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Ecological Importance Evaluation and Ecological Function Zoning of Yanshan-Taihang Mountain Area of Hebei Province

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Abstract: Ecological importance evaluation can clearly identify the ecological service functions and ecological values of a region. This paper takes the Yanshan-Taihang Mountain area in Hebei Province as the research area, utilizing 2020 land use data. With the help of various analytical models and GIS spatial analysis methods, this paper selects water conservation, soil and water conservation, biodiversity, carbon sequestration and oxygen release to evaluate the importance of ecosystem services, and selects soil and water loss sensitivity and land desertification sensitivity to evaluate the ecological sensitivity, so as to identify the important areas of ecological protection in the study area, analyze their spatial change characteristics and divide the leading ecological functions according to the results. The results show that the moderately important and highly important areas in the Yanshan-Taihang region of Hebei Province account for more than 70% of the total study area. Based on the importance evaluation results, three types of dominant ecological function zones were obtained using self-organized feature mapping neural network analysis in the R language, and control measures were proposed. The research results can provide strategic support for local ecological protection and regional ecological restoration, as well as serving as a reference for the optimization of land spatial development patterns.

Keywords: Yanshan-Taihang; mountain region; Hebei province; ecosystem services; ecological sensitivity; ecological importance evaluation; self-organizing map; neural network

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1. Introduction

Ecological significance signifies the importance of an area for the maintenance of regional ecological security, and the essence of its evaluation is to spatially identify important areas for ecological protection [1]. Ecological importance assessment is based on natural ecological theory and aims at identifying areas of high ecosystem service importance and high ecological vulnerability [2,3]. It is the first task of evaluating the carrying capacity of resources and the environment and the suitability of territorial space development, as well as a prerequisite for identifying production and living space [4,5].

The introduction of a series of documents related to the construction of ecological civilization [6], such as the 13th Five-Year Plan for Ecological Environmental Protection and the 14th Five-Year Plan for Ecological Environmental Protection, reflects the importance of the construction of ecological protection and the positioning of future development. In recent years, the concepts of "two mountains" and "beautiful China" have been deeply rooted in people's minds, and the status of ecological civilization construction has been constantly raised [7]. In the process of ecological civilization construction, scientific ecological

management tools and methods such as ecological importance evaluation and ecological function zoning provide strong support [8]. At present, the ecological management of some regions exists as a "separate" situation. The lack of coordination and unity in ecological zoning systems [9], and how to plan ecological functional zones according to the characteristics of the regional ecological environment, need to be solved in order to coordinate the contradictions between society, the economy and the environment, to enhance the ecological environment and to promote sustainable development.

At present, most of the studies on the importance evaluation of ecological protection abroad adopt the protected land system concept, which is quite different from what is considered in domestic studies [10,11]. In China, the evaluation of ecological importance is mainly studied from two angles [12]: First, the ecological importance and its spatial distribution characteristics of a certain region are studied, and on this basis, the relationship between ecosystem service function and ecological sensitivity indicators is explored [13]. Second, more scholars use the evaluation results of ecological protection importance to carry out related research such as the division of leading ecological functional areas [14], the delineation of ecological space [15], the construction of ecological security patterns [16] and the delineation of the ecological protection red line [17], aiming at rationally planning ecological space, protecting key areas of ecological functions and then maintaining the integrity of the ecosystem. For example, Gao Mengyao et al. took Zhaotong, a mountainous city in southwest China, as their study area. The researchers coupled habitat quality and landscape pattern vulnerability to divide the study area into three types of ecological functional zones, and put forward suggestions for future development of different ecological zones [18]. These research methods mostly focus on the comprehensive index method [19], maximum method, coefficient of variation method and limit condition method. Reviewing the development trajectory of the evaluation of the importance of ecological protection not only highlights the deepening of mankind's knowledge of the natural environmental system, but also reveals the complex interactions and linkages between human–land relations, human behaviors and the goal of sustainable development [20].

The Yanshan-Taihang region of Hebei Province is an important ecological barrier and water-shedding area in China. The region has a special geographic location, including mountains, plateaus, hills, plains and other landforms, with obvious climatic and topographic diversity [21,22]. This area is an important water conservational area of the Haihe and Luanhe rivers, and is an important water source and sandstorm source control area in Beijing and Tianjin. As an important ecological barrier in Hebei Province, the Yanshan-Taihang region has rich ecological functions, and its ecological health is crucial to the regional ecological environment and socioeconomic development. Due to the over-reliance of economic growth on the development of natural resources and the neglect of ecological environmental protection, the ecological problems in the region have become increasingly serious, with a frequent occurrence of soil erosion, water resource shortages and destruction of vegetation, which have limited the potential for sustainable development of the regional economy. Therefore, regional ecological management work is urgently needed to cope with these challenges. Carrying out the evaluation of the importance of ecological protection in the Yanshan-Taihang Mountains in Hebei Province can clarify the ecological service function and ecological value of the region, reflect the sensitivity of the ecological environment and provide a comprehensive understanding of the ecological environment status of the region. Identifying the importance of ecosystems, zoning ecological functions and proposing targeted ecosystem management measures to promote the differentiated management and control of ecosystem services in the Yanshan-Taihang region of Hebei Province are important for the construction of an ecological security barrier between Beijing, Tianjin and Hebei.

2. Materials and Methods

2.1. Overview of the Study Area

The Yanshan-Taihang region of Hebei Province includes 22 counties in the cities ofBaoding, Zhangjiakou and Chengde, with a land area of about 2541.2 km^2, This area belongs to the transition zone from the Inner Mongolia Plateau and Loess Plateau to the North China Plain. It has varied topography and geomorphology and is rich in ecological resources such as forests, wetlands and grasslands. Key ecological construction tasks have taken place in this region, such as the construction of the Three North Protective Forests, greening of the Taihang Mountain Range, returning farmland to forests and pastures to grasslands, sand control and prevention and the restoration of wetlands. The study area is located in the temperate continental monsoon area. The study area is located in the temperate continental monsoon climate zone, with high terrain in the northwest and low terrain in the southeast (as shown in Figure 1). In Baoding City, there are the following counties: Laishui County, Fuping County, Tang County, Laiyuan County, Wangdu County, Yixian County, Quyang County and Shunping County; in Zhangjiakou City, there are Xuanhua County, Zhangbei County, Kangbao County, Guyuan County, Shangyi County, Weixian County, Yangyuan County, Huai'an County and Wanquan County; finally, in Chengde City, there are Chengde County, Pingquan County, Longhua County, Fengning Manchu Autonomous County and Kancheng Manchu Autonomous County. There are important ecosystem service functions and typical ecological and environmental problems in the study area, which, together with the advantage of the region's unique location nearby the synergistic development of the greater Beijing–Tianjin–Hebei region, makes the Hebei Yanshan-Taihang region one of the most important areas for ecological construction in the Beijing–Tianjin–Hebei region.

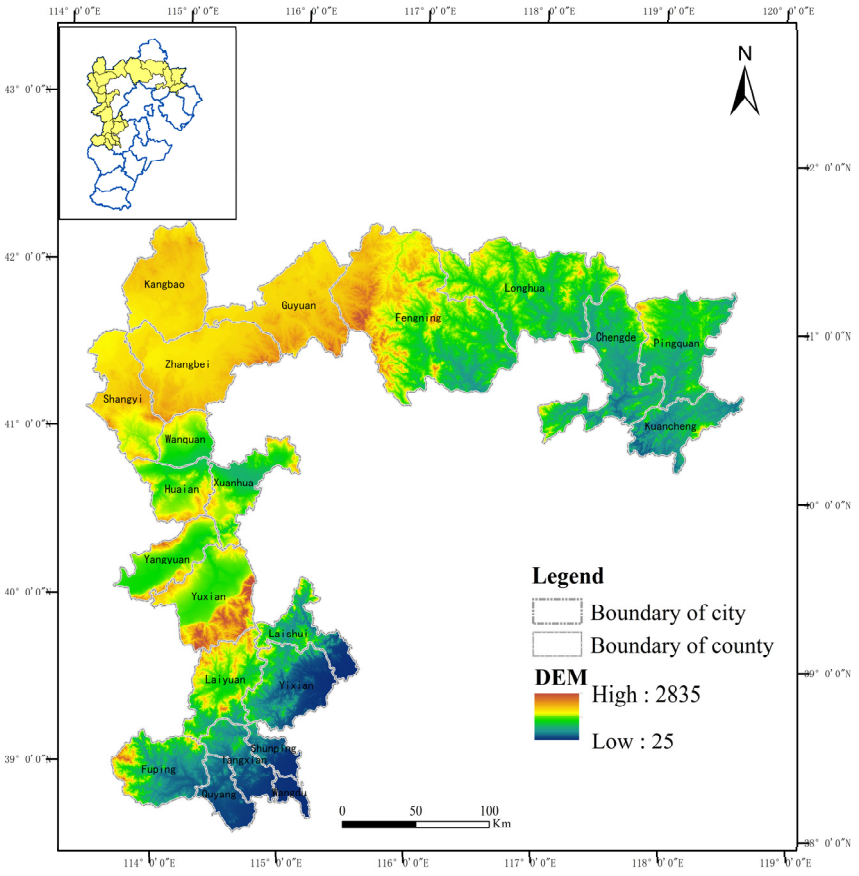


Figure 1. Overview of the study area.

2.2. Data Sources and Access

The data in this paper mainly include normalized vegetation index, meteorological data, elevation data, soil data and administrative division data. In ArcGIS (10.7), the data were projected to 1984 coordinates (WGS_1984_UTM_Zone_50N) and resampled to 1 km spatial resolution.

Among them, the current land use data in 2020 were selected, and the land use data were classified into six types, namely, cropland, forest land, grassland, watershed, construction land and unutilized land. With reference to the classification system from the remote sensing monitoring of land use of the Chinese Academy of Sciences (CAS) and combined with the actual situation, the data were processed and calculated using the InVEST(3.13.0) model. DEM data were obtained from Geospatial Data Cloud (http://www.gscloud.cn/). NDVI data were obtained from MOD13 product (https://ladsweb.modaps.eosdis.nasa.gov). Meteorological data were obtained from the National Earth System Science Data Center (http:/hvww.geodata.cn/), including temperature and rainfall. Soil data were obtained from the China Soil Dataset (http:/westdc.estgisac.cn/) in the World Soil Database (HWSD).

2.3. Research Methods

This study assesses the importance of ecological conservation based on the importance of ecosystem service functions and ecological sensitivity. The evaluation of the importance of ecosystem service function and ecological sensitivity took 22 counties and districts as evaluation units with 2020 as the reference period, comprehensively considering the actual situation of the Yanshan-Taihang Mountain in Hebei Province, referring to relevant documents such as Main Function Zoning of Hebei Province, 14th Five-Year Plan for Building Beijing–Tianjin–Hebei Ecological Environment Supporting Area in Hebei Province, 14th Five-Year Plan for Ecological Environment Protection in Hebei Province, etc. Finally, it was determined that ecosystem service function would be evaluated from water conservation, soil and water conservation, biodiversity maintenance, carbon sequestration and oxygen release, and ecological sensitivity would be evaluated from two aspects, i.e., soil erosion and land desertification. The InVEST model and model evaluation method were adopted in the evaluation process, and each evaluation index was normalized to 0~1 for calculation. Finally, according to the method of natural discontinuity, the importance of ecosystem service function was divided into five grades: extremely important, highly important, highly important, moderately important and generally important, and the ecological sensitivity was divided into five grades: low sensitivity, generally sensitive, moderately sensitive, highly sensitive and extremely sensitive. The evaluation results were divided into functional areas by SOM cluster analysis.

2.3.1. Ecosystem Services Assessment

Importance assessment of ecosystem services refers to the process of evaluating the value of various services provided by ecosystems in specific regions. The assessment can reflect the importance of various services provided by ecosystems to human society and the natural environment, and reveal the weak links of ecosystem services, so as to take corresponding protection and restoration measures and promote more sustainable and effective natural resource management and environmental protection.

1. Water Conservation

Water conservation was assessed according to the water yield module of the InVEST (3.13.0) model. This module is based on the water balance estimation method proposed by Fu [23] and Zhang [24], and calculates the water yield in the study area by integrating factors such as annual precipitation, plant available water (PAWC), land use type and the maximum root burial depth of soil. The specific formula is as follows:

$$Y_{Xj} = [\vdash (AET_{xi}/P_x)] \times Px \quad (1)$$

$$AET_{xj}/P_X = \left(1 + W_x \times R_{xj}\right)/\left(1 + W_x \times R_{xj} + 1/R_{xj}\right) \quad (2)$$

$$R_{xj=}(K \times ET_0)/P_x \quad (3)$$

$$W_x = Z \times (AWC_x/P_x) \quad (4)$$

In the formula, Y_{xj} is the annual water production of land use type j on grid x (mm); P_x is the annual rainfall of grid unit x (mm); AET_{xj} is the annual actual evapotranspiration (mm) of land use type j on grid x; R_{xj} is the dryness index; K is the coefficient of evapotranspiration; ET_0 is the potential evapotranspiration; W_x is a non-physical parameter; Z is the Zhang coefficient, and based on the actual situation in the research area, the value of Z in this article is 1.5; AWC_x is the effective available water for vegetation (mm).

2. Soil conservation

Soil conservation was calculated based on the modified general soil loss equation (RUSLE) [25]. Soil conservation is the difference between potential soil erosion and actual soil erosion [26]. Soil erosion is influenced by various factors, including rainfall conditions, soil properties, plant cover, terrain and even cultivation patterns. Using soil erosion models to account for existing conditions can be used to monitor soil erosion and prevent land degradation. The specific formula is as follows:

$$A = Ap - Ar = R \times K \times L \times S \times (1 - C \times P) \quad (5)$$

where A is the amount of soil and water conservation (t/hm a); Ap is the potential amount of soil erosion; Ar is the actual amount of soil erosion; R is the rainfall erosivity factor (MJ·mm/hm^2·h.a); K is the soil erodibility factor (t·hm^2·h/hm^2·MJ·mm); L and S are topographic factors, where L represents slope length factor and S represents slope factor; C is vegetation cover factor; P is the factor of soil and water conservation measures.

3. Biodiversity conservation

Biodiversity conservation is the foundation and guarantee for ecosystem services. Biodiversity maintenance is one of the most important functions provided by ecosystems. Therefore, this paper mainly calculates the habitat quality index [27] based on the habitat quality module of the InVEST (3.13.0) model, so as to reflect the function of providing biodiversity services (the InVEST model assumes that areas with good habitat quality have high biodiversity). The specific formula is as follows [28]:

$$Qxj = Hj\left\{1 - \left[D_{xj}^z/\left(D_{xj}^z + K^z\right)\right]\right\} \quad (6)$$

where Qxj is the habitat quality of grid x in LULC (land use type) type j; D_{xj} is the stress level of grid x in LULC type j; H_j represents the habitat suitability of LULC type j; K is the semi-saturation parameter—the value in this paper is 0.05, and the value of Z is 1.5. Referring to the official manual of the InVEST (3.13.0) model, the maximum impact distance, weight and sensitivity of threat factors of each land use type are assigned.

4. Carbon fixation and oxygen release

Carbon fixation and oxygen release were calculated using the carbon storage module in the InVEST (3.13.0) model. This module can reflect the relationship between land use change and carbon storage, and divide the carbon storage of the ecosystem into four basic carbon pools: aboveground biological carbon, underground biological carbon, soil carbon and dead organic carbon [29]. According to the stocks of the four carbon pools, the current carbon storage or carbon sequestration with time can be estimated. The specific formula is as follows [30,31]:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (7)$$

Among them, C_{above} is aboveground carbon storage, C_{below} underground carbon storage, C_{soi1} is soil carbon storage and C_{dead} is dead organic carbon storage.

The following table shows Carbon storage parameters for carbon sequestration and oxygen release services.

Land Use Type	Cabove	Cbelow	Csoil	Cdead
Cultivated land	18.873	12.457	86.759	2.41
Woodland	36.339	7.268	120.758	3.354
Grassland	17.374	20.849	105.847	2.94
Waters	0	0	81.1	0
Subcategory of construction land	16.153	3.321	72.92	0
Unutilized land	0	0	0	0

2.3.2. Ecological Sensitivity Evaluation

Ecological sensitivity assessment can assess the potential risks and vulnerabilities of specific areas or activities to ecosystems. According to the characteristics and current situation of the ecosystem in the study area, soil erosion and land desertification were selected to evaluate and analyze the regional ecological sensitivity.

1. Soil and Water Loss

Based on the Guidelines for Delimitation of Ecological Protection Red Line issued by the Ministry of Environmental Protection in 2017 [32], we conducted a sensitivity evaluation of soil erosion, and selected indicators such as rainfall erosivity, soil erodibility, slope gradient and length and vegetation coverage based on the basic principles of the general soil erosion equation. The single factor evaluation results reflecting the sensitivity of various factors to soil erosion will be multiplied using geographic information system technology, and the formula is as follows:

$$SS_i = \sqrt[4]{R_i \times K_i \times LS_i \times C_i} \quad (8)$$

where SS_i is the sensitivity index of soil and water loss; R_i is rainfall erosivity; K_i is soil erodibility; LS_i is the slope length and gradient; C_i is vegetation coverage. Among them, the calculation methods of R_i, K_i and LS_i are consistent with those of soil and water conservation services.

2. Land desertification

Sensitivity of land desertification refers to the possibility of land desertification under natural conditions [33]. Sensitivity evaluation of land desertification is to identify areas prone to desertification and evaluate the sensitivity of desertification to human activities [34]. Based on the Guidelines for the Delimitation of Ecological Protection Red Line, indicators such as dryness index, sandstorm days, soil texture and vegetation coverage are selected. Using the spatial analysis function of geographic information systems, we multiplied the results of each single factor calculation to obtain the evaluation results of land desertification sensitivity in the study area.

$$Di = \sqrt[4]{Ii \times Wi \times Ci \times Ki} \quad (9)$$

In the formula, Di is the sensitivity index of evaluating regional land desertification; Ii, Wi, Ki and Ci are the sensitivity grade values of the evaluation area dryness index, sandstorm days, soil texture and vegetation coverage respectively.

2.3.3. Comprehensive Evaluation of the Importance of Ecological Protection

Based on the evaluation results of each single index, the CRITIC method is used to give weights to all indexes in the importance and ecological sensitivity of ecosystem services [35] (Table 1), and the ecosystem service importance score (*ESI*) and ecological sensitivity score (*ES*) were calculated separately. The calculation process is as follows: (10) and (11). Finally,

the comprehensive score of ecological protection importance was calculated by means of the limit condition method (Formula (12)). The importance of ecological protection was divided into five grades using the natural discontinuity method.

$$ESI = \sum_{i=1}^{4} Ai \times Wi \quad (10)$$

$$ES = \sum_{j=1}^{2} Cj \times Wj \quad (11)$$

$$EI = MAX\{ESI, ES\} \quad (12)$$

Table 1. Weight of evaluation index of ecological protection importance in Yanshan-Taihang Mountains, Hebei Province.

Factor Layer	Indicator Layer	Weight
Importance of ecosystem services	Water conservation	0.18
	Carbon fixation and oxygen release	0.23
	Soil and water conservation	0.38
	Biodiversity conservation	0.21
Ecological sensitivity	Soil and water loss	0.47
	Land desertification	0.53

2.3.4. Dominant Ecological Function Zoning

A self-organizing map (SOM) is an unsupervised artificial neural network [36] which simulates the connection mode of neurons in human cerebral cortex and generates a low-dimensional and discrete map by learning the data in the input space, which can be used for clustering analysis. Compared with traditional clustering algorithms, this algorithm has a stronger nonlinear modeling ability and adaptability [37]. By analyzing the results of SOM network training, the similarity between nodes can be divided into multiple clustering results, each representing an ecosystem service group with spatial and functional similarities. This article extracted data on six evaluation indicators that were extremely important or sensitive in the 22 counties and districts in the research area. Using the "Kohonen" software package in the R language (4.3.3), the data were first preprocessed. The scale function was used to adjust the mean of each variable to 0 and the standard deviation to 1 for Z-score standardization in order to eliminate the influence of dimensionality. Among them, determining the number of X and Y dimensions and topology types was the shutdown step of the recognition process. The number of X and Y dimensions is the final number of clusters. According to the research situation in this article, the number of X dimensions was set to 1 and the number of Y dimensions was set to 3, so that the final number of clusters was 3 types. Based on the above parameters, we identified and obtained the final clustering results and displayed the spatial zoning in ArcGIS (10.7).

3. Results

3.1. Spatial Distribution Difference of Ecosystem Services

The importance of water conservation shows a spatial distribution state of high in the east and low in the west (as shown in Figure 2a). The extremely important and highly important areas were 7878 km^2 and 11,327 km^2, respectively, accounting for 13.39% and 19.26% of the total study area (as shown in Table 2), respectively. These were mainly in Guyuan County, Fengning Manchu Autonomous County, Longhua County and Chengde County in the north; Heping Spring County in the south of Yuxian County; Wangdu County, Shunping County, Quyang County and Yixian County in the south and Laishui County in the southeast. Most of these areas are located in the Yanshan water conservation functional

area, with high annual precipitation, including the Wangkuai and Xidayang reservoirs, which play an important role in maintaining regional water quality and water conservation.

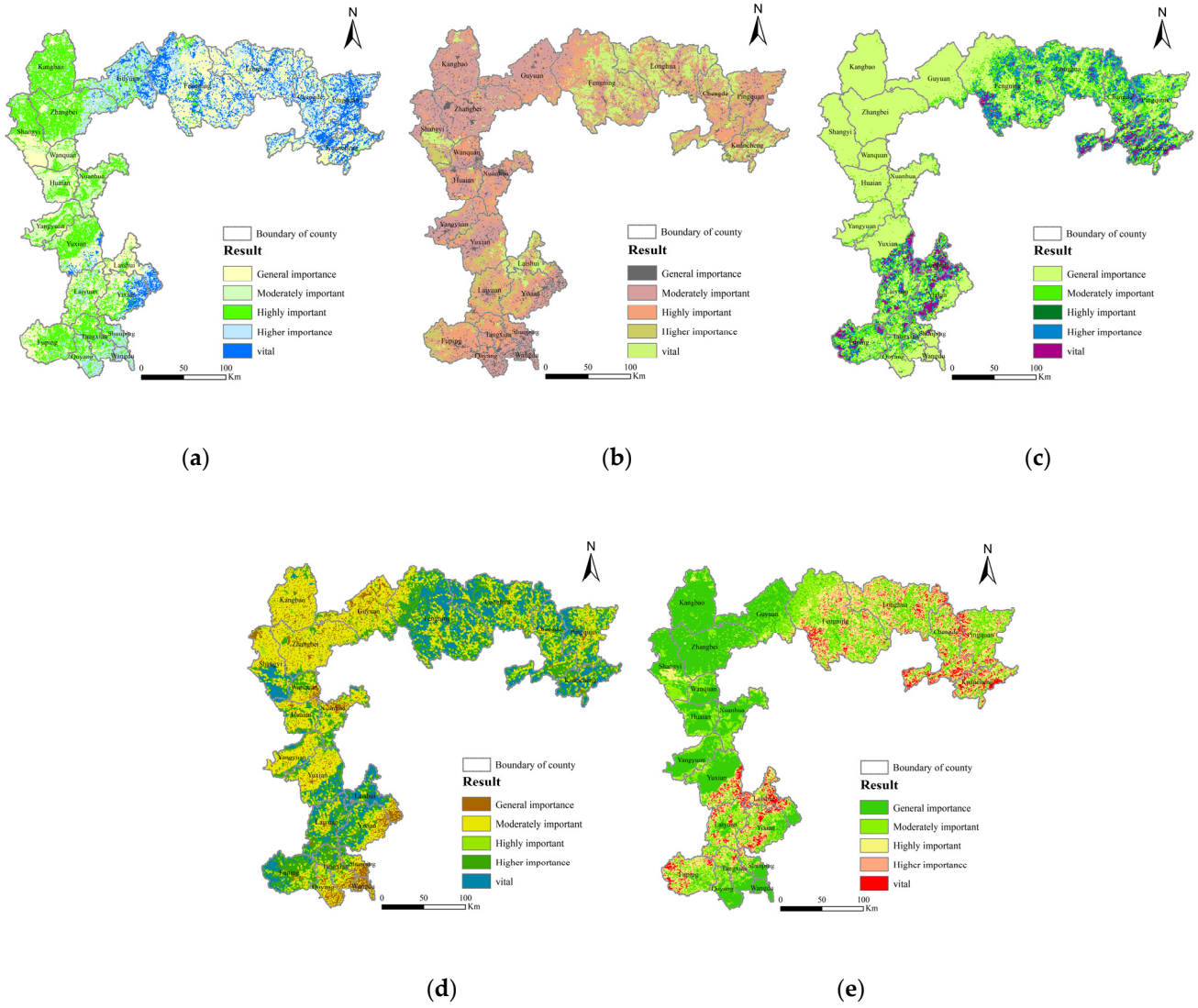


Figure 2. Group diagram of ecosystem service evaluation results. In the figure, (**a**) represents the evaluation result of water source conservation; (**b**) is the evaluation result of carbon fixation and oxygen release; (**c**) is the result of soil conservation evaluation; (**d**) is the evaluation result of biodiversity conservation and (**e**) shows the evaluation results of the importance of ecosystem service functions.

The evaluation results of the importance of carbon sequestration and oxygen release show that the eastern Yanshan Mountain and the southern Taihang Mountain are high in importance, while the intersection of the Yanshan and Taihang mountains is obviously low (as shown in Figure 2b) and has strong spatial heterogeneity (non-uniformity and complexity in spatial distribution). The extremely important and highly important areas were 8361 km^2 and 8142 km^2, respectively, accounting for 14.15% and 13.78% of the total study area (as shown in Table 2). The extremely important areas are mainly distributed in Fengning Manchu Autonomous County, Longhua County, Kuancheng Manchu Autonomous County, Laishui County and the south of Shangyi County, while the highly important areas are mainly distributed in Laiyuan County, Pingquan County, the south of Yuxian County, the southwest of Shangyi County and the west of Fuping County. These areas have a large range of forested land and shrub land, which is of great significance

for regulating climate and maintaining and balancing the stability of carbon dioxide and oxygen in the atmosphere.

Table 2. List of importance rating results of ecosystem service functions.

	Water Conservation		Carbon Fixation and Oxygen Release		Soil and Water Conservation		Biodiversity Conservation		Ecosystem Service Function Score	
	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
General importance	18,396.31	31.45%	3120.34	5.31%	34,773.55	60.33%	4948.16	8.42%	22,274.77	38.27%
Moderately important	6077.32	10.39%	23,223.20	39.52%	12,105.71	21.00%	22,006.80	37.46%	15,377.14	26.42%
Higher importance	15,141.11	25.88%	15,963.39	27.17%	7481.01	12.98%	6349.71	10.81%	10,624.55	18.26%
Highly important	11,150.13	19.06%	8049.53	13.70%	2757.11	4.78%	13,240.27	22.54%	6454.05	11.09%
Very important	7732.30	13.22%	8402.33	14.30%	516.86	0.90%	12,207.68	20.78%	3467.50	5.96%
Total	58,497.17	100%	58,758.79	100%	57,634.24	100%	58,752.62	100%	58,198.01	100%

Soil and water conservation services are high in the south of Taihang and east of the Yanshan Mountains (as shown in Figure 2c). The proportion of moderately important and highly important areas is relatively high, while the proportion of highly important and extremely important areas is relatively low, among which moderately important and highly important areas account for 34.52% of the total study area, and highly important and extremely important areas account for 5.78% of the total study area (as shown in Table 2). The extremely important areas are mainly distributed in Laishui County, Yixian County and Fuping County. Because of the great intervention of human beings on soil erosion, attention should be paid to soil and water conservation and control measures in the future. The results show that the importance of soil and water conservation in these places follows a good trend.

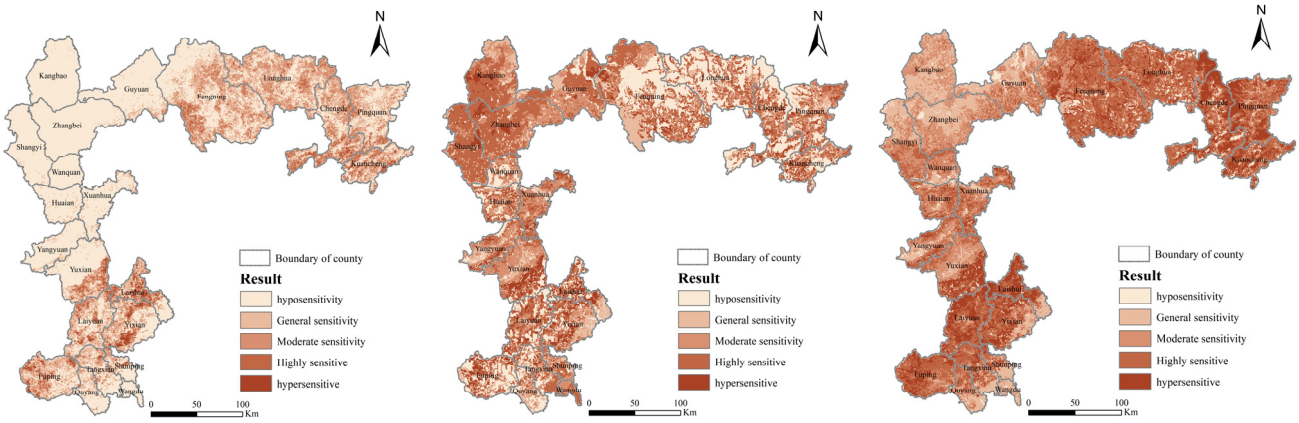
The function of the biodiversity maintenance service shows a similar spatial distribution to that of the carbon sequestration and oxygen release service, which is higher in eastern Yanshan Mountain and southern Taihang Mountain (as shown in Figure 2d). It can be seen from the figure that the extremely important areas are scattered and relatively concentrated in the northwest of Fengning Manchu Autonomous County, Laiyuan County, Laishui County, Yixian County, Tangxian County and Fuping County, accounting for 20.65% of the total study area (as shown in Table 2). Most of the extremely important high-value areas have national scenic spots or national forest parks, such as Baishi Mountain Scenic Area and Gubeiyue National Forest Park, whose overall ecological structure is relatively stable, and whose soil fertility is relatively high. Most of the heigher areas fall around the extremely important areas, and also show scattered distribution, accounting for 22.54% of the total study area.

Most ecosystem services are rated as generally or moderately important, covering 64.69% of the study area (as shown in Figure 2e). Among them, the generally important parts are concentrated in Zhangjiakou City of Yanshan-Taihang Mountain in Hebei Province, and the extremely important, highly important and highly important parts are scattered in Baoding City and Chengde City as a whole. The distribution characteristics are basically similar to those of the mountains in Baoding City and Chengde City, and most of them are located in low mountains and hills or basin marginal areas. The mountain area accounts for a relatively large proportion. Because of its high-density vegetation coverage, abundant water resources and biodiversity, the importance level of ecosystem services in the region is higher. It is of great significance to maintain the stability of the ecosystem in the Beijing–Tianjin–Hebei region.

3.2. Spatial Distribution Difference of Ecological Sensitivity

The sensitivity of soil erosion is scattered (Figure 3a), and highly sensitive and extremely sensitive areas are concentrated in the east and south of the study area, accounting for 47.05% of the total study area (as shown in Table 3), mainly distributed in Fengning Manchu Autonomous County, Longhua County, Chengde County, Pingquan County and Kuancheng Manchu Autonomous County in the east of Yanshan Mountains and Laishui

County, Laiyuan County, Fuping County, Yixian County and Tangxian County in the south of Taihang Mountains. These regions are mostly located in low mountain and low hilly areas, with staggered peaks, large terrain fluctuations and heavy rainfall, which are prone to soil erosion.



(**a**) (**b**) (**c**)

Figure 3. Group map of ecological sensitivity evaluation results. In the figure, (**a**) represents the evaluation result of soil erosion; (**b**) is the evaluation result of land desertification; (**c**) is the result of ecological sensitivity assessment.

Table 3. List of ecological sensitivity evaluation results.

Sensitivity Grading	Soil and Water Loss		Land Desertification		Ecological Sensitivity Score	
	Area	Proportion	Area	Proportion	Area	Proportion
Hyposensitivity	4487. 49	8.74%	15,220.10	26.10%	6994.86	13.78%
General sensitivity	10,829.10	21.09%	6372.68	10.93%	11,281.77	22.23%
Moderate sensitivity	11,740.85	22.87%	11,754.28	20.16%	14,002.98	27.59%
Highly sensitive	17,605.54	34.29%	19,321.44	33.13%	6875.70	13.55%
Extremely sensitive	6684.55	13.02%	5643.18	9.68%	11,594.05	22.85%
Total	51,347.53	100%	58,311.67	100%	50,749.36	100%

The sensitivity of land desertification is mainly identified in the highly sensitive areas (Figure 3b), accounting for 33.13% of the total study area (as shown in Table 3), and is widely concentrated in Zhangbei County, Shangyi County and Kangbao County of Zhangjiakou City and Laiyuan County, Yixian County and Laishui County of Baoding City. Most of these areas belong to hills and mountains, which are easily affected by soil erosion, especially in places with uneven precipitation and steep terrain, which easily form desertified land. In addition, the over-cultivation, unreasonable irrigation and fertilization methods of human activities destroy the soil structure and increase the risk of land desertification.

From the ecological sensitivity results weighted by soil erosion and land desertification (Figure 3c), it can be seen that the difference of the proportion of each grade in the ecological sensitivity evaluation is small, but the moderately sensitive area is more prominent, accounting for 27.59% (as shown in Table 3). This is followed by the extremely sensitive area, generally sensitive area, low sensitive area and highly sensitive area. Moderate sensitive areas account for a large proportion, which indicates that the overall ecological sensitivity of Yanshan-Taihang Mountain area in Hebei Province is relatively good, and the overall ecological environment has not been seriously damaged. However, there are many extremely sensitive areas, such as Laiyuan County, Laishui County, Fuping County and Yixian County in Baoding City, Kuancheng Manchu Autonomous County, Fengning Manchu Autonomous County, Chengde County and Pingquan City in Chengde City. The

extremely sensitive areas in these counties are relatively high, mainly because the areas are located in low mountains with many peaks, high rock exposure and poor erosion resistance, which are easily affected by soil erosion and easily lead to land degradation. In addition, due to previously low levels of economic development in these counties, it was common for human activity to over-exploit the land in pursuit of economic benefits, which had a serious impact on the local ecological environment. The ecological environment restoration ability in the region was insufficient, and the ecological restoration process was slow. A variety of reasons have led to the sensitivity of the ecological environment in these counties. In the future, the ecological environment management in this area should be strengthened.

3.3. Ecological Importance Assessment Results

The comprehensive evaluation results of ecological importance show the characteristics of high value in the east and south (as shown in Figure 4). See Table 4 for the proportion of different grades in 22 counties and districts. Among them, the areas of general importance, moderate importance, high importance, high importance and extreme importance account for 6.78%, 31.32%, 40.39%, 19.48% and 2.03% of the total study area, respectively, and the total areas of moderate importance and high importance account for 71.71% of the total study area, which is enough to show that the ecological environment in Yanshan Taihang Mountain area of Hebei Province should not be underestimated. The extremely important areas are mainly distributed in Chengde County, Pingquan County and the Kuancheng Manchu Autonomous Region in the south of Yanshan First Vein in Hebei Province; and Laiyuan County, Laishui County, Yixian County, Yuxian County and Fuping County in the south of Taihang Mountain in Hebei Province. Among them, Chengde County, Fengning Manchu Autonomous County and Longhua County account for a relatively high proportion of extremely important areas, reaching 47.93% of the total sensitive area (as shown in Table 4). The extremely important area in the south of Yanshan First Vein in Hebei Province is rich in biodiversity, which plays an important role in water conservation for Beijing and Tianjin. The ecosystem of the extremely important area in the south of Taihang Mountains in Hebei Province is fragile, and the phenomenon of soil erosion is serious, so it is necessary to pay more attention to wind and sand control. Highly important areas are mostly distributed between extremely important areas and highly important areas, which play a transitional buffer role.

Table 4. Summary of ecological importance grade evaluation results of 22 counties in Yanshan-Taihang Mountain, Hebei Province. Units: area, km^2; proportion, %.

County Name	Very Important		Highly Important		Higher Importance		Moderately Important		General Importance	
	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
Chengde County	146.65	10.40	1067.51	9.36	1465.26	6.19	883.24	4.82	84.74	2.13
Fengning Manchu Autonomous County	118.46	22.38	1968.10	17.26	3941.45	16.66	2412.81	13.15	219.85	5.54
Fuping County	92.68	3.94	927.37	8.13	506.25	2.14	846.15	4.61	57.37	1.45
Guyuan County	0.00	2.63	186.05	1.63	1120.31	4.74	1550.67	8.45	628.43	15.83
Huai'an County	0.00	0.97	197.65	1.73	651.53	2.75	510.84	2.79	288.36	7.26
Kangbao County	0.00	0.49	99.77	0.87	1774.47	7.50	1120.81	6.11	289.04	7.28
Kuancheng Manchu Autonomous County	87.46	6.30	765.90	6.71	672.77	2.84	344.10	1.88	29.03	0.73
Laishui County	175.67	5.12	662.79	5.81	330.42	1.40	370.27	2.02	76.06	1.92
Laiyuan County	162.56	5.22	997.92	8.75	649.94	2.75	573.81	3.13	20.09	0.51
Longhua County	48.05	15.15	957.09	8.39	2437.31	10.30	1773.52	9.67	184.92	4.66
Pingquan City	72.51	9.54	923.61	8.10	1241.28	5.25	909.54	4.96	69.91	1.76
Quyang County	1.02	0.16	77.61	0.68	226.93	0.96	491.62	2.68	267.85	6.75
Shangyi County	0.00	3.01	305.04	2.67	1487.42	6.29	643.77	3.51	125.83	3.17
Shunping County	16.18	0.44	99.38	0.87	245.69	1.04	268.58	1.46	71.47	1.80
Tang County	23.00	0.98	279.77	2.45	498.97	2.11	519.78	2.83	93.45	2.35
Wanquan District	0.00	0.32	66.35	0.58	360.65	1.52	395.16	2.15	300.58	7.57
Wangdu County	0.00	0.00	0.00	0.00	208.69	0.88	143.32	0.78	7.75	0.20
Yuxian	117.56	4.30	497.75	4.36	1051.00	4.44	1292.93	7.05	193.62	4.88

Table 4. *Cont.*

County Name	Very Important		Highly Important		Higher Importance		Moderately Important		General Importance	
	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
Xuanhua District	2.41	0.90	210.76	1.85	961.91	4.07	567.45	3.09	242.52	6.11
Yangyuan County	1.37	0.85	240.75	2.11	457.34	1.93	735.04	4.01	360.08	9.07
Yi County	123.65	6.04	771.97	6.77	663.64	2.81	856.96	4.67	112.09	2.82
Zhangbei County	0.00	0.86	102.72	0.90	2700.64	11.42	1131.96	6.17	246.16	6.20
Total	1189.23	100	11,405.86	100	23,653.87	100	18,342.33	100	227.26	100

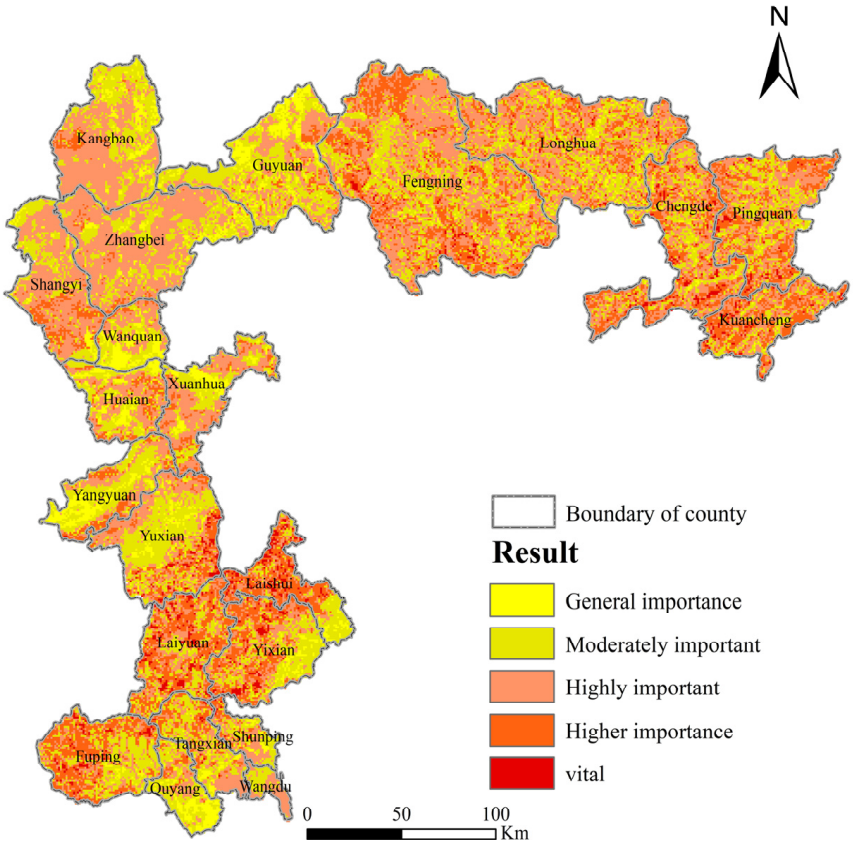


Figure 4. Results of ecological importance evaluation.

3.4. Results of Leading Ecological Function Zoning and Control Measures

We statistically analyzed the highly sensitive or important areas of various indicators in 22 counties and districts in Yanshan Taihang Mountains, Hebei Province. Using the self-organizing map (SOM) clustering method and the Kohonen software package in RStudio, three clustering results were obtained (Figure 5). According to the clustering results, it can be seen that soil erosion is prominent in Cluster 1, with a relatively large proportion of ecosystem services compared to other ecosystems. Cluster 2 shows a high proportion of land desertification, soil conservation and soil erosion, while the proportion of other ecosystem services is relatively low. The proportion of ecosystem services in Cluster 3 is relatively balanced, with small differences among them. According to the clustering results, different ecosystem service characteristics are named as a soil erosion ecological prevention and control zone (Cluster 1), ecological fragile zone (Cluster 2) and composite equilibrium zone (Cluster 3). We imported the clustering results into GIS and visualized the dominant ecological functional zoning of Yanshan Taihang Mountains in Hebei Province through data visualization (Figure 6).

Figure 5. R language clustering output.

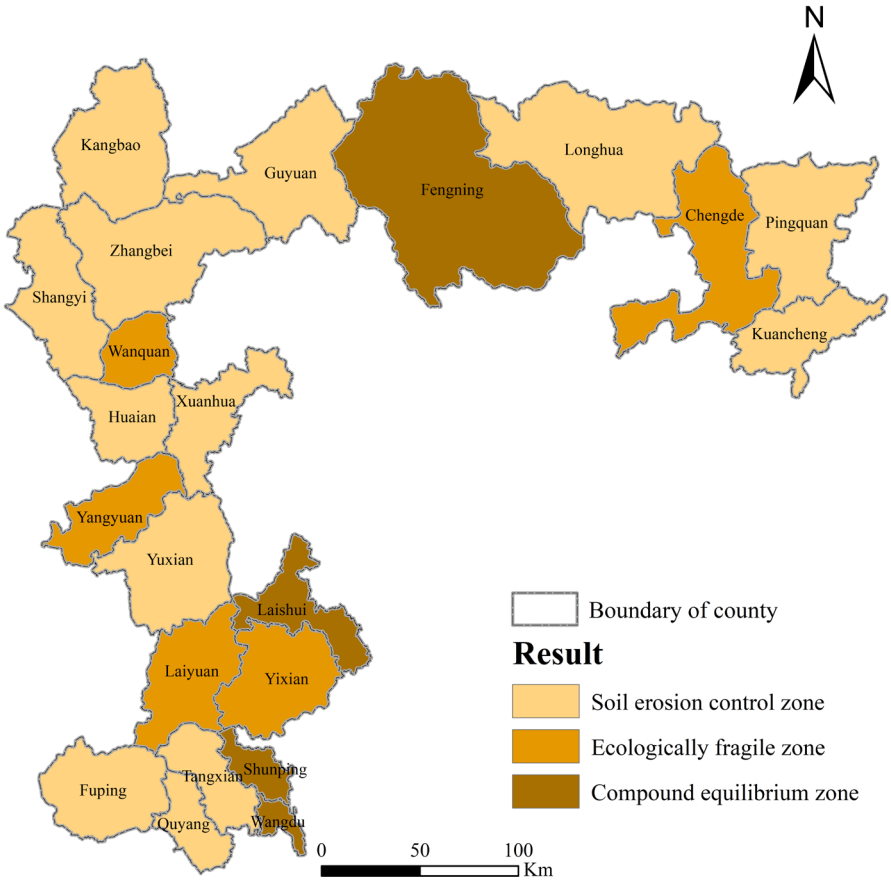


Figure 6. Partition result diagram.

The characteristics of soil erosion in the soil erosion prevention and control area are more significant than other ecosystem services, which are distributed in 15 counties of Yanshan-Taihang Mountain in Hebei Province, namely Longhua County, Pingquan City and Kuancheng Manchu Autonomous County in Chengde City; Guyuan County, Kangbao County, Zhangbei County, Shangyi County, Huai'an County, Xuanhua District and Yuxian County in Zhangjiakou City; Fuping County, Tangxian County and Quyang County in Baoding City. From the regional distribution of soil erosion problems, it can be seen that soil erosion is serious in most of the counties of Zhangjiakou City, and there are also a few counties in Chengde City and Baoding City with this problem. Natural conditions and human activities are the main reasons for this phenomenon. The natural conditions in Zhangjiakou area are harsh, arid and windy, and the terrain is relatively broken. The land use structure in Longhua County, Pingquan City and Kuancheng Manchu

Autonomous County is unreasonable. Fuping County, Tangxian County and Quyang County are mountainous environments. Due to long-term over-exploitation, the natural environment is poor, the regional vegetation is destroyed and the ecological environment is extremely fragile. In addition, the rapid growth of the population, rapid increase in demand for living materials, excessive reclamation and grazing or other unreasonable production and construction activities have intensified the predatory development and utilization of land resources, accelerated the occurrence of soil erosion and caused extremely serious damage to the regional ecological environment. In view of the problem of soil erosion, it is necessary to comprehensively use various means to control and reduce the occurrence of soil erosion from the source. Specifically, vegetation coverage can be increased by afforestation and grassland restoration, land development and utilization can be strictly controlled and engineering measures such as soil and water conservation and ecological restoration can be implemented to reduce the risk of soil erosion. This can improve the water-bearing function of the ecosystem and provide a high-quality water supply for the Beijing–Tianjin–Hebei region.

The importance of land desertification, soil and water conservation and soil erosion is relatively high in ecologically fragile areas, while other ecosystem services remain at a low level. This area is mainly distributed across Wanquan District and Yangyuan County of Zhangjiakou City, Chengde County of Chengde City and Laishui County and Yixian County of Baoding City. Although ecological protection and restoration projects such as returning farmland to forests and grasslands have been continuously implemented, the large-scale human development activities like urban construction have accelerated soil erosion, reduced the ability of roots to hold soil and increased the risks of soil erosion and rocky desertification due to climate change and the wide distribution of mountains. Therefore, we should strengthen vegetation restoration and protection, formulate strict land use planning, establish a perfect dynamic monitoring system of soil and water loss, build a forest ecological complex, change the bad living habits and development methods of local residents, improve the regional ecological environment and form a virtuous circle of the ecological system.

In the compound equilibrium area, except for soil and water conservation services, the other five ecosystem services have little difference, mainly distributed in Fengning Manchu Autonomous County, Laishui County, Shunping County and Fuping County. Most of these four counties are mountainous and hilly areas, with natural forests, plantations, wetlands or forest parks with national characteristics, including the Yesanpo National Forest Park in Laishui County, Tianshengqiao National Forest Park and Yunhua Valley Scenic Area in Fuping County and Hailiutu National Wetland Park in Fengning Manchu Autonomous County. The existence of these ecosystems improves the stability of ecosystems, maintains ecological balance and biodiversity and can also provide a water supply, purify natural water bodies and regulate the microclimate, which all play an important role in regional ecological environment protection.

4. Discussion

This paper assesses ecological importance in the Yanshan-Taihang region of Hebei by integrating ecosystem service functions and ecological sensitivity to identify key areas for protection. Based on the results of the ecological importance assessment, different ecological function zones were classified, and the future development directions and management of different ecological function zones were planned. This paper is of certain significance for improving the ecological environment policies in the study area and promoting green development in the new era. However, there are still some deficiencies in this paper:

Firstly, the timeliness and accuracy of the data used in this paper are slightly insufficient. The existing data may lag behind the dynamic changes of the ecosystem, and climate and socio-economic factors are constantly changing, so the evaluation results have certain limitations. Future research could consider adopting more refined remote sensing

monitoring technologies or combining field research with big data analysis to improve the timeliness and accuracy of data.

Secondly, the InVEST model used may overlook regional characteristics, leading to inaccuracies. In the future, further research will be conducted on the improvement of model principles and parameter verification, and field observations will be increased to obtain measured data to support the research results, so as to better provide basic data and theoretical references for the formulation of multi-scale regional ecological protection policies, territorial spatial planning and ecological protection planning practices, aiming to create a win-win scenario for both socio-economic development and ecological protection.

Thirdly, in terms of research scale, different spatial scales can affect research results. In the future, the research scale can be expanded to smaller micro scales or larger regional scales to explore the ecological function performance at different scales.

Finally, while the methods and findings offer valuable insights for similar regions, it is crucial to consider local characteristics and refine data accuracy and evaluation methods for applicability. The research of Ding Yuyuan and others has similarities with this article, both starting from county-level units and identifying ecological regions based on ecosystem service evaluation [38]. They took Longxian County in Shaanxi Province (an ecologically fragile area) as an example and evaluated five key ecosystem service quality values: soil conservation, water source conservation, habitat quality, food supply and ecological leisure. Using the OWA method, they divided the county into four control zones. Unlike their research, which combined the OWA method to simulate different scenarios based on ecosystem service evaluation to identify ecological control areas, this article combines a self-organizing mapping neural network to divide the performance of ecosystem services with similar characteristics based on ecosystem service evaluation. In terms of indicator selection, in addition to basic ecological service functions, this article also selected ecological sensitivity indicators to evaluate ecological sensitivity separately, making the overall evaluation more comprehensive and scientific. Future assessments should integrate disciplines like economics and sociology to create a comprehensive evaluation system that better reflects actual conditions.

5. Conclusions

In this paper, 22 counties in the Yanshan-Taihang Mountain area of Hebei Province were taken as research objects, and ecological importance was evaluated from two aspects (ecosystem service function importance and ecological sensitivity). Based on this, a self-organizing feature mapping neural network was used for ecological function zoning to coordinate the contradictions between society, economy and environment, and maintain regional ecological security. The conclusions are as follows:

1. The evaluation results of the importance of ecosystem services were mainly generally important and moderately important, which accounted for 64.69% of the total study area. Among them, the generally important parts were concentrated in Zhangjiakou City, Yanshan-Taihang Mountain, Hebei Province, and the extremely important, highly important and highly important parts were scattered in Baoding City and Chengde City. In the evaluation results of ecological sensitivity, the differences in the proportions of each grade were small, but the moderately sensitive area was more prominent.
2. The total area of moderately important and highly important regions in the ecological importance assessment accounted for 71.71% of the total study area. In addition, Chengde County, Fengning Manchu Autonomous County and Longhua County had a relatively high proportion of extremely important areas, and Chengde County and Fengning Manchu Autonomous County also occupied a large proportion in the highly important levels.
3. Statistical analysis was conducted on the highly sensitive or important areas of various indicators in 22 counties and districts in Yanshan Taihang Mountains, Hebei Province. The self-organizing mapping clustering method was used to obtain three

dominant zoning results, which were named as the soil erosion ecological prevention and control zone, ecological fragile zone and composite equilibrium zone, in sequence. A comprehensive use of various means is needed to control and reduce the occurrence of soil erosion in ecological prevention and control areas from the source. For ecologically fragile areas, it is necessary to strengthen vegetation restoration and protection, and form a virtuous cycle of the ecosystem. For the future of the composite equilibrium zone, excessive development should be restricted to ensure the integrity and coordination of ecological protection and economic development.

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