ASSESSMENT OF ENVIRONMENTAL SUITABILITY OF HUMAN SETTLEMENTS BASED ON IDENTIFIED TOWN-SCALE DOMINANT ECOLOGICAL FUNCTIONS IN HUANGSHAN CITY, CHINA

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Abstract. Ecological functions and environmental characteristics were examined by taking Huangshan City, China, as the research object in this study. On the basis of the evaluated ecological function importance, a method for identifying the dominant ecological function of towns was determined. Then, the towns were divided into groups in terms of their dominant ecological functions, and the differences in the environmental suitability of human settlements in these town groups were explored. The results showed that (1) the most important degrees of biodiversity, water conservation, soil and water conservation functions in Huangshan City were 70.57%, 51.28%, and 39.87%, respectively. (2) Among the 108 towns in Huangshan City, 67 towns with water conservation as the dominant ecological function (TWC group); 33 towns with biodiversity as the dominant ecological function (TBD group); and 8 towns with soil and water conservation as the dominant ecological function (TSW group). (3) The largest proportion was low suitability areas in the TSW group (39.38%), the smallest proportion was high suitability areas in the TWC group (1.13%). A reasonable identification of dominant ecological functions can provide a reference for regional environmental planning and management of human settlements.
Keywords: *soil and water conservation functions, water conservation, biodiversity, net primary productivity, ecological functional zone*

Introduction

Ecological environmental quality has improved in recent years, but some environmental issues still exist in China. Thus, a method for solving environmental problems and promoting a constructed ecological civilization from the ecological function perspective must be considered. Ecological function is provided by the ecosystem according to its biological characteristics. However, single, and interactive ecological functions may complicate ecosystem stability (Hasan et al., 2021). Small-scale administrative units are easier to grasp by the government, with environmental problems solved in a timely manner within the township scope. Therefore, identifying the ecological functions of towns plays an important role in protecting the ecological environment and maintaining ecological balance (Guerry et al., 2015). In this study, a

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scientific method was used to identify the dominant ecological functions of villages and towns. Then, on the basis of regional spatial partitions, the environmental suitability of human settlements in areas with different ecological functions was analyzed. This approach can provide a reference for developing and utilizing national space, promoting rural ecological revitalization and service areas for ecological civilization construction, and promoting the development of human society (Yao, 2020).

Recently, research on the importance and vulnerability of ecological functions (Cui et al., 2021) has become a research hotspot. The relevant achievements have been gradually applied to effectively support territorial spatial planning with respect to regional ecological environment protection. For example, Wang et al. (2019) used the Technical Guide for Evaluation of Resource and Environment Carrying Capacity and Appropriability of Land Space Development issued by the Chinese Ministry of Natural Resources in 2020 to partition ecological functions in Liupanshui City, Fujian Province, China. The methods of model evaluation (Li et al., 2021), simplified model evaluation (Wang and Wu, 2022), and the net primary productivity (NPP) quantitative index evaluation (Wu and Meng, 2022) have been applied in the evaluation of ecological function importance. Many studies have also been performed to identify ecological lands (Liu et al., 2021), ecological security patterns (Liu et al., 2023), and habitat conservation areas (Wang et al., 2022). However, the main focus of those studies was impact of ecological function importance on specific river basins and ecological land use. The identification of ecological functions has rarely been reported on a small scale. However, the dominant ecological functions must be identified before the government can implement relevant ecological protection policies. An excellently developed ecological environment can provide a good living environment for human beings. Since the establishment of the human settlement environment index by Feng et al. (2008), many scholars have applied this model to evaluate the environmental suitability of human settlements in different spatiotemporal forms (Xia et al., 2020; Feng and Zheng, 2022). Terrain (Tang et al., 2019) and climate (Li et al., 2018) analyses have determined the importance of spatial relationships between natural environments and human settlements and their distribution (You et al., 2020; Zhang et al., 2022) to humans. This model has been proven applicable for many areas in China.

As an excellent demonstration city of ecological construction, Huangshan City is facing great pressure in maintaining environmental quality under the rapid development of the tourism sector, indicating the need for relevant ecological research. In this study, Huangshan City was taken as an example to construct an index to evaluate the importance of ecosystem service functions while assessing the suitability of human settlement environments. On the basis of the evaluated ecological function importance, the dominant ecological functions were identified, and towns were grouped according to their dominant ecological function. Finally, the differences in suitability degrees of human settlement environments of the town groups with different dominant ecological functions were analyzed. This study will provide a reference for regional environmental planning and management of human settlements and scientific guidance for the establishment of rural ecological civilization in Huangshan City.

Materials and methods

Study area

Huangshan City (E 117°12′–118°54′, N 29°23′–30°31′) is located in the mountainous area of the southern part of Anhui Province, China. Its total area is 9,807 km², covering three districts and four counties. The city is located in a water conservation and biodiversity area along the Tianmu-Huaiyu Mountain District (*Fig. 1*). Furthermore, Huangshan City is rich in natural resources and is mountainous and hilly; thus, it is considered an important ecological functional zone by the national government. Its forest coverage rate is 84.8%, covering forests, lakes, grasslands, and other ecosystem types.

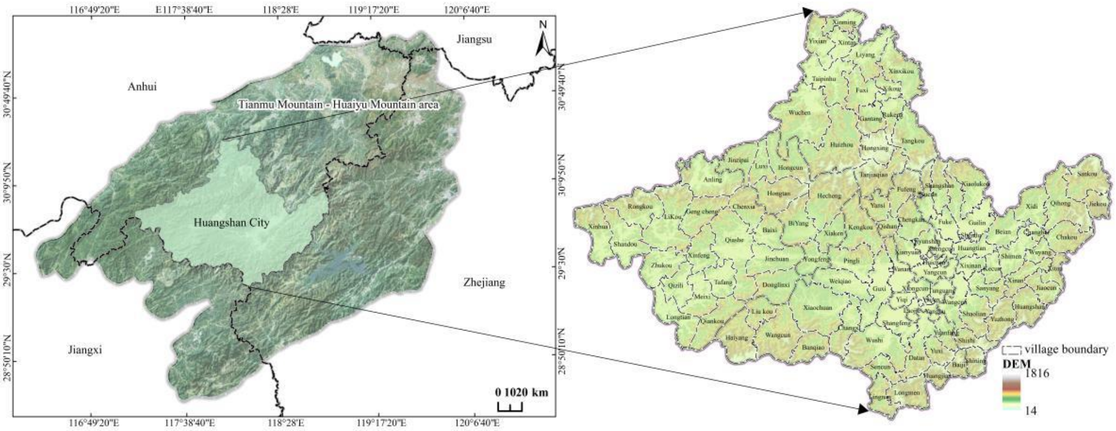

Figure 1. *Map of Huangshan City*

Data type and source

The data used in this study included altitude, soil, net primary productivity (NPP), precipitation and air temperature, remote sensing image (MODIS), land use type, and relative humidity. Altitude data were collected from the Geospatial Data Cloud (http://www.gscloud.cn), with a spatial resolution of 30 m. Soil data were obtained from the National Earth System Science Data Center (http://www.fao.org), with a spatial resolution of 1 km. NPP data from 2000 to 2020 were obtained from MOD17A3HGF version 6.0 (https://lpdaac.usgs.gov), with a spatial resolution of 1 km. The grid data of annual precipitation and temperature from 2000 to 2020 (Peng, 2019, 2020) were collected from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn), with a spatial resolution of 1 km. MODIS data in 2020 were collected from EARTHDATA (https://ladsweb.modaps.eosdis.nasa.gov), with a spatial resolution of 250 m. Land use data (including construction lands, forestlands, grasslands, water, and croplands) in 2020

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were obtained from Esri (https://www.arcgis.com), with a spatial resolution of 10 m. The data on relative humidity (Xu, 2022) in 2020 were obtained from the registration and publication system of the Resources and Environmental Science Data Center (https://www.resdc.cn), with a spatial resolution of 1 km.

For the data processing and analysis, the six-degree band of the CGCS2000_GK_CM_20 projection coordinate system in ArcGIS software, with a 30 m × 30 m grid, was used as the evaluation unit.

Evaluation methods

Assessment of ecological function importance

Ecological function importance refers to the importance of an ecosystem function to human survival and development (Alexander et al., 1998). The purpose is to determine the distribution of different ecological functions in a region prior to developing conservation and management strategies (Xiang et al., 2011). In this study, ecological function importance was calculated by the NPP quantitative index method. It is based on NPP data and combining altitude, soil, and climate factors, mainly including water conservation, sand fixation, biodiversity maintenance, or soil and water conservation functions (Liu et al., 2018). Three ecological functions were selected: water conservation, biodiversity, and soil and water conservation, according to the position of this study area in the Chinese Ecological Function Zoning. Finally, the result was divided into four grades (generally important, moderately important, important, and extremely important) according to the corresponding natural breakpoint.

The water conservation function was evaluated using the water conservation service capacity index (Deng et al., 2022) of the ecosystem as follows:

$$\mathrm{WR} = NPP_{mean} \times F_{sic} \times F_{pre} \times (1 - F_{slo}) \tag{Eq.1}$$

where WR is the water conservation service capacity index; NPP_{mean} is the annual average net primary productivity; F_{sic} is the soil seepage factor; F_{pre} is the precipitation factor; and F_{slo} is the slope factor.

The biodiversity function was assessed using the ecosystem biodiversity service capability index (Ma et al., 2021) as follows:

$$S_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt}) \tag{Eq.2}$$

where S_{bio} is the biodiversity service capability index; F_{tem} is the temperature factor; and F_{alt} is the altitude factor.

The soil and water conservation function were evaluated using the ecosystem soil and water conservation service capacity index (Tang et al., 2021) as follows:

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$$S_{pro} = NPP_{mean} \times (1-K) \times (1-F_{slo}) \quad \text{(Eq.3)}$$

where S_{pro} is the soil and water conservation service capacity index, and K is the soil erosion factor.

Identification of dominant ecological functions

The identification of dominant ecological functions was based on the land area classified as extremely important areas of ecological function. The data of the areas classified as the most important areas of ecological regulatory function were extracted using the ArcGIS extraction tool, and then the areas were counted. The dominant ecological functions were identified according to the proportion of different dominant ecological functions in extremely important areas as follows:

$$\mathrm{TDEF} = \max S_i \quad \text{(Eq.4)}$$

where TEDF is the dominant ecological function index of a town; S_i is the ratio of the most important area of ecological regulation function; i refers to different types of ecological functions, i=1,2,3; and n is the number of ecological functions.

Human settlement environment index

The human settlement environment index (Xu et al., 2020) was characterized using the topographic index, vegetation index, hydrology index, and temperature and humidity index.

Topographic index:

$$RDLS = \frac{ALT}{1000} + \frac{\left\{[max(H)-min(H)]\times\left[1-\frac{P(A)}{A}\right]\right\}}{500} \quad \text{(Eq.5)}$$

where RDLS is the topographic index; ALT is the average elevation in the region; max (H) and min (H) are the highest and lowest elevations, respectively; P(A) is the flat area in the region, i.e., the area with a relative height difference of <30 m (Chen et al., 2013); and A is the total area.

Vegetation index:

$$\mathrm{NDVI} = \frac{NIR-Red}{NIR+Red} \quad \text{(Eq.6)}$$

where NDVI is the normalized vegetation index, which was calculated from MODIS data; NIR is the near-infrared band reflectance; and Red is the red band reflectance.

Hydrology index:

$$\mathrm{HI} = \alpha \times N\mathrm{AP} + \beta \times N\mathrm{WD} \quad \text{(Eq.7)}$$

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where HI is the hydrology index; NAP is the normalized average annual precipitation; NWD is the normalized distance from water; and α and β are the corresponding weights, which are 0.8 and 0.2, respectively (Hao and Ren, 2009).

Temperature and humidity index:

$$\mathrm{THI} = 1.8\mathrm{t} + 32 - 0.55 \times (1 - f) \times (1.8t - 26) \quad \text{(Eq.8)}$$

where THI is the temperature and humidity index; t is the monthly average temperature; and f is the monthly average relative humidity.

Human settlement environment index:

$$\mathrm{HEI} = \alpha \times N\mathrm{RDLS} + \delta \times N\mathrm{NDVI} + \chi \times N\mathrm{HI} + \beta \times N\mathrm{THI} \quad \text{(Eq.9)}$$

where HEI is the human settlement environment index; NRDLS, NNDVI, NHI, and NTHI are the normalized topography index, vegetation index, hydrology index, and climate index, respectively; and α, δ, χ, and β are the corresponding weights, which are 0.28, 0.28, 0.19, and 0.25, respectively, in the study of Feng et al. (2008).

Then, the environmental suitability grades of the topography index, vegetation index, hydrology index, and temperature and humidity index were divided on the basis of the actual situation (Feng and Zhen, 2022) in Huangshan City (*Table 1*).

Table 1. *Single-factor classification of human settlement suitability in Huangshan City*

Suitability	Topography index	Vegetation index	Hydrologic index	Humidity-temperature index
Low suitability	<0.2	≥0.9	≥0.5	≥270
Relatively high suitability	[0.2,0.5]	[0.8,0.9]	[0.4,0.5]	[220,270]
Moderate suitability	[0.5,0.8]	[0.7,0.8]	[0.3,0.4]	[170,220]
Relatively low suitability	[0.8,1.0]	[0.6,0.7]	[0.2,0.3]	[120,170]
Low suitability	≥1.0	<0.6	<0.2	<120

Results

Assessment of ecological function importance

The “most important water conservation area” of Huangshan City is mainly distributed along the Xin’an River and its tributaries, with an area of 6827.40 km², accounting for 70.57% of the land area of the city and is distributed mainly in the towns of Qimen County, Tunxi District, Yixian County, and Huizhou District. The “more important water conservation area" of Huangshan City covers 1782.05 km², accounting for 18.42% of its land area, and is distributed in Xiuning County and the southern towns of Shexian County. The "relatively important water conservation area" covers 1037.71 km², accounting for 10.73% of the land area, and is scattered in some towns of Shexian County and Xiuning County. Some important areas of water conservation are sporadically distributed in Tunxi District. The details are shown in *Fig. 2a*.

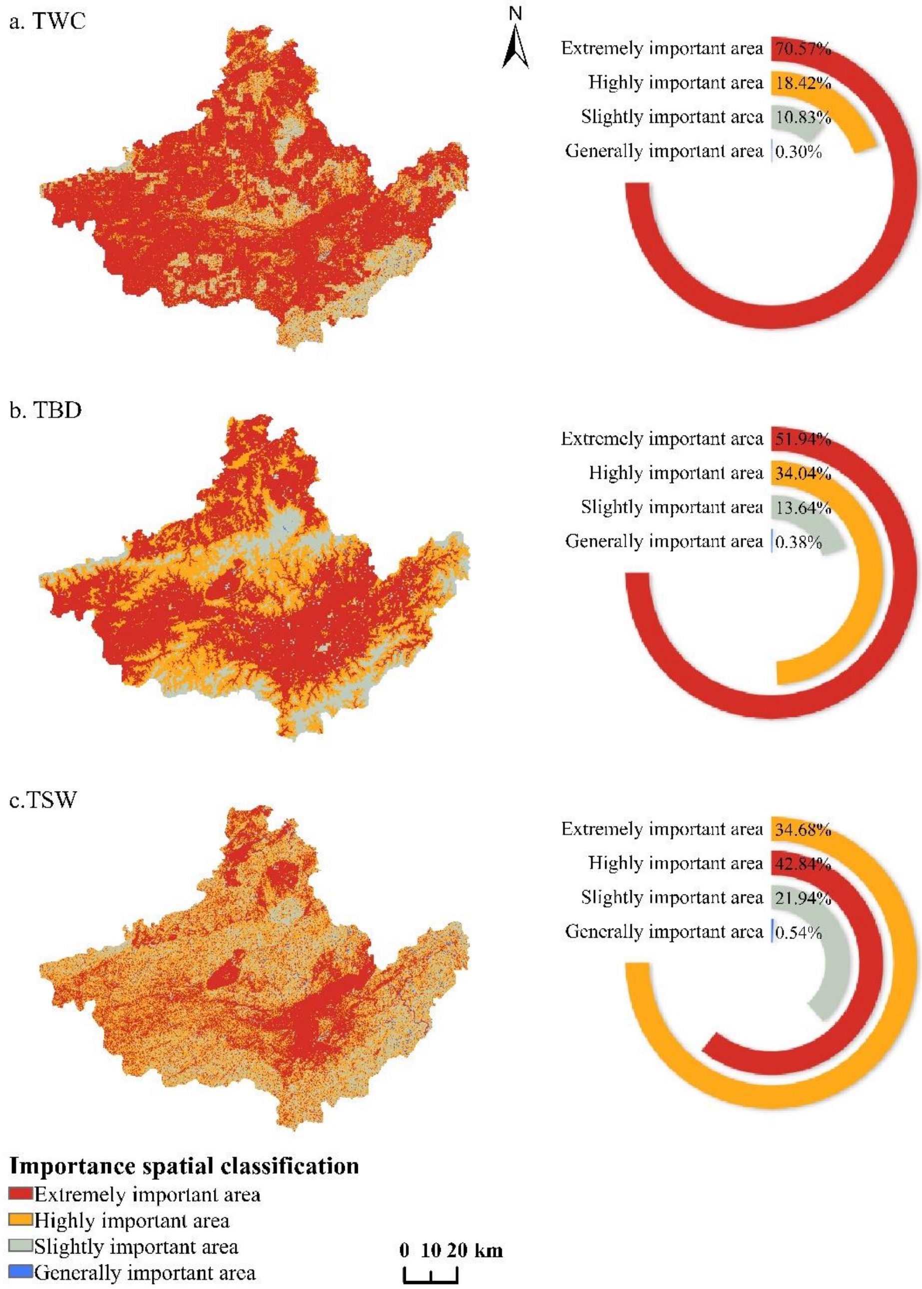

Figure 2. *Spatial distribution of important ecological functions in Huangshan City (TWC group: towns with water conservation; TBD group: towns with biodiversity; TSW group: towns with soil and water conservation)*

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The “most important biodiversity area” of Huangshan City covers 4960.61 km², accounting for 51.28% of its land area, and is distributed mainly in some towns of Tunxi District, Qimen County, Huangshan District, and Huizhou District. The “more important biodiversity area” covers 3345.02 km², accounting for 34.58% of the total land area, and is distributed in some towns of Yixian County, Huizhou District, and Xiuning County. The “important biodiversity area” of Huangshan City covers 1310.47 km², accounting for 13.55% of its land area, and is scattered in some towns of Huangshan District, Xiuning County, and Shexian County. The “relatively important biodiversity area” is scattered in some towns of Shexian County. The details are shown in *Fig. 2b*.

The “most important soil and water conservation area” of Huangshan City covers 3857.00 km², accounting for 39.87% of its land area, and is distributed mainly in some towns of Qimen County, Yixian County, Huangshan District, and Xiuning County. The “more important soil and water conservation area” covers 3366.91 km², accounting for 34.80% of the land area, distributed mainly in some towns of Tunxi District, Huizhou District, and Huangshan District. The “relatively important soil and water conservation area” covers 2398.00 km², accounting for 24.79% of the land area, and is scattered in some towns of Shexian County and Xiuning County. The “relatively important soil conservation area” is scattered in some towns of Shexian County. The details are shown in *Fig. 2c*.

Identification of dominant ecological functions at the township scale

The proportion of “most important areas” in Huangshan City indicates that 68 towns have dominant ecological functions of water conservation, 32 towns have dominant ecological functions of biodiversity, and 8 towns have dominant ecological functions of soil and water conservation (*Fig. 3*). These towns in Huangshan City can be divided into three town groups based on their dominant ecological functions: towns with water conservation as the dominant ecological function (TWC group); towns with biodiversity as the dominant ecological function (TBD group); and towns with soil and water conservation as the dominant ecological function (TSW group). The TWC group is distributed in the west; the TBD group is distributed in the northern and central parts; and the TSW group is distributed in the south (*Fig. 4*).

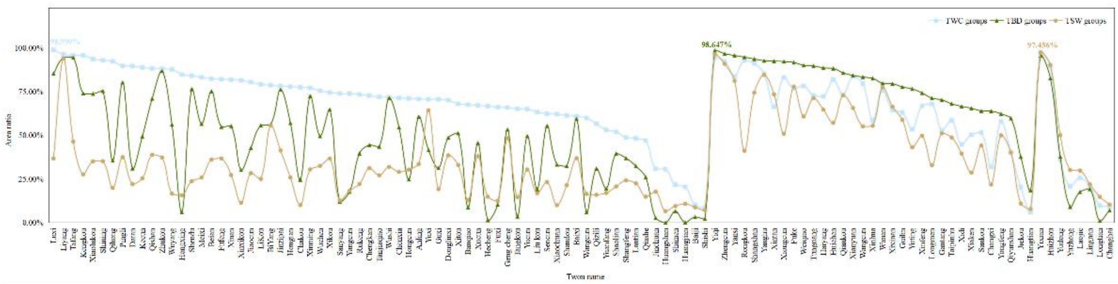

Figure 3. *Town groups with different dominant ecological functions in Huangshan City*

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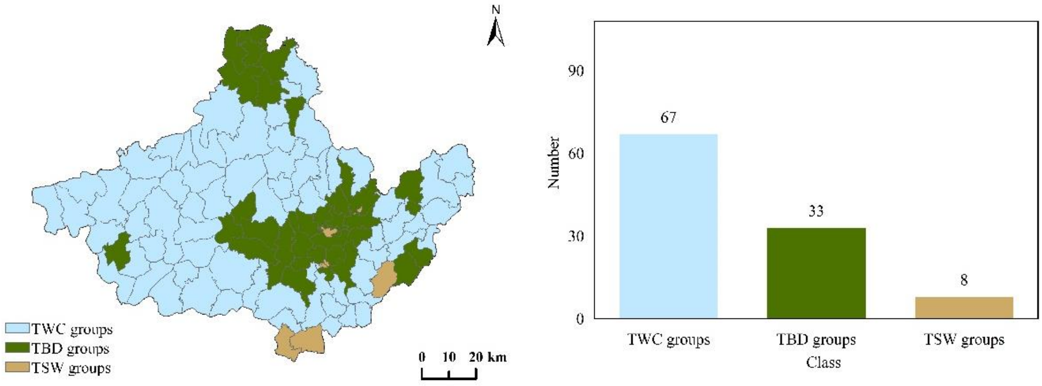

Figure 4. *Spatial distribution of town groups with different dominant ecological functions in Huangshan City (TWC group: towns with water conservation function; TBD group: towns with biodiversity function; TSW group: towns with soil and water conservation function)*

Assessment of environmental suitability for human settlement

The spatial distribution of the topographic index is reduced from Huangshan Mountain Resort, Guniujiang Nature Reserve in the west, Qingliangfeng Nature Reserve in the east, and many mountains in the south. The low topographic index is distributed in the flat areas, such as Tunxi District, Huizhou District, Yixian County and Shexian County in Huangshan City (*Fig. 5a*). The spatial distribution of the vegetation index shows an uptrend from urban residential areas to mountainous forests. The low vegetation index are distributed in the residential areas with a large population, such as Tunxi District, Huizhou District, Yixian County, and Shexian County in Huangshan City (*Fig. 5b*). The spatial distribution of the hydrology index is highly similar to that of the topographic relief. The high hydrology index are concentrated in the Xin'an River and its tributaries (*Fig. 5c*). The spatial distribution of the temperature–humidity index shows an uptrend from mountains to the four sides of the area. The low temperature and humidity index is distributed in mountains with high altitudes and relatively low temperatures. The high and humidity index is distributed in urban areas or river areas in Huangshan City (*Fig. 5d*).

Then, the natural suitability of the human settlement environment of the town groups in Huangshan City with different dominant ecological functions was comprehensively analyzed on the basis of the human settlement environment indices and standards (*Table 2*; *Fig. 6*). (1) In the TWC group, the relatively low suitability area covers 2273 km², accounting for the highest proportion (34.29%), and is mainly distributed in the mountainous areas along the towns of Likou, Jiaocun, Xikou, and Wangcun. The high suitability area covers 75 km², accounting for the lowest proportion (1.13%), and is mainly distributed in the towns of Liyang, Wushi, Tanjiaqiao, and Biyang. (2) In the TBD group, the relatively high suitability area covers 875.04 km², accounting for the highest proportion (37.72%), and is mainly distributed in the towns of Shangshan, Guilin, Haiyang, and Yansi; by contrast, the low suitability covers 52.75 km², accounting for the

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lowest proportion (2.27%), and is mainly distributed in the towns of Huangtian, Qiyun, Sankou, and Jiekou. (3) In the TSW group, the low suitability covers 104.52 km², accounting for the lowest proportion (39.38%), and is mainly distributed in the towns of Longtian, Changgai, and Lingnan; by contrast, the relatively high suitability area covers 7.34 km², accounting for the lowest proportion (2.77%), and is mainly distributed in the town of Changgai and the subdistricts of Huizhou and Yuzhong.

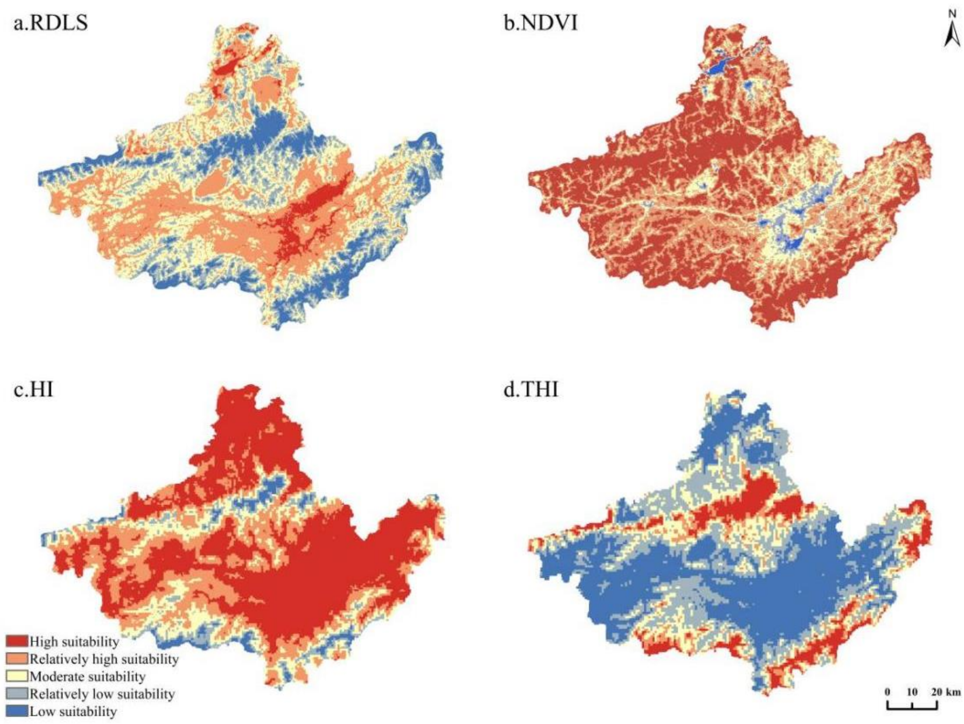

Figure 5. *Spatial distribution of single-factor environmental suitability for human settlement in Huangshan City (RDLS: topographic index; NDVI: normalized difference vegetation index; HI: hydrology index; THI: temperature and humidity index)*

Table 2. *Areas and proportions of the town groups in Huangshan City with dominant ecological functions*

Suitability /Groups	High suitability		Relatively high suitability		Moderate suitability		Relatively low suitability		Low suitability	
	Area/ km²	Proportion/ %	Area/ km²	Proportion/ %	Area/ km²	Proportion/ %	Area/ km²	Proportion /%	Area/ km²	Proportio n/%
TWC	75	1.13	894	13.49	2191	33.05	2273	34.29	1196	18.04
TBD	239.12	10.31	875.04	37.72	808.55	34.85	344.40	14.85	52.75	2.27
TSW	19.90	7.50	7.34	2.77	36.75	13.85	96.91	36.51	104.52	39.38

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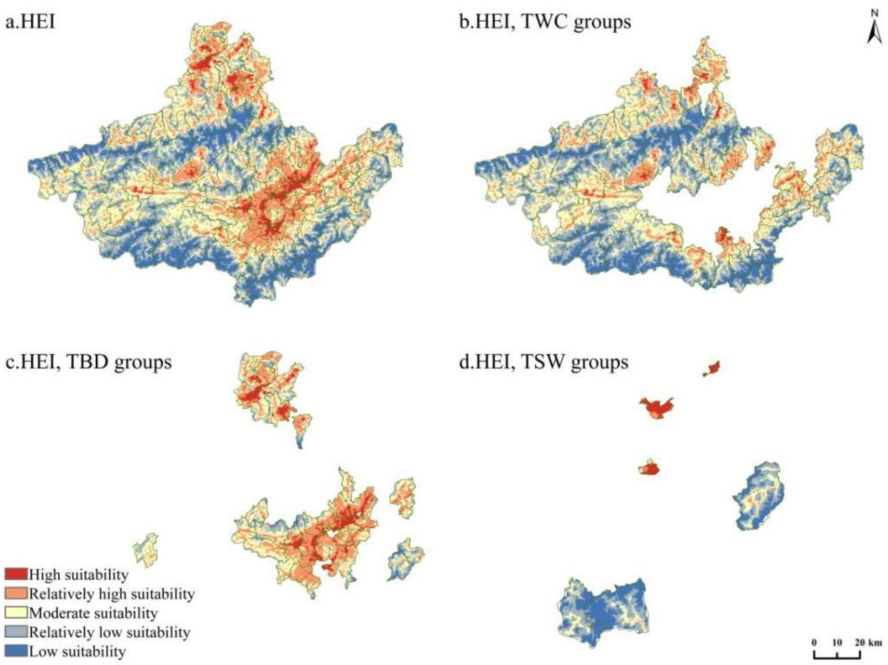

Figure 6. *Spatial distributions of the environmental suitability of human settlements for the town groups in Huangshan City with dominant ecological functions (HEI: human settlement environment index; TWC group: towns with water conservation function; TBD group: towns with biodiversity function; TSW group: towns with soil and water conservation function)*

Discussion

Huangshan city is a vital part of the Tianmu-Huaiyu Mountain District, and there are apparent differences between the economic development and environmental governance capabilities here. It is located in the mountainous area with rich peaks and rivers, belongs to the northern subtropical zone. In view of the importance of ecological and geographical location and research limitations of the study area, this paper constructed an identification model of dominant ecological functions at the township scale, evaluated the environmental suitability of human settlements of Huangshan city.

There were some differences found in environmental suitability of human settlements of the different town groups with dominant ecological functions in Huangshan city. The TWC group for human settlement is relatively low suitability, accounting for about 34.29% of the entire TWC group. Most of these towns in Huangshan city are located mountainous, with rich in forest resources and water resources, such as Yellow Mountain, Guniujiang Nature Reserve and Xin’an River (Chen et al., 2022). For these towns, the limiting the environmental suitability of human settlements is the topography and hydrology (Zhao et al., 2023). A reasonable ecological protection measures directly and indirectly affected the water conservation function of the TWC group. Some strategies for these towns should strengthen cooperation for publicity and forest protection education while

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encouraging local communities to spontaneously and consciously implement protection behavior (Cao et al., 2021). The TBD group for human settlement is relatively high suitability, accounting for about 37.72% of the entire TBD group. These towns have gentle terrain and convenient transportation. The population and economy of Huangshan city all gather here, becoming an important bearing area for the development of the city, for example, Tunxi Old Street (Liu et al., 2022). Huangshan city is one of the 35 priority areas for biodiversity conservation in China. It adheres to the integrated protection and systematic management of mountains, rivers, forests, farmland, lakes, grass and sand, and achievements have been made in biodiversity conservation. For these towns, a unified biodiversity priority protection and management system should be formulated, the optimal allocation of biological communities should be promoted, and economic development should be sought on the basis of environmental protection (Xiang et al., 2023). The TSW group for human settlement is low suitability, accounting for about 39.38% of the entire TSW group. The topography, climate and vegetation limit the environmental suitability of human settlements in these towns. Most of these towns in Huangshan city are located in high mountains, with a cold and windy climate, barren land, serious soil erosion, and the ecological environment here is fragile (Ma et al., 2018). The soil and water conservation function of the TSW group is very necessary and practical. For targeted development, those towns should take biological and engineering measures to strengthen soil and water protection and prevent soil erosion (Li and Shi, 2022).

Therefore, the research results in the paper can provide a scientific basis for the correct analysis of the spatial distribution of ecological functions in Huangshan city, and help the government, enterprises, residents, and other individuals to better protect and use its ecological resources in Huangshan city. Moreover, each town can form linkages while establishing and improving public participation (Wen, 2018), paying full attention to public needs, and mobilizing the public to achieve people-oriented ecological revitalization.

Conclusion

Huangshan City is a typical tourist city that is rich in natural resources and has a large ecological utilization space. In this study, the distribution of dominant ecological functions and human settlement suitability of the city were analyzed. The conclusions can be summarized as follows:

The ecological functions were evaluated to establish three evaluation methods. The results, which were based on data from 2000 to 2020, indicate that water conservation is the most important function, followed by biodiversity and soil and water conservation.

The number of towns with dominant ecological functions of water conservation, biodiversity, soil and water conservation were 67, 33, and 8, respectively.

Huangshan City has a few suitable residential areas. The most proportion of the high suitability areas for human settlement is TBD groups.

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