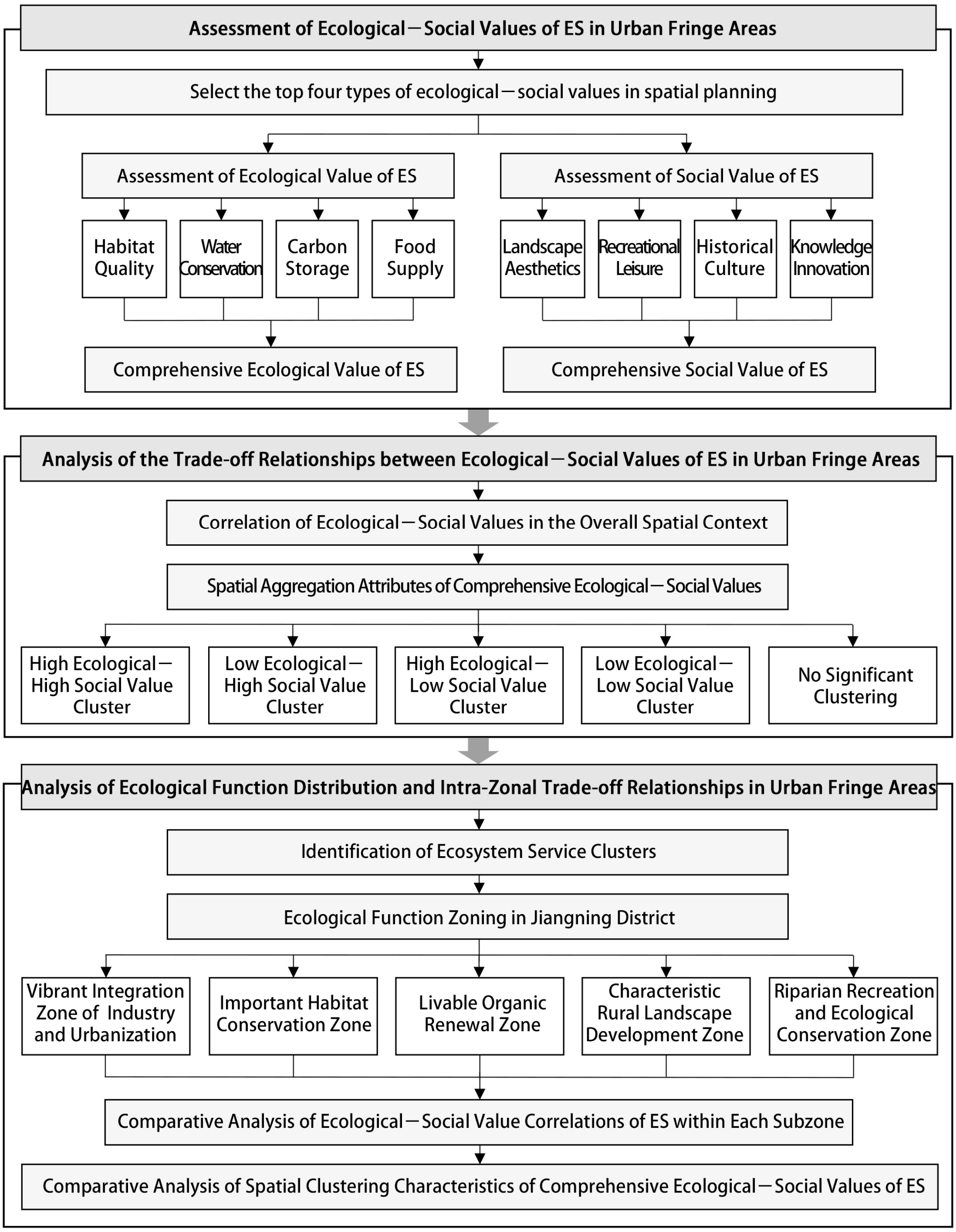


Figure 2. Framework of proposed research methods.

3.1. Selection of Ecosystem Service Value Types

Drawing on the classification frameworks of the United Nations Millennium Ecosystem Assessment (MA) and the widely recognized Common International Classification of Ecosystem Services (CICES) [24], this study systematically reviews 14 types of ecological and social values associated with ecosystem services. These values have been documented over the past decade in Jiangning District's planning initiatives for rural–urban integration, ecological construction, environmental protection, urban renewal, and comprehensive spatial land use planning. Given the key environmental challenges posed by urbanization, these values were classified into four levels: not mentioned (0 points), briefly mentioned (1 point), incorporated as planning principles or goals (2 points), or systematically applied through relevant theories or evaluations to guide spatial planning (3 points). These scores were then aggregated to derive quantitative insights into the extent to which each value has been applied in recent spatial planning efforts within Jiangning District (Figure 3). Among ecological values, the top four most frequently applied types were water conservation, habitat quality, food supply, and carbon storage. Among social values, the top four types were landscape esthetics, knowledge innovation, recreational leisure, and historical culture. These eight values have been widely applied in Jiangning District's recent spatial planning, serving as representative indicators. Therefore, these eight values were selected for use in this study.

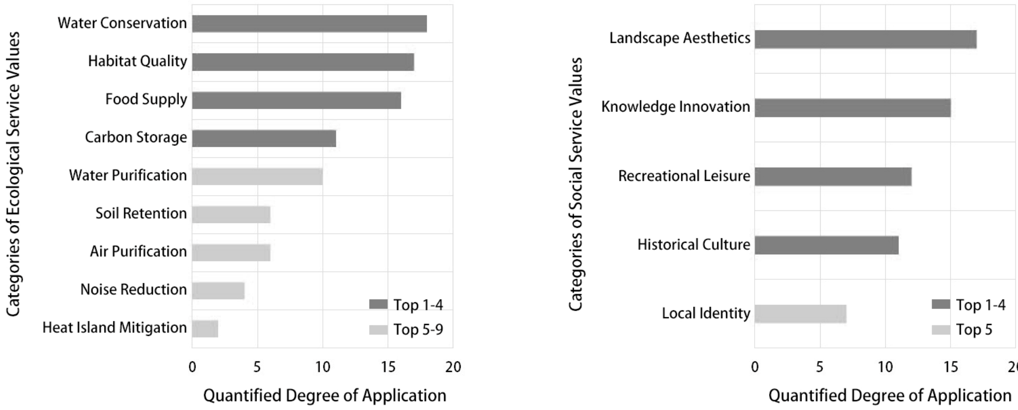


Figure 3. Quantitative analysis of the degree of ecosystem service value application in recent spatial planning efforts in Jiangning District.

3.2. Ecosystem Service Ecological Value Assessment

3.2.1. Methods for Assessing Ecological Values

The value of water conservation is reflected in its role in reducing surface runoff, recharging groundwater, mitigating seasonal flow fluctuations, and ensuring water quality. These efforts collectively support the continuous supply and maintenance of water resources. The evaluation of water conservation is carried out by calculating the amount of water conserved using the water balance equation [25]. In Formula (1), Q_x represents the water conservation amount (mm) for grid cell x, P_x denotes the average annual precipitation for grid cell x, R_x indicates the surface runoff coefficient for grid cell x, and ET_x denotes the average annual evapotranspiration.

$$Q_x = P_x - P_x \times R_x - ET_x \quad (1)$$

The value of habitat quality is used to quantify the extent to which ecosystems provide suitable habitats for natural biological communities, reflecting the survival conditions and reproductive capacity of species in specific habitats. Habitat quality is assessed using the habitat quality module of the InVEST model, which produces a dimensionless index ranging from 0 to 1, as shown in Formula (2) [26]. In this formula, Q_{xj} represents the habitat quality of grid cell x within land type j; D_{xj} denotes the level of disturbance affecting grid cell x in land type j, reflecting the degree of habitat degradation; K is the half-saturation constant; H_j refers to the habitat adaptability for land type j; and Z represents a conversion factor inherent to the model.

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^Z}{D_{xj}^Z + K^Z} \right) \right] \quad (2)$$

The value of food supply refers to the production capacity and sustainability of various food crops intended for human consumption, which reflects the agricultural production function of ecosystems. The evaluation of food supply is based on the ratio of the $NDVI$ value for cultivated land grids to the total $NDVI$ value for all cultivated land [27]. In Formula (3), G_x denotes the food production (kg) for grid cell x, G_{sum} represents the total food production from the total area, $NDVI_x$ indicates the $NDVI$ value for cultivated land grid x, and $NDVI_{sum}$ refers to the aggregate $NDVI$ values for cultivated land within the study area.

$$G_x = \left(\frac{NDVI_x}{NDVI_{sum}} \right) \times G_{sum} \tag{3}$$

The value of carbon storage refers to the natural process through which carbon dioxide is converted into organic matter and stored within ecosystems. This process reflects the capacity to sequester carbon and reduce greenhouse gas emissions. Carbon storage is assessed through the carbon storage module of the InVEST model [28]. In Formula (4), C_i denotes the total carbon density for land type i, while C_{iabove} represents the above-ground carbon density, C_{ibelow} signifies the below-ground carbon density, C_{isoil} indicates the soil organic carbon density, and C_{idead} refers to the carbon density of dead organic matter (all measured in t·hm^{-2}).

$$C_i = C_{iabove} + C_{ibelow} + C_{isoil} + C_{idead} \tag{4}$$

The overall ecological value of ecosystem services is assessed using a linear weighting approach, with the weights for the four ecological values determined through the Delphi method, as presented in Table 1.

Table 1. Weight of ecological values of ecosystem services in Jiangning District.

Weight of Ecological Value			
Habitat Quality	Water Conservation	Carbon Storage	Food Supply
0.260	0.246	0.252	0.242

3.2.2. Data Sources for Assessing Ecological Value

The necessary data for assessing the selected ecological value types are detailed in Table 2. All data were collected in 2023 and later resampled to obtain raster data with a consistent resolution of 30 m.

Table 2. Data sources required for assessing ecological values of ecosystem service in Jiangning District.

Data Components	Sources and Preprocessing
Biophysical coefficients	InVEST User Guide (https://www.sustainablehighways.org/ (accessed on 5 January 2023))
Average annual temperature, precipitation, and evaporation	Data obtained from the Resource and Environmental Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 10 January 2023)), followed by spatial interpolation processing.
Carbon density	Carbon density dataset for terrestrial ecosystems in China (2010–2020) (https://nesdc.org.cn/ (accessed on 8 January 2023)).
Normalized Difference Vegetation Index	Landsat-8 remote sensing images downloaded from the Geospatial Data Cloud site (https://www.gscloud.cn/ (accessed on 8 January 2023)), processed using band calculations.
Food production	Jiangning District Statistical Yearbook 2022 (http://www.jiangning.gov.cn/sjfb/tjnj/ (accessed on 9 January 2023))

3.3. Assessment of the Social Values of Ecosystem Services

3.3.1. Methods for Assessing Social Values

The social values of ecosystem services encompass landscape esthetics, recreational leisure, historical culture, and knowledge innovation. Landscape esthetics not only directly reflect regional features but also serve as a vital medium for recognizing and expressing local values, highlighting the esthetic significance of ecosystems. Recreational leisure provides the public with various outdoor spaces for recreation and entertainment, emphasizing the importance of social interactions and leisure activities. Historical culture is evident in elements such as historical sites, the preservation of intangible cultural heritage, and the protection of cultural relics. These aspects demonstrate how ecosystems embody the lifestyles and cultural traditions of humanity across different historical periods. Knowledge innovation offers the public opportunities for scientific education, creative learning, and research, fostering both knowledge and innovation, thus reflecting the ecosystem's role in knowledge enrichment and intellectual development.

The spatial mapping of the social values of ecosystem services was conducted using MaxEnt 3.3.3. The environmental variable data and latitude–longitude coordinates of the social value points were input separately into the model's environmental variable and species distribution modules. A random selection of 75% of the data were used as training samples, while the remaining 25% were reserved for testing. The bootstrap repetition was set to 10, and the accuracy of the evaluation results was assessed using the area under the receiver operating characteristic curve (AUC).

The MaxEnt model, developed by Phillips et al., allows for the evaluation of the output value model to extrapolate the distributions of social values from known locations to unknown areas. The final value index, ranging from 0 to 10, along with its spatial distribution map, was generated using ArcGIS [29].

The overall social value was calculated using a linear weighting method, with the weights determined through the Delphi method, as shown in Table 3.

Table 3. Weight of ecosystem service ecological values in Jiangning District.

Weight of Social Values			
Landscape Esthetics	Recreational Leisure	Historical Culture	Knowledge Innovation
0.257	0.252	0.250	0.241

3.3.2. Data Sources for Assessing Social Values

The MaxEnt model requires both social value point data and environmental variable data. Points of Interest (POIs) in 2023 were selected as the social value data, and 69,326 POI entries from Jiangning District were obtained using the Gaode Map application interface. The POI data were then classified, filtered, and cleaned using a combination of tags and keywords (Table 4).

Table 4. Method for screening POI data in Jiangning District.

Types	**Filtered by Labels**	**Filtered by Keywords**	**Examples**
Landscape Aesthetics	Scenic Attractions, Leisure Activities, Natural Landmarks	Scenery, Forest, Grass, Flower, Apricot, Bamboo, Willow, Plum, Mountain, Rock, Peak, Valley, Cliff, Cave, Gorge, Island, Slope, Spring, Water, River, Sea, Lake, Stream, Bay, Ravine, Pond, Wetland, Village, Field, Garden, Courtyard, Bridge, Wheel, Square, Dock, etc.	Shike Lake Ecological Park, Verbena Flower Sea, Nanjing Niushou Mountain Cultural Tourism Zone—Yinlong Lake Square
Recreational Leisure	Leisure Activities, Sports and Fitness Services, Lifestyle Services	Recreation, Entertainment, Amusement, Activities, Sports, Fitness, Rehabilitation, Vacations, Picking, Fishing, Board Games, Hot Springs, Hotels, Cinemas, Clubs, Amusement Parks, Farms, Resorts, Rural Tourism, Inns, Towns, Squares, Centers, Bases, etc.	Tangshan No.1 Natural Hot Spring Resort, Huluba Tourism Fishing Center, Ginkgo Lake Golf Club
Historical Culture	Scenic Attractions, Educational and Cultural Sites, Leisure Activities	Pavilions, Towers, Platforms, Halls, Temples, Mansions, Buildings, Pagodas, Palaces, Tombs, Mausoleums, Steles, Ancestral Halls, Villages, Historical Residences, Historical Sites, Ruins, Fossils, Stone Inscriptions, Antiquities, History, Buddhism, Confucianism, Taoism, Ethics, Filial Piety, Culture, Memorials, etc.	Ancient Buildings of Yangliu Village, Daishan Memorial Hall, Huanglongxian Tea Culture Museum
Knowledge Innovation	Scenic Attractions, Educational and Cultural Sites, Lifestyle Services	Innovation, Intelligence, Technology, Popular Science, Science, Exhibitions, Presentations, Expansion, Team-Building, Training, Education, Creativity, Cultural Innovation, Experiments, Practice, Experiences, Exploration, Research, Development, Industries, Design, Bases, Parks, Zones, Ports, Academies, Institutes, Camps, etc.	Tangshan Fangshan National Geopark, Jiangning High-tech College Student Creative and Entrepreneurial Park, Xitian Ecological Civilization Education Base

This study identifies ten environmental variables that capture the key environmental characteristics of Jiangning District, encompassing both natural and anthropogenic factors. The natural factors include elevation, slope, Normalized Difference Vegetation Index, proximity to water bodies, and patch count, while the anthropogenic variables consist of land use type, distance to roads, distance to tourist attractions, distance to rural residential areas, and distance to government centers. All data, as shown in Table 5, were collected in 2023, with a raster data spatial resolution of 30 m.

Table 5. Data sources for environmental variables required for social value assessment.

Data Components	Sources and Preprocessing
Elevation and slope	Geospatial Data Cloud site (https://www.gscloud.cn/ (accessed on 8 January 2023))
Normalized Difference Vegetation Index	Landsat-8 remote sensing imagery obtained from Geospatial Data Cloud site (https://www.gscloud.cn/ (accessed on 8 January 2023)), processed through band calculations.
Distance to water bodies and roads	Vector data sourced from Open Street Map (https://www.openstreetmap.org/ (accessed on 11 January 2023)), cropped and analyzed to calculate distances using the Euclidean distance.
Land use types and distance to rural residential areas	Multi-temporal land use remote sensing monitoring data obtained from the Resource and Environmental Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 10 January 2023)). Distances to rural residential areas are calculated using Euclidean distance.
Patch count	Land use data (https://www.gscloud.cn/ (accessed on 8 January 2023)) reclassified and analyzed using Fragstats V4.4.
Distance to tourist attractions	POI data downloaded from the Gaode Map API (https://lbs.amap.com/ (accessed on 11 January 2023)), filtered, and cleaned, with distances calculated using the Euclidean distance.
Distance to government centers	Administrative boundary and point data sourced from the Resource and Environmental Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 10 January 2023)). Distances are calculated using the Euclidean distance.

3.4. Analysis of the Ecological–Social Value Trade-Offs in Ecosystem Services

3.4.1. Analysis of the Correlation Between Ecological–Social Values in Ecosystem Services

The Pearson correlation coefficient is commonly used to examine the paired relationships between ecosystem service values, providing a foundation for understanding the characteristics in a given region [30]. The correlation coefficient matrix was calculated and visualized using the Corrplot package in R. A negative correlation coefficient indicates an inverse relationship between two values, reflecting a trade-off, while a positive coefficient suggests a synergistic relationship.

3.4.2. Analysis of the Spatial Clustering Characteristics of Ecological–Social Values in Ecosystem Services

The bivariate local Moran's I statistic helps to uncover spatial correlations between two or more ecosystem service values [31]. The bivariate local spatial autocorrelation model in the GeoDa 1.22 was used to analyze the spatial clustering characteristics of trade-off relationships among comprehensive ecosystem service values. The bivariate local spatial autocorrelation clustering map classifies the study area into five types of spatial aggregation of ecological–social value: high–high, high–low, low–high, low–low, and no significant relationship.

3.5. Methods for Ecosystem Functional Zoning

3.5.1. Identification of Ecological Service Clusters

To identify ecosystem service clusters, this study evaluated the similarity between ecosystem service values through iterative calculations and relative distances. Units with high dissimilarity were grouped into distinct ecosystem service clusters, highlighting differences in both the quantity and type of ecosystem service values across regions. This analysis serves as a key foundation for ecological functional zoning [20]. The K-means clustering algorithm was employed, using the Factoextra package in R, in order to identify these clusters. By analyzing the significance of the classification results for regional ecological management, this study examined the trends in within-cluster sum of squares for cluster counts ranging from 2 to 10. The elbow method was used to determine the optimal number of ecosystem service clusters.

3.5.2. Ecological Functional Zoning and Analysis of Intra-Zone Trade-Offs

Based on the identification results of ecosystem service clusters, spatially adjacent areas with functional consistency or similarity were integrated, according to the principle of regional conjugation, to form coherent spatial units. Small, isolated, or peripheral areas were merged, minor adjustments were made, and smoothing of ecosystem service clusters was performed according to the specific characteristics of each patch. The clusters were then aggregated into ecological function zones based on their dominant value types, enhancing the overall coherence and manageability of the zoning. The overall characteristics of each ecological functional zone were assessed from three perspectives: spatial distribution, connection to land use, and value characteristics. The area proportions of different land use types within the ecological functional zones were calculated, and the cluster centers for ecosystem service values in each zone were identified. A rose diagram was then created, with distance values representing the average of each service value. This average was then compared to the standardized mean of all values in the study area, in order to derive the relative ecosystem service value statistics.

4. Assessments of Ecological–Social Values and Trade-Offs of Ecosystem Services in Jiangning District

4.1. Spatial Patterns of Ecological–Social Values of Ecosystem Services in Jiangning District

4.1.1. Spatial Patterns of Individual Ecological–Social Values in Jiangning District

By analyzing individual ecological values (Figure 4), it was found that water conservation is particularly high in the forests and certain agricultural areas of the southwestern, eastern, and southern parts of Jiangning District. Conversely, areas with extensive impervious surfaces in the northern low-altitude urban development exhibit poor water source conservation capacity. The spatial distribution of habitat quality closely mirrors that of carbon storage, with regions rated as good or higher primarily located in forested mountain areas far from high-density urban centers. In contrast, the eastern Yangtze River and the northern and southern ends of the Qinhuai River experience significant disturbances due to industrial development and tourism activities, resulting in lower values for both categories. The food supply follows a spatial distribution pattern, with higher values in the south and east and lower values in the north and west. Areas rated as "good" or above are mainly found in the southern and eastern regions, with nutrient-rich soils and extensive farmlands.

The AUC values for both the training and testing models for each social value exceeded 0.7, indicating the high reliability of the simulation results. When analyzing individual social values (Figure 5), the landscape esthetic value presented higher levels in the north and lower levels in the south, with both the eastern and western ends also exhibiting lower values. Areas rich in natural landscapes, scenic spots, and distinctive rural complexes tend to have higher values. The knowledge innovation value was clustered near research institutions, science exhibition venues, and modern industrial parks, followed by urban parks, rivers, and villages that are easily accessible and close to agricultural land. Recreational leisure value was mainly observed in densely populated urban areas and university towns, with additional concentrations around tourist attractions that leverage natural features and cultural heritage sites. Historical and cultural value displayed a spatial pattern of higher levels in the north and lower levels in the south, characterized by multi-point clustering, influenced by historical landscapes, local customs, and the distribution of industrial sectors.

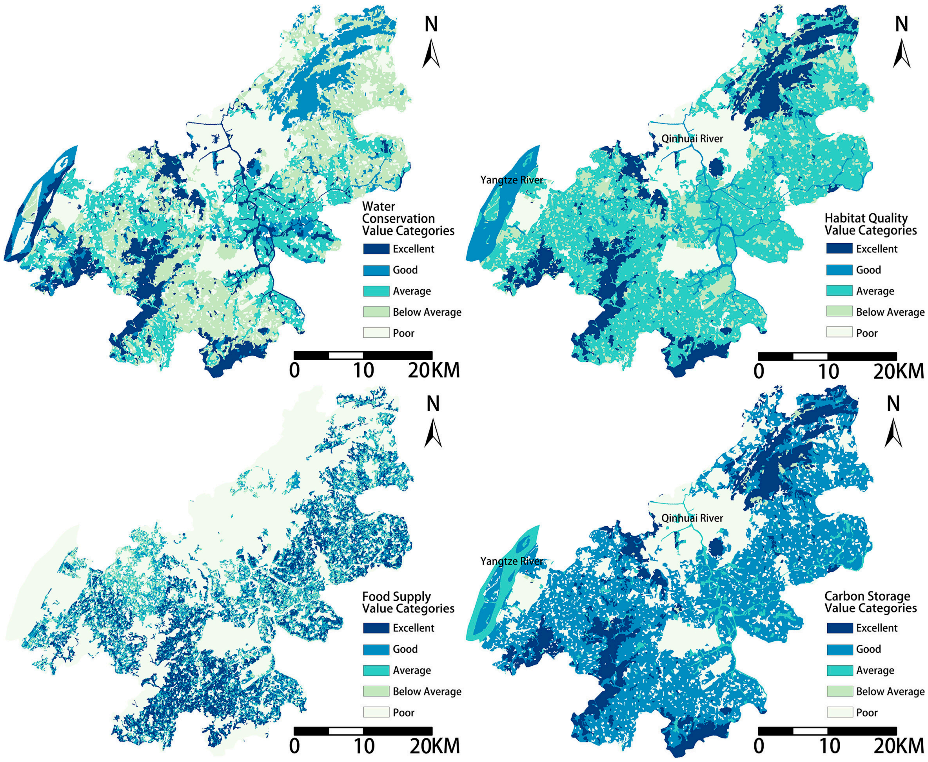


Figure 4. Spatial distribution of ecosystem service ecological value levels in Jiangning District.

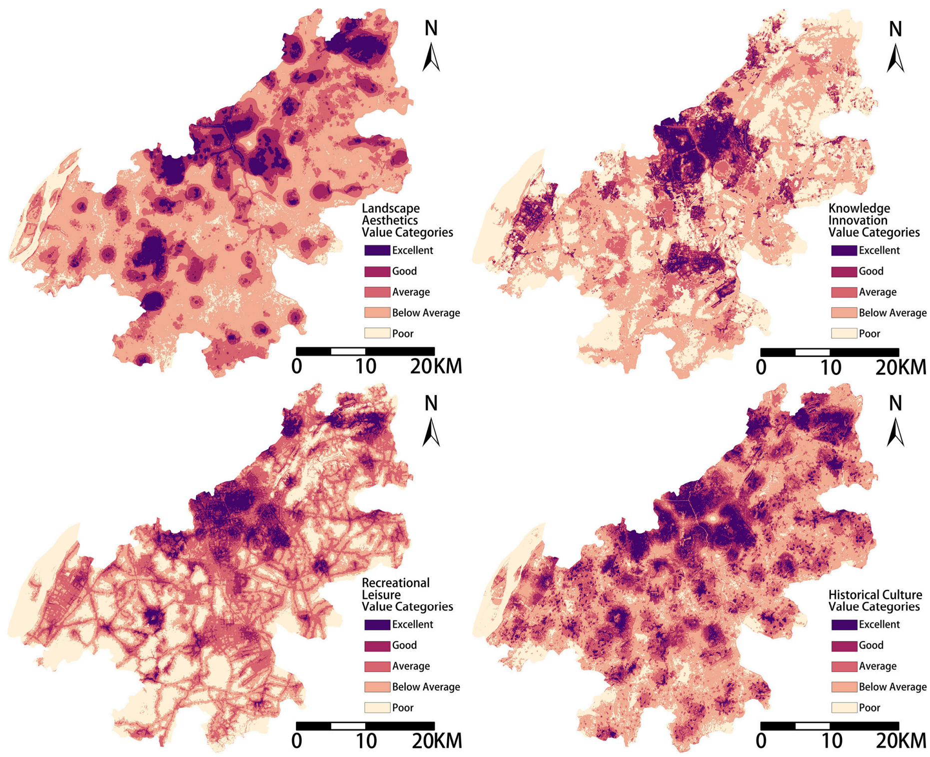


Figure 5. Spatial distribution pattern of social value levels of ecosystem services in Jiangning District.

4.1.2. Spatial Patterns of Comprehensive Ecological–Social Values in Jiangning District

The results indicated that Jiangning District has significant potential for comprehensive value. It is home to farmland, vegetable plots, and forests and grasslands that support the cultivation of various food crops, fruits, vegetables, timber, and livestock. These resources ensure a reliable supply of diverse food, freshwater, and raw materials. The high-altitude forest and grassland areas, which are widely distributed, continuous, and minimally disturbed by human activity, serve as significant sources of comprehensive ecological service value. They also play a significant role in maintaining natural ecological processes. Forest areas, which are less impacted by urbanization, maintain a relatively intact ecological structure and serve as significant carbon sink regions. They also play a significant role in maintaining natural ecological processes. Additionally, the distinctive landscape pattern of interspersed agriculture and forestry in the southern and eastern regions effectively enhances the overall ecological value (Figure 6). In contrast, the spatial distribution of social value related to comprehensive ecological services in Jiangning District shows higher values in the north and lower values in the south, with inland clusters. The main urban area in the north, along with the clustered new towns, is a key source of social value (Figure 7).

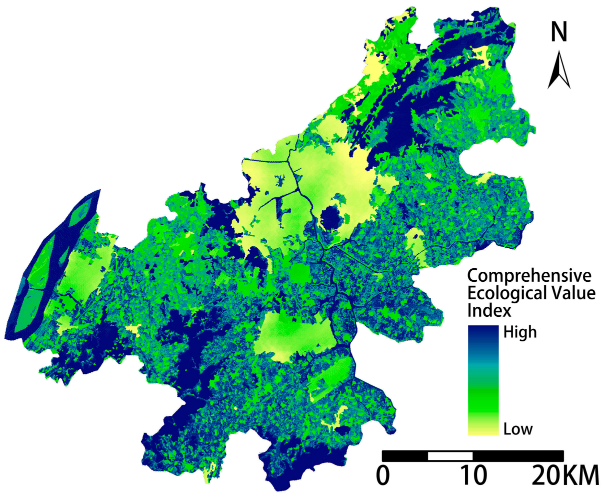


Figure 6. Spatial distribution pattern of comprehensive ecological value of ecosystem services in Jiangning District.

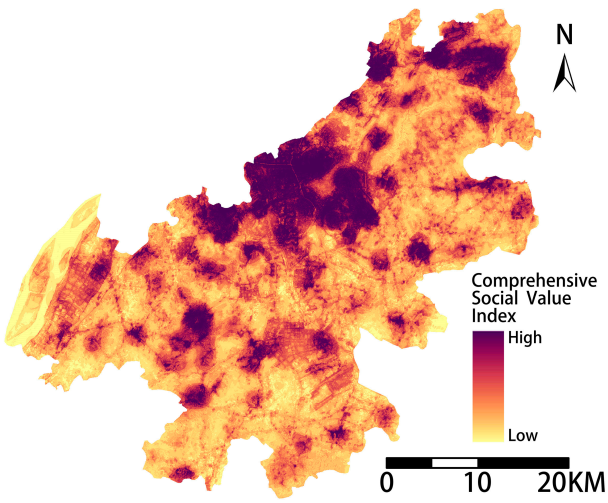


Figure 7. Spatial distribution of comprehensive social value of ecosystem services in Jiangning District.

The spatial distribution of both comprehensive ecological and social service values in Jiangning District reveals several challenges: First, the areas with high and medium–high comprehensive ecological value are relatively few. This highlights the need to address weaknesses in individual ecological components and improve the overall ecological network. Second, high social value zones are mainly clustered in distant locations, resulting in low connectivity, which limits the potential for high overall social value performance in the region. Third, potential conflicts may arise between the distributions of ecological and social values, requiring a more precise analysis of the trade-offs between the two.

4.2. Trade-Offs Between Ecological–Social Values of Ecosystem Services in Jiangning District

4.2.1. Correlation Between Ecological–Social Values in Jiangning District

Analyzing the correlations between ecosystem service values is crucial for understanding the characteristics of regional ecosystem services. Each pair of ecosystem service values in Jiangning District was tested for significance at the $p < 0.01$ level. In the correlation coefficient matrix, red indicates a negative correlation, while blue represents a positive correlation (Figure 8).

Negative correlations were identified between food supply and both habitat quality and carbon storage within the categories of ecological and social values. In contrast, strong positive correlations emerged between habitat quality and carbon storage, habitat quality and water conservation, and water conservation and carbon storage, highlighting the direct impacts of land use patterns on ecosystem services. Notably, the synergy between habitat quality and carbon storage was the strongest, consistent with the findings of Zhang et al. in their study on urban–rural transitional areas in southwestern China [13]. The explanation for this is that food supply often depends on agricultural expansion and intensive land use, which can degrade habitat integrity and negatively impact local biodiversity. Moreover, the lower vegetation density in farmland reduces its carbon sequestration capacity, leading to a decrease in overall carbon storage. There is a positive feedback loop among habitat quality, carbon storage, and water conservation values. Improvements in habitat quality foster biodiversity, which enhances ecosystem stability and increases both carbon storage and water conservation capacities. The ecosystem regulation ability of urban fringe areas is also closely linked to surface runoff absorption and their capacity to mitigate flooding and waterlogging disasters [32], underscoring the significance of water conservation functions. This emphasizes the need to accurately address the coordination of regional ecological values, including ecological integrity protection, carbon reduction, and resource supply.

From the perspective of social value groups, there was better compatibility among various values, which is in alignment with previous research [14]. Strong correlations were observed between recreational leisure and historical culture, landscape esthetics and historical culture, recreational leisure and knowledge innovation, and landscape esthetics and recreational leisure. This is because social values usually do not conflict in terms of resource demands. The needs of different social groups can be met simultaneously through multifunctional public spaces, reflecting the shared characteristics of such spaces and resources. However, the synergy between landscape esthetics and knowledge innovation was weaker, likely as knowledge innovation often depends on educational and cultural resources, while landscape esthetics focuses more on visual and sensory experiences. These two social values prioritize different aspects of demand. This suggests that, through effective spatial planning, various social values can generate mutually beneficial synergistic effects. These effects, in turn, promote the overall enhancement of regional social value.

Examining the trade-offs between ecological and social value groups revealed that only two pairs—landscape esthetic value with habitat quality and with carbon storage—showed positive correlations. The remaining pairs were negatively correlated. The correlation patterns between different values indicate the complexity and multi-dimensional needs characterizing regional development. In terms of correlation strength, two pairs exhibited strong correlations, seven pairs showed moderate correlations, six pairs had weak correlations, and one pair showed no significant correlation. Notably, the strongest negative correlation was between water conservation and knowledge innovation. Among the ecological values, water conservation exhibited the most significant trade-off with social values, while carbon storage showed the weakest negative correlation with social values. This may be linked to the widespread distribution of forests, grasslands, and farmlands with high carbon storage in Jiangning District. In addition, food supply was negatively correlated with all social values, supporting the conclusions of related studies [14]. This is because agricultural land competes with other land uses, limiting the availability of land for most other services [33]. Regarding social values, knowledge innovation had the most significant negative correlation with other ecological values, while landscape esthetic value demonstrated a lower level of trade-off with each ecological value, particularly with food supply. However, the interaction mechanisms between these values are quite complex; for example, research has indicated that the loss of traditional agricultural landscapes may diminish esthetic value and even weaken the emotional bonds that people have with these places [34].

Moreover, relevant research has shown that the value of ecosystem services in urban fringe areas is both broad and diverse [35]. These areas provide spaces that visually reflect natural processes, providing opportunities for people to learn about ecology and engage in environmental education [36]. Furthermore, traditional rural settlements and old industrial communities often have unique historical and cultural heritage. Local residents often form emotional and cultural attachments to urban fringe areas, imbuing them with significant spiritual value [37].

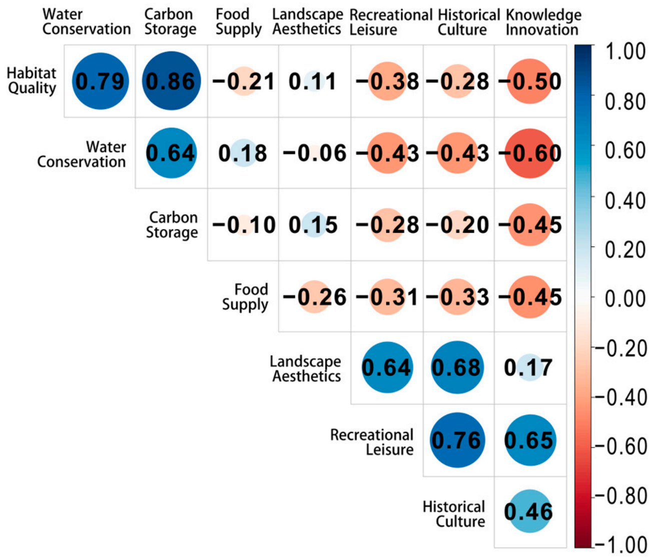


Figure 8. Correlation coefficient matrix of ecological–social values of ecosystem services in Jiangning District.

In general, there are notable trade-off relationships between ecological and social values in Jiangning District, although the compatibility within the groups of ecological and social values is relatively strong. This finding supports previous research [38], which has suggested that increases in most ecological values often lead to decreases in social values, and vice versa. Therefore, it is crucial to specifically identify, plan for, and manage the trade-off relationships between ecological and social values of ecosystem services in urban fringe areas from a spatial perspective.

4.2.2. Spatial Clustering Characteristics of Ecological–Social Value in Jiangning District

The LISA Clust Map (Figure 9), generated using a bivariate local autocorrelation model, revealed the spatial heterogeneity of trade-offs between ecological and social values within Jiangning District's comprehensive ecosystem services. Areas with lower compatibility between these values exhibited higher levels of statistical significance (Figure 10).

The high ecological, high social value clusters (7.23%) are mainly concentrated in regions such as Niushou Mountain, Tangshan, Ginkgo Lake, and Shitang Village. These areas are characterized by rich natural landscapes, including mountainous terrain, water bodies, and dense vegetation, convenient transportation and well-developed infrastructure. In contrast, the low ecological, low social value clusters (6.99%) are more scattered, typically situated around rural settlements and industrial or mining areas. The green spaces in these regions are vulnerable to high-intensity industrial or agricultural activities and have not been developed into tourist or leisure zones. The low ecological, high social value clusters (15.29%) are mainly found in highly urbanized zones, close to major tourist attractions or industrial parks. High-density development in these regions has severely degraded habitats, creating significant conflicts between ecological and social values. Meanwhile, the high ecological, low social value clusters (30.86%) are located along the eastern, western, and southern edges of Jiangning District. Although these areas are sparsely populated and maintain strong ecological integrity, they are constrained by challenging terrain and transportation conditions. Their potential non-material benefits remain largely untapped, providing opportunities to enhance their integrated ecological and social benefits.

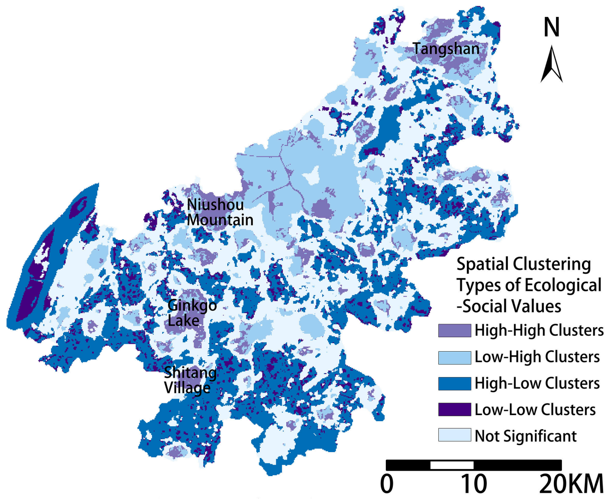


Figure 9. LISA clustering of ecological–social values in ecosystem services.

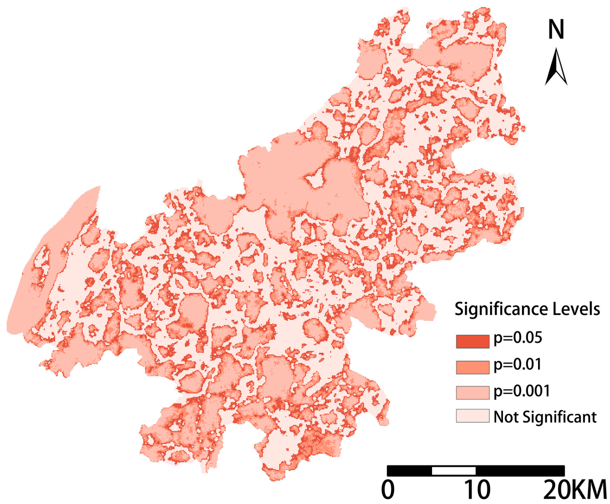


Figure 10. LISA significance of ecological–social values in ecosystem services.

In conclusion, trade-off relationships between low–high and high–low clusters predominate in Jiangning District. Their spatial distribution is characterized by significant fragmentation, with a relatively even spread across various land use types. This results in more complex interactions between humans and the environment, underscoring the urgent need to optimize the ecological functional space in urban fringe areas at a more detailed scale.

5. Ecological Functional Zoning and Intra-Zone Trade-Offs in Jiangning District

5.1. Identification Results of Ecosystem Service Clusters

The identified ecosystem service clusters revealed the differences in the quantity and types of ecological and social values of ecosystem services, reflecting the supply conditions of ecosystem services in different regions, as well as how spatial planning and land uses influence the value levels of these services. These clusters can serve as a primary basis for ecological functional zoning. An analysis of changes in the cluster variance explanation curve revealed a clear inflection point in the sum of squared errors (Figure 11), which indicated that five was the optimal number of ecosystem service clusters.

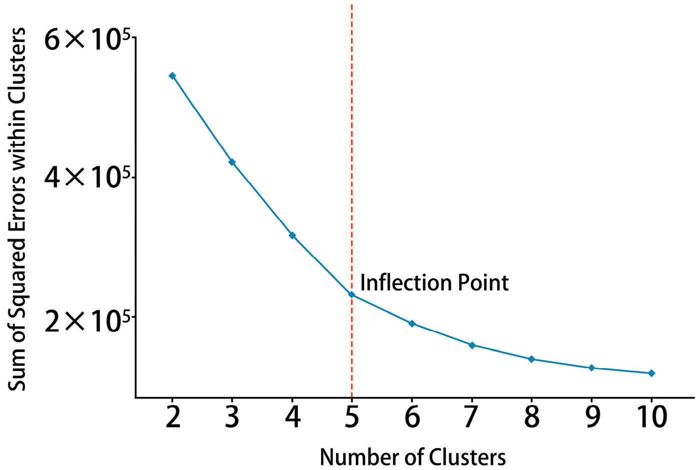
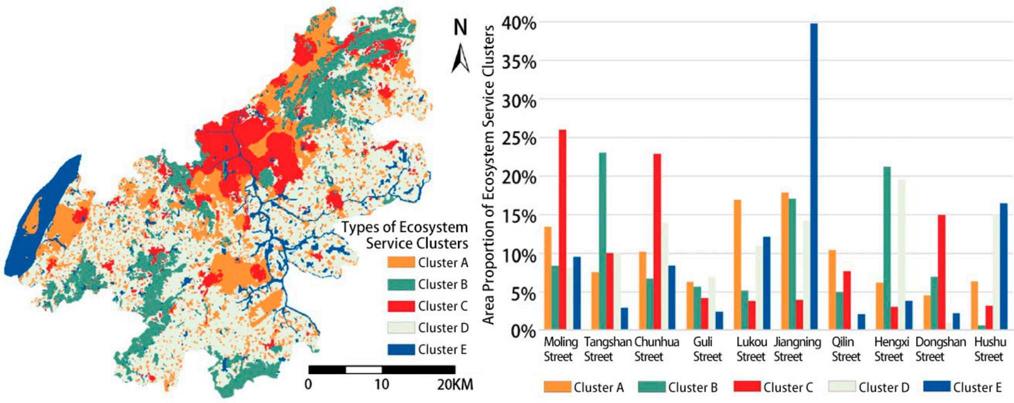


Figure 11. Sum of squared errors within cluster statistics.

The five types of ecosystem service clusters were named clusters A through E, and the area proportion of each cluster was calculated by street (Figure 12). Cluster A accounts for 23.35% of Jiangning District's area, ranking second in area proportion, and is primarily distributed in Lukou Street and Jiangning Street, followed by Moling Street, Qilin Street, and Chunhua Street, with the lowest distribution in Dongshan Street. Cluster B accounts for 18.04% of Jiangning District's area, concentrated in Tangshan Street, Hengxi Street, and Jiangning Street, with minimal distribution in Hushu Street. Cluster C covers 13.17% of the district, with the highest proportion in Moling Street, followed by Chunhua Street and Dongshan Street, while in the other seven streets, its distribution is less than 10%. Cluster D, covering 34.55%, has the largest area but is nearly absent in Qilin Street and Dongshan Street. Cluster E, covering 10.89%, is the smallest in area but represents nearly 45% of the area in Jiangning Street, with much lower distributions across the other nine streets. Overall, the clusters ranked in area, from largest to smallest, as follows: D > A > B > C > E. Clusters E, C, and B exhibit clear spatial differentiation across streets, Cluster A shows relatively minor spatial variation, and Cluster D has the broadest distribution.



(a) LISA Clustering of Ecological − Social Values in the Riparian Recreation and Ecological Conservation Zone

(b) Area Proportion of Each Ecosystem Service Cluster by Administrative Street

Figure 12. Spatial distribution pattern of ecosystem service clusters in Jiangning District and area proportion by street.

5.2. Results of Ecological Functional Zoning in Jiangning District

Due to the overly complex spatial nesting relationships between the ecosystem service clusters, they are not suitable to be directly used as ecological functional zoning results. In adherence to the principle of regional conjugation and considering the spatial distribution, land use characteristics, and dominant value types of each ecological function zone, five main ecological function zones were delineated: the Vibrant Integration Zone of Industry and Urbanization, the Important Habitat Conservation Zone, the Livable Organic Renewal Zone, the Characteristic Rural Landscape Development Zone, and the Riparian Recreation and Ecological Conservation Zone (Figure 13). These zones exhibit distinct spatial differentiation patterns. From the perspective of "land sharing" versus "land sparing" [39], the Important Habitat Conservation Zone, Characteristic Rural Landscape Development Zone, and Riparian Recreation and Ecological Conservation Zone should generally follow a conservation-oriented landscape model based on the dominant land uses. Conversely, areas such as the Vibrant Integration Zone of Production and Urbanization, the Livable Organic Renewal Zone, and other regions involving tourism, mixed land uses, forest recreation, and similar activities are characterized by a sharing-based spatial configuration that integrates various land uses.

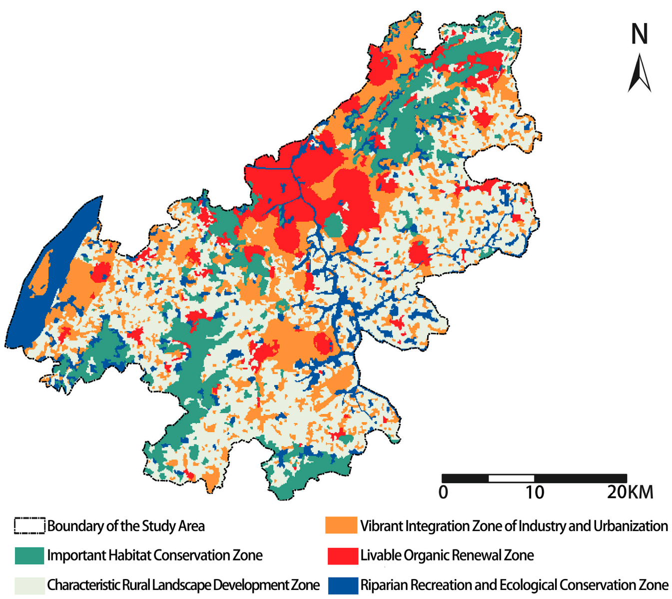


Figure 13. Ecological functional zoning in Jiangning District.

5.2.1. Vibrant Integration Zone of Industry and Urbanization

The Vibrant Integration Zone of Industry and Urbanization is mainly located in the Binjiang area, Lukou New Town, and the towns of Moling, Guli, and Qilin (Figure 14A). In this zone, social values slightly outweigh ecological values, with a notable emphasis on historical culture, recreational leisure, and water conservation. In contrast, values such as carbon storage, knowledge innovation, and landscape esthetics are relatively lower (Figure 14B). This area plays a key role in driving the development of the robust industrial sector in Jiangning, underscoring the need for enhanced knowledge innovation. The limited distribution of forests, grasslands, and water bodies hinders the effectiveness of regulatory services. Furthermore, inefficient agricultural land outside of the designated permanent farmland offers significant potential for conversion and re-greening. This can be achieved through moderate development and the addition of green spaces, enhancing various values such as carbon storage and landscape esthetics.

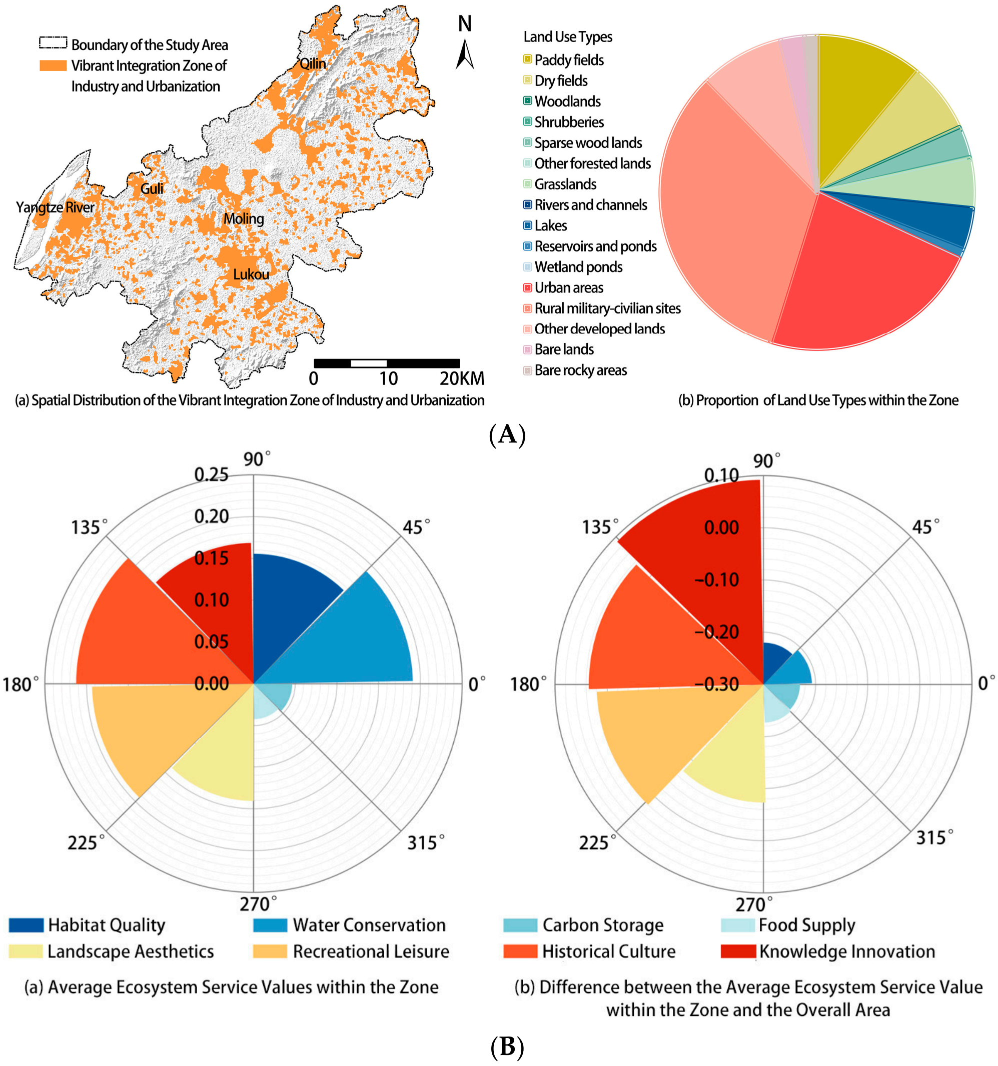
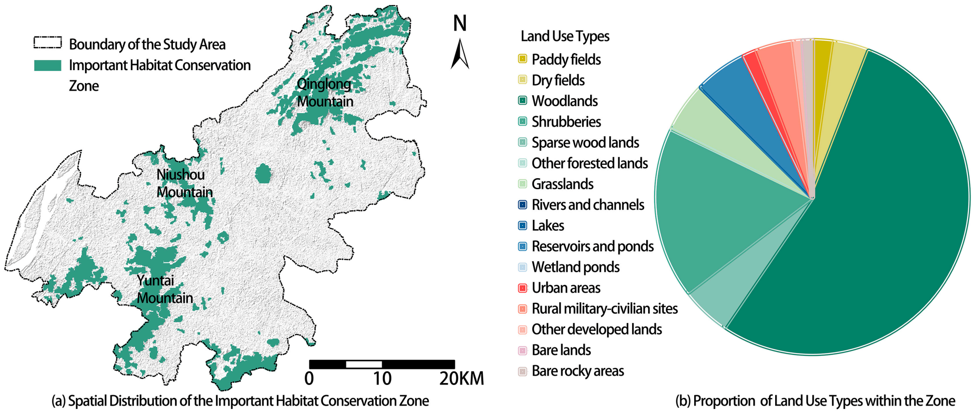


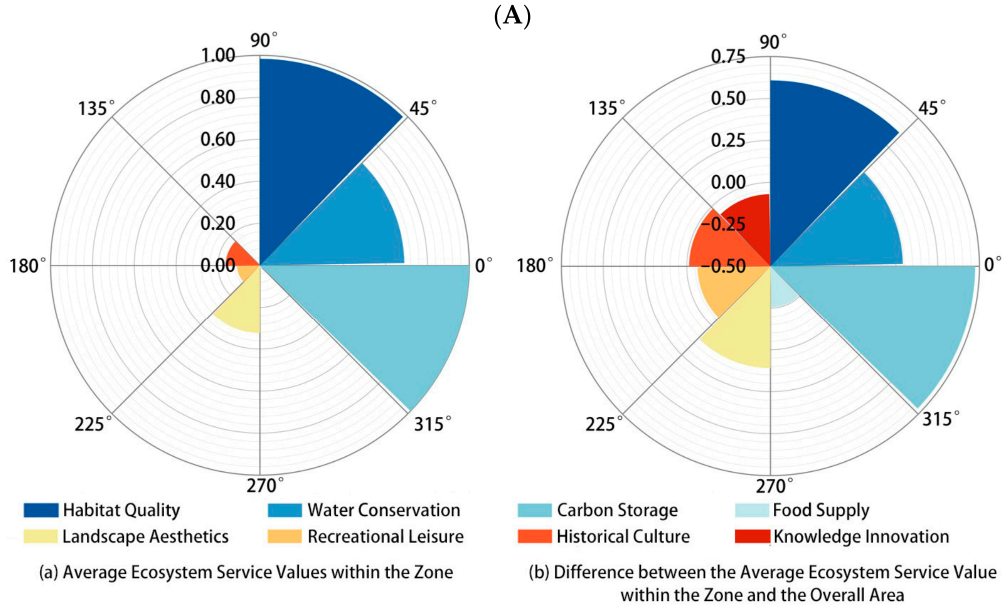
Figure 14. Spatial pattern of the Vibrant Integration Zone of Industry and Urbanization and the distribution of ecosystem service values. (**A**) Spatial distribution of the Vibrant Integration Zone of Industry and Urbanization and land use distribution. (**B**) Average ecosystem service values within the zone and the differences from overall values.

5.2.2. Important Habitat Conservation Zone

The Important Habitat Conservation Zone mainly covers large mountainous and hilly regions, including Qinglong Mountain, Niushou Mountain, and Yuntai Mountain, which are home to diverse habitats and rich vegetation communities (Figure 15A). This area excels in carbon storage, habitat quality, and water conservation, while food supply and knowledge innovation are its weakest value categories (Figure 15B). The zone is the ecological and landscape backbone not only of Jiangning District but of the entire city of Nanjing, underscoring the need to protect carbon sinks and wildlife habitats. It plays a vital role in safeguarding biodiversity and supporting carbon sequestration. However, the presence of numerous fragmented green patches emphasizes the need to balance ecological protection with urban development by establishing an interconnected and multi-functional ecological security network.



(**A**)



(**B**)

Figure 15. Spatial pattern of the Important Habitat Conservation Zone and the distribution of ecosystem service values. (**A**) Spatial distribution of the Important Habitat Conservation Zone and land use distribution. (**B**) Average ecosystem service values within the zone and the differences from overall values.

5.2.3. Livable Organic Renewal Zone

The Livable Organic Renewal Zone is mainly concentrated in densely populated areas, including Dongshan Sub-city, Baijia Lake Central Area, Tangshan New City, and Chunhua New Town (Figure 16A). This zone holds notable social value, particularly in terms of recreational leisure and landscape esthetics. However, its ecological value is significantly lower than that of other zones (Figure 16B). The main contributing factors include the limited availability of large urban parks and green corridors, as well as the lack of systematic protection for fragmented and degraded ecological areas. As an essential space for the daily lives of Jiangning District residents and a flourishing tourism industry, locations with strong geographical advantages—such as waterfront areas, industrial zones, and areas with distinctive landscapes—hold significant potential for redevelopment. There is an urgent need to enhance land use efficiency in these areas, addressing diverse social demands while simultaneously improving overall ecological quality.

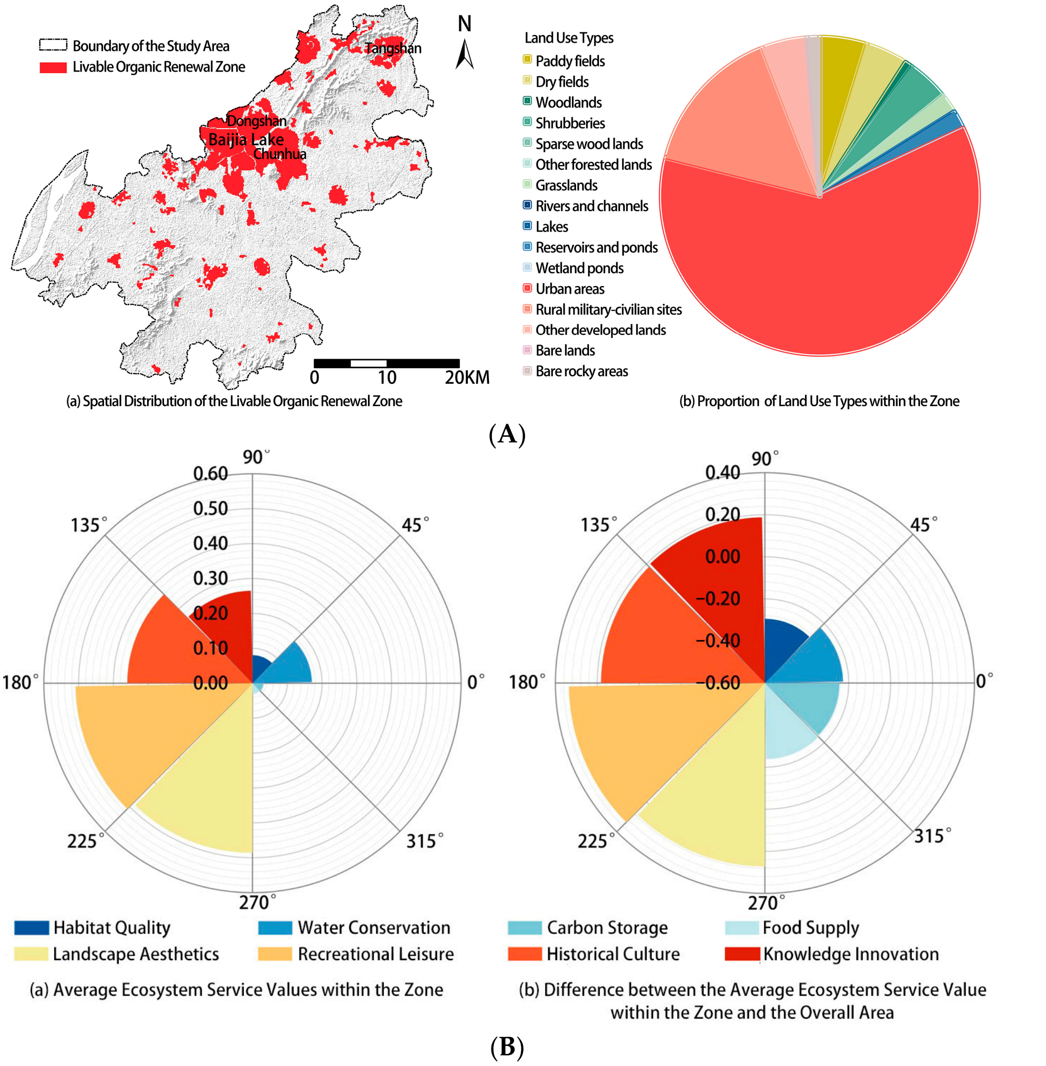


Figure 16. Spatial pattern of the Livable Organic Renewal Zone and the distribution of ecosystem service values. (**A**) Spatial distribution of the Livable Organic Renewal Zone and land use distribution. (**B**) Average ecosystem service values within the zone and the differences from overall values.

5.2.4. Characteristic Rural Landscape Development Zone

The Characteristic Rural Landscape Development Zone spans the eastern, southern, and western parts of Jiangning District, encompassing paddy fields, dry lands, and rural settlements (Figure 17A). While this zone excels in grain production and offers certain water conservation benefits, its other ecosystem services are notably lower (Figure 17B). This underscores how the fragmented and relatively uniform land use patterns in the area constrain the overall potential of ecosystem services. Previous studies have shown that protecting agricultural areas surrounding urban regions is crucial for ensuring food security and promoting urban sustainability [40]. As such, these areas should also be considered in strategic landscape planning. Despite the presence of extensive farmland, countryside parks, and historic towns and villages, the zone struggles with weak social value. Issues such as the uniformity of agricultural landscapes, limited opportunities for rural knowledge engagement, and inadequate protection of cultural heritage are prevalent. Moving forward, it is important to enhance this zone's development by securing food supply and water regulation while also gaining a deeper understanding of natural and public resources. Tailored development strategies can then address the diverse cultural and social needs of local residents.

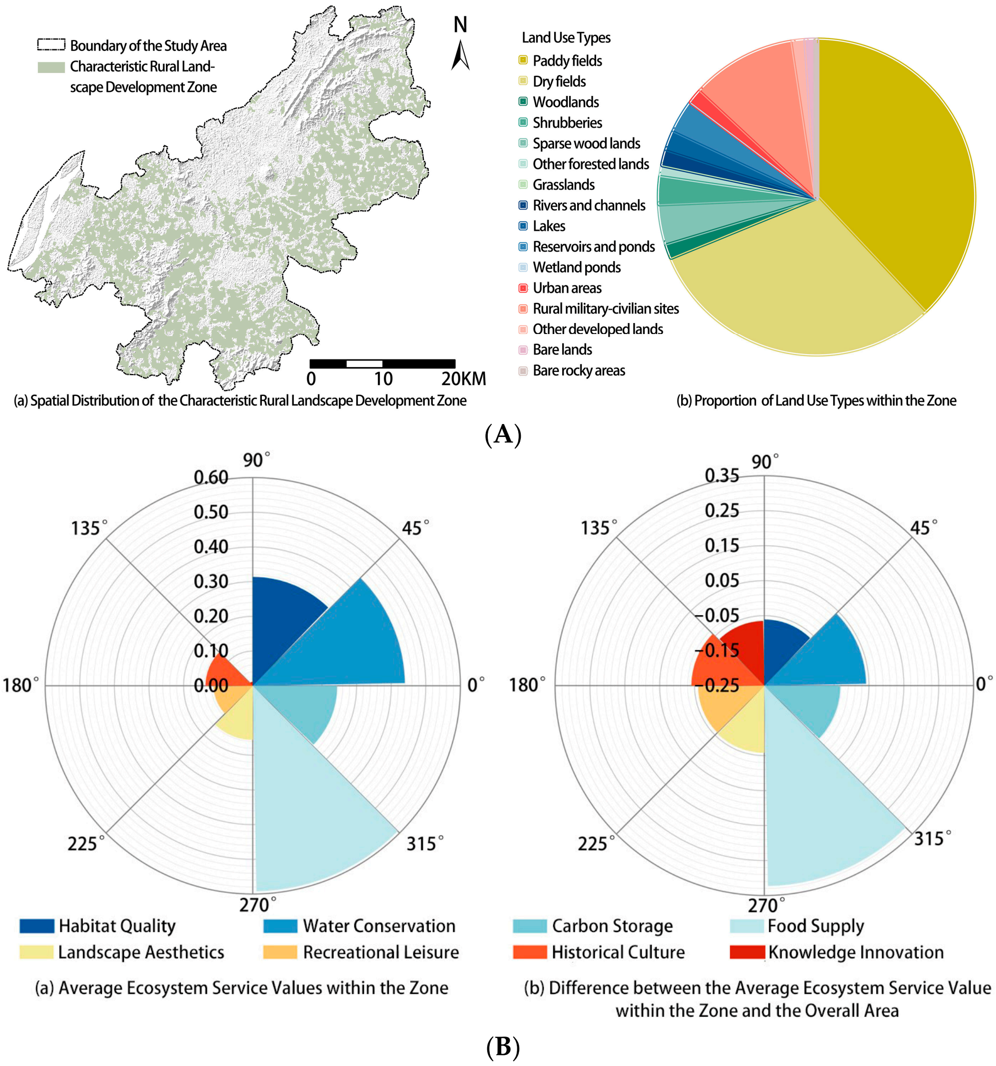


Figure 17. Spatial pattern of the Characteristic Rural Landscape Development Zone and the distribution of ecosystem service values. (**A**) Spatial distribution pattern of the Characteristic Rural Landscape Development Zone and land use distribution. (**B**) Average ecosystem service values within the zone and the differences from overall values.

5.2.5. Riparian Recreation and Ecological Conservation Zone

The Riparian Recreation and Ecological Conservation Zone is located along the Yangtze River and Qinhuai River basins, as well as around key water bodies such as Panlong lake, Jiulong lake, Guli reservoir, and Shecun reservoir (Figure 18A). This zone excels in water conservation and habitat quality but has significant potential for improvement in terms of carbon storage, recreational spaces, and cultural heritage values (Figure 18B). This area plays a crucial role in shaping a cityscape where parks seamlessly blend with water features, while also protecting water-related cultural heritage. However, the current water system suffers from poor connectivity, fragmented green spaces around large lakes and reservoirs, inadequate accessibility, and unevenly distributed waterfront recreational facilities. There is an urgent need to develop an interconnected water network that integrates various basins and supports the healthy evolution of aquatic ecosystems. By implementing flexible management and lenient interventions in waterfront areas, water-related recreational functions can be expanded, fostering the synergy of ecological and social values.

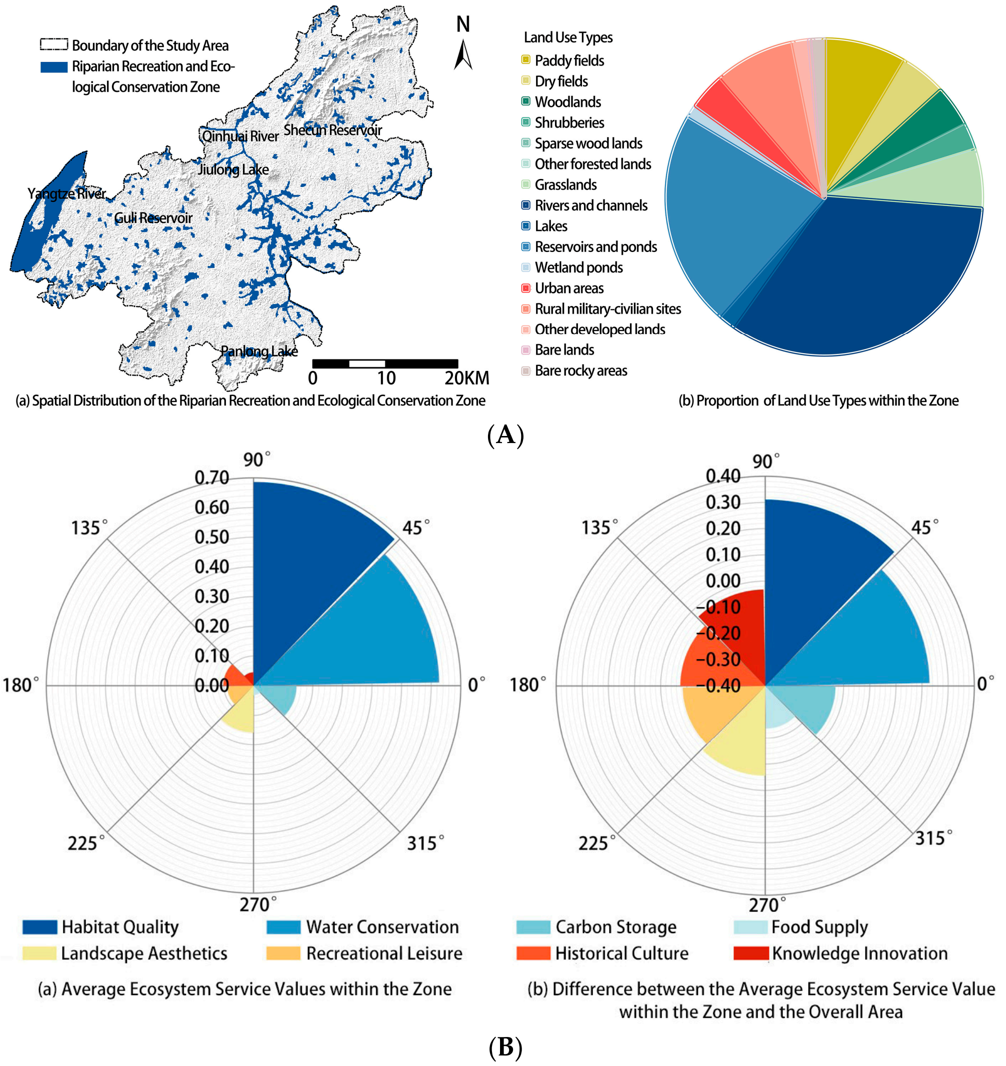


Figure 18. Spatial pattern of the Riparian Recreation And Ecological Conservation Zone and the distribution of ecosystem service values. (**A**) Spatial distribution pattern of the Riparian Recreation And Ecological Conservation Zone and land use distribution. (**B**) Average ecosystem service values within the zone and the differences from overall values.

5.3. Trade-Offs Within Ecological Function Zones in Jiangning District

5.3.1. Comparative Analysis of the Correlation Between Ecological–Social Values of Ecosystem Services Across Zones

The statistical results—in terms of Pearson correlation coefficients across different zones (Figure 19)—show that, within each ecological function zone, ecological and social values generally exhibit a synergistic relationship. However, the relationships between ecological and social values tend to reflect trade-offs. In areas dominated by large expanses of construction land or farmland, the trade-off between ecological and social values is particularly pronounced. Intensive industrial and agricultural practices often neglect landscape diversity, undermining the intrinsic health of ecosystems. Moreover, synergistic effects are more common among social values than among ecological values.

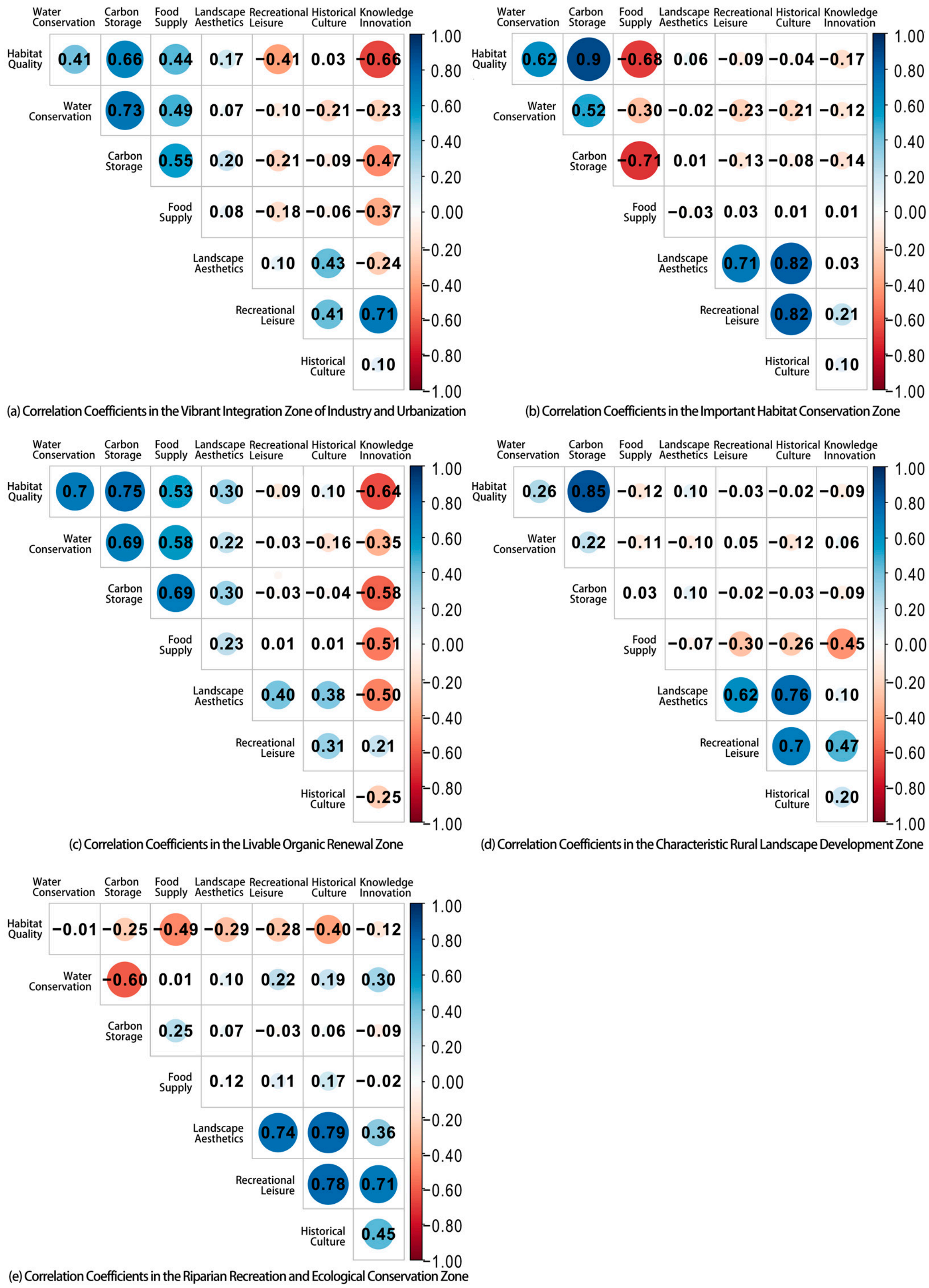


Figure 19. Correlation coefficient matrices of ecological–social values of ecosystem services in the ecological functional zones of Jiangning District.

5.3.2. Comparative Analysis of the Spatial Clustering Characteristics of Comprehensive Ecological–Social Values of Ecosystem Services Across Zones

Based on zoning data, the dominant spatial clusters representing the ecological and social values of ecosystem services within each ecological function zone were identified (Figure 20). Most zones are characterized by clusters that indicate a trade-off between ecological and social values. In the Important Habitat Conservation Zone, the Riparian Recreation and Ecological Conservation Zone, and the Characteristic Rural Landscape Development Zone, clusters with high ecological but low social values are most common.

These areas should prioritize preserving and enhancing spaces of high ecological value while also exploring opportunities to improve non-material benefits, such as natural education and eco-tourism. In contrast, the Livable Organic Renewal Zone is dominated by clusters with low ecological and high social values. Strategies such as controlling visitor numbers and increasing the connectivity of green spaces should be implemented to mitigate the negative environmental impacts of human activities.

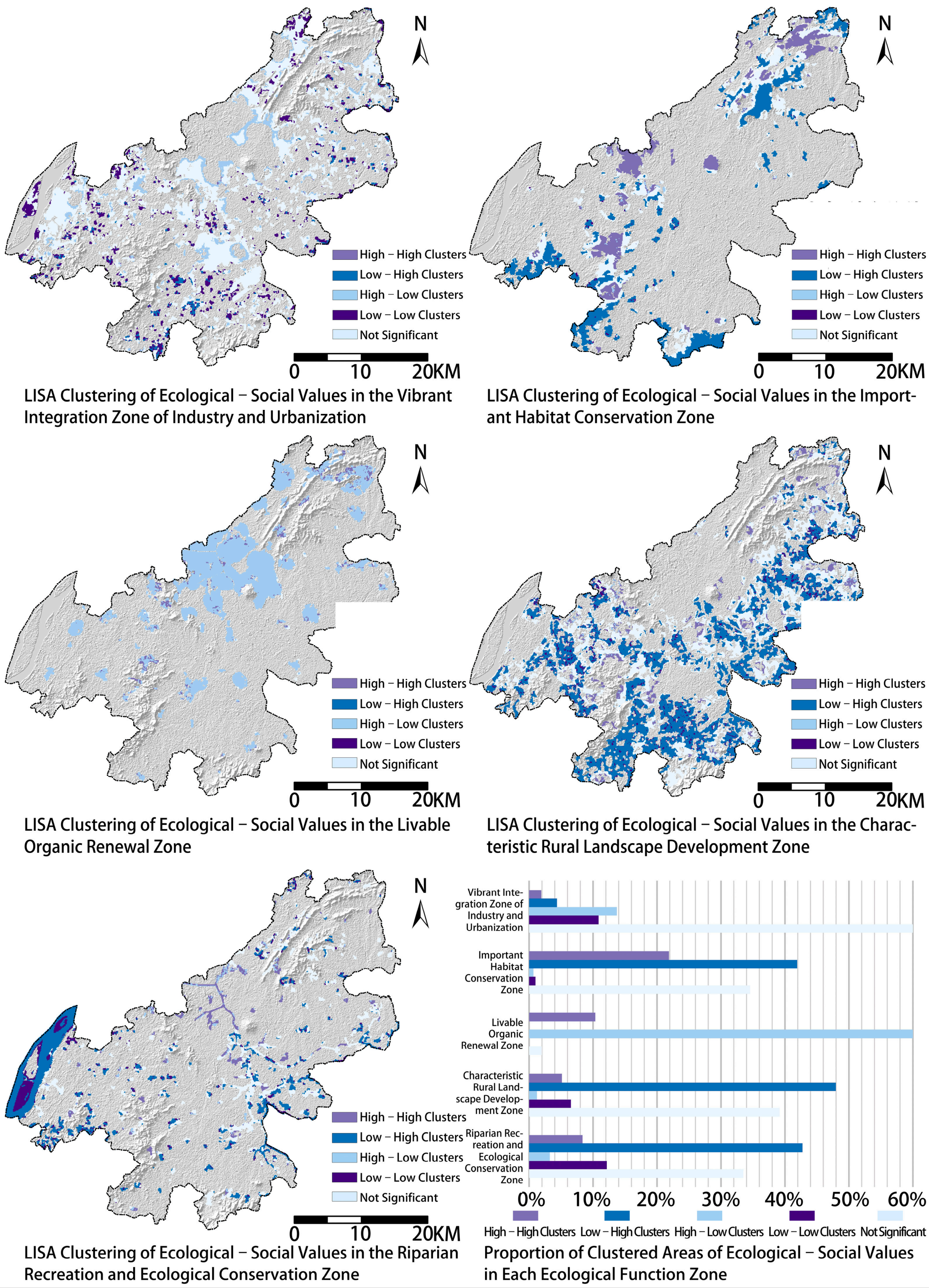


Figure 20. Types and proportions of spatial clusters for ecological–social values within ecological functional zones in Jiangning District.

Meanwhile, clusters representing synergies between ecological and social values are relatively sparse across all zones. Low ecological and low social value clusters are mainly found in areas with poor landscape quality and late-stage ecological restoration efforts, particularly within the Vibrant Integration Zone of Industry and Urbanization and the Riparian Recreation and Ecological Conservation Zone. In these areas, prioritizing the restoration of ecological value is crucial to fostering positive synergies across the region. Conversely, high ecological and high social value clusters are mostly located within the Important Habitat Conservation Zone, where access to both major roads and water bodies is often excellent. This suggests that proximity to infrastructure, along with the integrity and connectivity of ecological structures, are key factors in maximizing ecological–social benefits. Strengthening the management and protection of these green spaces is essential for maintaining this ecological–social synergy.

6. Spatial Optimization Strategy for Ecological Functional Zones in Jiangning District Based on Trade-Off Relationships

This study takes into account the critical environmental issues that need to be addressed during the process of urbanization in Jiangning District, as well as the interactions between ecosystem services and ecological–social values, both in a region-wide manner and within each ecological functional zone. It is proposed that the spatial optimization objective for the ecological functional zones in Jiangning District involves reducing trade-offs and promoting synergistic benefits between ecosystem services and ecological–social values.

In the Vibrant Integration Zone of Production and Urbanization, numerous trade-off relationships exist between ecosystem services and ecological–social values. These are often found in regions with a large spatial concentration characterized by low ecological value and high social value. The direction of spatial optimization involves promoting the green development of industrial spaces while enhancing the synergistic effects of multi-functional spaces. This includes building ecological industrial parks to strengthen the integration of production and environmental sustainability, introducing low-impact development technologies to reduce human interference, and rehabilitating urban public spaces to foster the synergy of social values.

In the Important Habitat Conservation Zone, the main trade-offs occur both within the ecological value group and between ecological and social values; meanwhile, the social values generally align well with each other. In terms of spatial clustering, there is a noticeable pattern of high ecological and low social value clusters. The direction for spatial optimization in this area involves protecting natural resources and ecological structures while enhancing natural esthetics. This includes strictly prohibiting reckless farmland reclamation to safeguard core ecological functions, resolving conflicts between structural elements to maintain ecosystem stability, and utilizing forest landscape resources to create spaces that provide esthetic experiences.

In the Livable Organic Renewal Zone, the main trade-offs occur between ecosystem services and ecological and social values, followed by trade-offs within the social value group. Ecological values tend to be highly compatible, with most areas exhibiting a low ecological and high social value clustering. The direction for spatial optimization in this area involves enhancing the utilization efficiency of existing spaces and improving ecological and environmental quality. This involves expanding green spaces in the old city from various perspectives to increase the supply of ecological values, restoring the ecological network system to ensure the stability of the ecological structure, and promoting the development of multi-functional spaces to diversify the use of existing land.

In the Characteristic Rural Landscape Development Zone, there are notable trade-offs between food supply, water conservation, and social values, with potential conflicts arising among ecological values; however, the compatibility within the social value group is relatively strong. In addition, the spatial clustering mainly exhibits high ecological and low social value areas. The spatial optimization strategy for this zone should focus on promoting the sustainable development of ecological agriculture while preserving the unique local cultural heritage. This involves adjusting diverse planting structures to enhance compound environmental benefits, optimizing the agricultural development area to control the intensity of land development, and revitalizing rural areas with distinctive characteristics, all while advancing cultural development in a targeted manner.

In the Riparian Recreation and Ecological Conservation Zone, trade-offs mainly occur between ecological and social values and within the ecological value group. Water conservation and social values, as well as the social value group, exhibit a high degree of compatibility. Spatially, this is mainly reflected in a high ecological and low social value cluster. The direction for spatial optimization in this area involves protecting the intrinsic health of the water ecosystem while cautiously expanding leisure industries. This involves ecological restoration of nearshore areas to preserve the water system's intrinsic health, adjusting and optimizing structural components to minimize the impacts of human activities, and flexibly managing waterfront spaces to support moderate tourism and sightseeing development.

7. Conclusions

Urban fringe areas play a critical role in coordinating land resources and fostering urban–rural integration, acting as sensitive zones where natural environments and human societies often intersect. Addressing pressing issues such as the decline in ecosystem functions, the rising demand for high-quality urban–rural development, and the increasing contradictions in ecosystem service values, this study investigated a method for delineating ecological function zones, focusing on the trade-offs between ecological–social values in ecosystem services. Moreover, it clarified how these values interact as we move from a broader spatial context to more localized zones.

The findings indicated that the trade-off relationships between ecological and social values are widespread in urban fringe areas, being observable at both regional and zonal levels. Based on the ecosystem service clustering results, Jiangning District was categorized into five ecological function zones: the Vibrant Integration Zone of Industry and Urbanization, Important Habitat Conservation Zone, Livable Organic Renewal Zone, Characteristic Rural Landscape Development Zone, and Riparian Recreation and Ecological Conservation Zone. Each of these zones exhibited significant differences in terms of the types and characteristics of the service values that they provide. Resolving the trade-offs between ecological and social values requires a deeper understanding of the varying relationships within the zones, necessitating the development of tailored and refined ecological management strategies to foster mutual benefits between ecosystems and living environments.

A comprehensive understanding of the complex interactions between ecosystem service values and social–ecological contexts is crucial for achieving multi-functional development goals in urban fringe areas. This study goes beyond a single perspective on ecological function zoning in these areas, clarifying the trade-offs between ecological and social values of ecosystem services across the overall spatial landscape of urban fringe areas. Based on the identification of ecosystem service clusters, ecological function zones were delineated, and an analysis of the trade-offs within each zone and their spatial differentiation characteristics was conducted. A systematic, progressive trade-off analysis framework was constructed, advancing from whole-area spatial assessment to sub-regional zones. This analytical framework is versatile and applicable to zoning management practices in other urban fringe areas with diverse ecological characteristics and complex urban–rural functions, particularly when aiming to mitigate trade-offs and enhance synergies. However, adjustments to the parameters and zoning types may be necessary to address the specific ecological, social, and management needs of each area.

Future research should further refine the study of ecological function zoning in urban fringe areas by optimizing the ecosystem service value assessment models, analyzing factors that influence trade-off relationships, and exploring the value perceptions and preferences of different stakeholders. This will promote ecological balance and enhance collaborative value in urban fringe ecosystems. In particular, incorporating the perspectives of diverse stakeholders—such as the government, the public, and businesses—through interviews, surveys, and consultative mechanisms will allow for an in-depth analysis of their positions, needs, and decision-making influence in the ecological–social value trade-offs of ecosystem services. This enhances the practical applicability of ecological zoning, thereby increasing its external validity.

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