Analysis the Distribution Pattern of biodiversity around Plateau Lake: A Composite Indicator Approach Using Habitat Quality Models and MaxEnt Models

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Abstract

Increasing fragmentation of habitats is accelerating the loss of biodiversity, especially in ecologically fragile green space(GSs) in high-altitude cities. The scientific assessment distribution patterns of biodiversity(DPOB) in Circum-Erhai lake region(CELR) is of great significance for the sustainability. We identified GSs using fractional vegetation coverage. The InVEST habitat quality (HQ) module assessed HQ, while GIS evaluated ecological sensitivity (ES). Subsequently, we used the MaxENT model to predict suitable living areas for key species. Finally, HQ, ES, and species distribution results served as biodiversity proxies to predict DPOB. Key findings: (1) CELR's overall biodiversity is relatively high, showing a "high in forests, low along Erhai shores" pattern. (2) Core GSs are scarce (1.21% of total GS area). (3) High-ecosystem-quality GSs dominate in high-altitude forests (77.6%). (4) Key-species-suitable GSs (19.34%) are mainly on Erhai's western flatlands. (5) Non-suitable areas cover 201.73 km² (18.59%). These findings help identify priority protected areas and promote the development of sustainable management strategies for GSs.

1. Introduction

The essential natural resource carriers and fundamental ecological components of the plateau urban ecology are plateau lakes [1–3], and their ecological integrity and urban sustainability are deeply interdependent. The green spaces (GSs) around the plateau lakes is a significant area for animal survival and has a great deal of potentiality for the preservation of biodiversity. The natural vulnerability of plateau lakes combined with intense human activity has caused biodiversity to suffer hitherto unheard-of harm [4, 5], making it difficult to sustainably export a range of ecosystem services. With the promulgation of the white paper on “China’s Biodiversity Conservation”, biodiversity conservation was regarded as an important national strategy, further highlighting the importance of clarifying the distribution pattern of biodiversity (DPOB) in the process of exploring the balance between economic-social development and ecological environment protection in high-altitude cities. However, in reality, it is becoming increasingly clear that merely preserving key species or enhancing habitat quality is insufficient to maintain biodiversity, making it challenging to achieve sustainable urban development. Therefore, in order to precisely calculate the DPOB and clarify the main factors that affect its spatial distribution, the above two methods above should be combined [6–8].

In recent years, core space identification on biodiversity conservation has gradually become a research hotspot in related fields in the domestic and overseas [9–12]. So far the research on the core space for biodiversity conservation mainly focus on global biodiversity conservation hotspot, national nature reserves and other geographical areas where natural habitats are dominant. The relevant research is mainly divided into two aspects [13, 14]. One is the spatial distribution of biodiversity based on habitat quality. InVEST is used to evaluate the regional HQ grade, and the results are used as alternative indicators of biodiversity [15, 16]. Another one is based on the spatial distribution of species richness, which uses niche models to analyze the potential distribution areas of species and thereby determine the DPOB [12, 17]. The maximum entropy model (MaxEnt) is among the most widely applied ecological niche models for studying species richness, predicting species distributions by quantifying stable relationships between species occurrence records and environmental factors. [18]. This model is a helpful instrument for evaluating the species distributions since it may generate high-precision simulation results with just a small quantity of species data [19]. Notwithstanding its utility, the MaxEnt model exhibits certain limitations..A principal shortfall lies in its inadequate integration of habitat quality parameters within environmental variables, coupled with minimal accounting for land-cover heterogeneity. This omission introduces discrepancies between projected distributions and facts. In contexts with insufficient species occurrence records, biodiversity assessment can be alternatively quantified via the InVEST Habitat Quality Module. The model expound the spatial dynamics of habitat degradation while concurrently mapping HQ) indices across landscapes [20]. The model recognizes that superior habitat quality correlates with enhanced species richness, whereas degradation directly impairs long-term biodiversity persistence and ecosystem resilience [21].

HQ refers to ecosystems' capacity to maintain biological in a sustainable manner, reflecting biodiversity levels and environmental suitability for human use. It is important when determining the ecological health of the area [16, 22]. The degree to which an ecosystem responds to changes in the natural environment and human disturbances is known as ecological sensitivity (ES), and it indicates the likelihood that ecological environmental issues may arise in a certain area. One of the best ways to categorize environmentally delicate places is through ES assessment, which takes into consideration both natural and human influences and can yield valuable information for ecosystem enhancementc [23–25]. Regional ecosystems can be comprehensively evaluated using data on land use, biodiversity threat sources, and ES aspects based on HQ and ES assessment [26].Endangered species are important indicator species of ecosystem disturbance and biodiversity degradation. We takes into account that endangered species usually have stricter requirements for their living environment and relatively weaker resistance to human activity disturbances and environmental changes. The habitat that guarantees endangered species survival is probably also appropriate for the survival of other species within the study area. As a result, endangered species can be regarded as alternative indicators that effectively reflect the level of biodiversity [17, 27].

In this study, combining the results of habitat quality quantified by the InVEST model for analysis, the results of species distribution prediction simulated by the MaxEnt model, and the results of ES assessment can overcome the limitations of a single model and obtain more reliable research results on biodiversity conservation. Urbanization has fundamentally disrupted ecological integrity by accelerating anthropogenic landscape fragmentation and systematically eroding habitat connectivity. These cascading effects impose critical thresholds of degradation on urban biodiversity [15], ultimately undermining sustainable planning pathways capable of reconciling socio-economic development with long-term ecological resilience [28].

The circum-Erhai lake region (CELR) is located in the southern section of the Hengduan Mountains, at the intersection of the three major biodiversity hotspots of India-Myanmar, the southwestern Mountains and the Himalayas. Animals and plants enjoy a wide variety of habitats in CELG because of its distinct topography and climate, making it a hotspot for biodiversity worldwide [31, 32]. Meanwhile, as a popular tourist city and the economic center of Dali Prefecture, CELR has undergone rapid urbanization and industrialization, leading to a reduction in biodiversity and ecological environment degradation [33]. Currently, CELR has become a region with prominent contradictions between ecological protection and economic development, facing severe challenges such as the relatively fragile natural ecosystem in the plateau area and the difficulty in restoring the ecosystem after it has been damaged [34–36]. However, there are relatively few related studies on the core spatial identification of biodiversity in plateau cities and plateau lakes, and the problem of biodiversity conservation in plateau areas urgently needs to be solved [37]. Therefore, there is an urgent need for research on the DPOB based on ecosystems and key species to provide guidance for biodiversity conservation and urban GSs planning. Release its sustainable supply capacity while ensuring the ecological integrity.

In this study, we evaluated the HQ and ES of CELR, predicted the potential distribution of key species, and used the simulation results of HQ, ES, and potential distribution as alternative indicators of biodiversity, revealing the DPOB in the green spaces of CELR. Aims to achieve the following three factors: (1) Explore the composite indicator Approach for the DPOB that combines ecosystems and species; (2) Improve the accuracy of predicting the DPOB; (3) Provide sustainable management strategies for the zoned protection of biodiversity in urban GSs.

2. Materials and Methods

2.1. Study area

The research area (25∘ 25' ~ 25∘ 58' N, 99∘ 58' ~ 100∘ 27' E) is located in the northwest of Yunnan Province, with a total area of 1565 km^2 (Fig. 1). The CELG refer to the areas of Dali City except the Erhai Lake, with an altitude ranging from 4084 m to 1335 m. The climate of CELG is subtropical plateau monsoon, with a small annual temperature difference and unclear seasonal changes attributable to the unique combination of lower latitude and higher altitude. In the early months and second half of the year, there is a spatial and temporal imbalance in rainfall, with less precipitation from January to May. In June, when the rainy season begins, there is intense rainfall [38]. The total amount of precipitation per year is 1051.1 mm. The distribution of the forest, grassland, cropland, and water body in the CELG exhibited an alternating pattern, with natural vegetation covering nearly 88% of the region.

2.2. Data collection

2.2.1. Species data

Based on List of key protected wild animals and plants in China, and List of national key protected wild animals/plants distributed in Dali, we first consulted the data on key protected species in China and found 20 national level I and 171 level II protected species in the study area. We classified the wild species in the study area into vulnerable, near threatened, endangered, critically endangered, extinct, and extinct based on the IUCN Red List of Threatened Species. Among them, there are more than 10 species within the CELR with occurrence records, including *Baer's Pochard, Ailurus fulgens, Pseudois nayaur, Corybas taliensis, Rhododendron platyphyllum, Anoectochilus roxburghii*, etc, which are the key species in this study. The occurrence records of key protected species were obtained from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/occurrence/search) and related published literatures. There are a total of 289 key species distribution points used for predicting the potential distribution of species using the MaxENT model. To ensure model accuracy and reduce spatial bias, only one distribution point was reserved for birds of the same ecological group in the same 30m × 30m grid. The final 182 key species distribution point data were used for this study(Fig. 2).

2.2.2. Environmental variables

According to the CELR's ecosystem types and ecological requirements of key species, we selected 26 environmental variables, taking into account climate, habitat and human activities. Environmental variable data include Landsat-8 satellite remote sensing images, land cover data, bioclimate variable data, DEM data, road vector data, nighttime light data, river data, water body data, etc. The sources and descriptions of environmental variables are shown in Table 1.

Table 1
Sources and descriptions of 26 environmental variables.

Categories	Descriptions	Variables	Sources
Climatic	Annual Mean TemperSature (°C)	Bio1	World Climate Data Website (https://www.worldclim.org/ (accessed on 10 JUN 2024))
	Mean Diurnal Range (Mean of monthly (max temp – min temp)) (°C)	Bio2	
	Isothermality (BIO2/BIO7) (×100) (°C)	Bio3	
	Temperature Seasonality (standard deviation × 100) (°C)	Bio4	
	Max Temperature of Warmest Month (°C)	Bio5	
	Min Temperature of Coldest Month (°C)	Bio6	
	Temperature Annual Range (BIO5–BIO6) (°C)	Bio7	
	Mean Temperature of Wettest Quarter (°C)	Bio8	
	Mean Temperature of Driest Quarter (°C)	Bio9	
	Mean Temperature of Warmest Quarter (°C)	Bio10	
	Mean Temperature of Coldest Quarter (°C)	Bio11	
	Annual Precipitation (mm)	Bio12	

Categories	Descriptions	Variables	Sources
	Precipitation of Wettest Month (mm)	Bio13	
	Precipitation of Driest Month (mm)	Bio14	
	Precipitation Seasonality (Coefficient of Variation) (mm)	Bio15	
	Precipitation of Wettest Quarter(mm)	Bio16	
	Precipitation of Driest Quarter (mm)	Bio17	
	Precipitation of Warmest Quarter(mm)	Bio18	
	Precipitation of Coldest Quarter(mm)	Bio19	
Habitat	Elevation (m)	ELEVATION	Based on DEM data,the surface analysis tool in ArcGIS software is used to obtain.
	Aspect (Degree)	ASPECT	
	SLOPE(Degree)	SLOPE	
	Distance from water source(m)	DW	Based on water data of land cover, the Euclidean distance tool in ArcGIS software is used to obtain.
	Normalized Difference Vegetation Index	NDVI	Based on Landsat-8 satellite remote sensing images,the raster calculator tool in ArcGIS software is used to obtain.
	Land cover	LC	Geospatial Data Cloud (https://www.GSscloud.cn/).
Human activity	Night-time lighting	NL	Nighttime lighting data of Luojia-1(http://59.175.109.173:8888/app/login.htm)

2.3. Technical route

The research steps are as follows:

- identifying the current status of CELR's GSs based on FVC;
- evaluating the HQ based on the InVEST model, and evaluating ES based on weighting method;
- determining the distribution of the HQ and ES grades, and thereby identify the key spaces for ecosystem conversation;

- simulate the potential distribution areas of key species based on Maxent model, thereby identify the key space for species protection and determine the main environmental factors that affect the distribution of key species;
- determining the DPOB in GSs in CELR based on the results of GSs, HQ, ES, and potential distribution (Fig. 3).

2.4. Green spaces identification

$$\mathrm{NDVI} = \frac{\mathrm{NIR}-\mathrm{RED}}{\mathrm{NIR}+\mathrm{RED}} \quad (1)$$

$$\mathrm{FCV} = (\mathrm{NDVI} - \mathrm{NDVIsoil})/(\mathrm{NDVIveg} - \mathrm{NDVIsoil}) \quad (2)$$

Whereas the term "GSs" has many diverse meanings, it primarily refers to the traditional urban GSs and regional natural environment in this study. To achieve high-precision GSs identification, we leveraged the convenience and refinement of remote sensing pictures [39–41]. Firstly, radiometric calibration and atmospheric correction in the environment for visualizing images (ENVI) is employed to transform the L1C level remote sensing images into L2A level remote sensing images. We then used infrared and near-infrared bands to construct the Normalized Difference Vegetation Index (NDVI), which yielded the Fractional Vegetation Cover (FVC) at a 95% confidence level. Lastly, high FVC (FVC > 70%) is identified as GSs based on the definitions of GSs, the actual conditions of the CELR, and the principles of vegetation coverage classification. The following is the calculating formula.

In formula (1),(2), NDVI stands for normalized difference vegetation index, NIR for near-infrared band pixel value, RED for red band pixel value, NDVImin for minimum normalized difference vegetation index value, and NDVImax for the maximum normalized difference vegetation index value.

2.5. Ecosystem protection key spaces identification

HQ is an important indicator of regional biodiversity and ecosystem services, reflecting the impact of human activities on habitats. Higher HQ typically corresponds to higher biodiversity levels [42]. ES reflects the degree of response of an ecosystem to external disturbances. Higher self-restoring capability is indicated by a lower ES. On the other hand, a greater ES denotes a poorer capacity for self-restoring [43]. It is possible to determine whether areas should prioritize development or ecological protection by evaluating ES and determining the distribution characteristics of various sensitive areas.

2.5.1. Habitat quality assessment

In the InVEST model, HQ assessment includes the calculation of habitat suitability and degradation, both fall between [0,1]. Among them, habitat suitability serves as the evaluation unit of habitat suitability, and habitat degradation is the degree of interference of threat sources to the habitat. The larger the HQ value is, the higher the suitability it represents. In this study, the HQ was used as an indicator for the assessment of biodiversity to reflect the level of biodiversity in CELR [44]. This indicates that biodiversity is higher in places with high HQ and comparatively lower in areas with low HQ. After determining the extent of habitat degradation, the HQ evaluation module assesses the HQ according to the degree of habitat degradation and habitat suitability. Degradation of habitat is first computed.

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) r_y i_{rxy} \beta_x S_{jr} \quad (3)$$

In formula (3), R is the number of threat sources. Dxj is the degree of habitat degradation of the grid x in the habitat type j. The grid number of the threat source (Yr), the threat source's weight (Wr), the grid's stress value (ry), and the grid unit's accessibility level (βx). The relative sensitivity of different habitat types to threat sources is referred to as Sjr. The threat level of the threat source in grid y to the habitat grid x is denoted by irxy.

The following formula is used to calculate habitat quality.

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^{z}}{D_{xj}^{z} + k^{z}}\right) \tag{4}$$

In formula (4), habitat suitability Hj denotes habitat suitability for j land-use types, and habitat quality Qxj denotes the habitat raster plot x for j land-use types. Z is the normalization constant, which is typically 2.5, k is the semi-saturation constant, or half of the maximum degree of degradation and Dxj is the degree of habitat degradation of the grid x in the habitat type j.

Four categories of data are included in the InVEST model, as per the HQ assessment principle, namely land cover, threat source, threat source spatial distribution, and various habitat sensitivity parameters. Referring to relevant literature [45–47], this study takes into account irrigated fields, dry farming fields,, closed forest land, sparse wood land, shrub land, other forest land, high-, medium-, and low-coverage grasslands, water bodies, reservoirs, and beaches as habitats (with habitat suitability values ranging from 0 to 1). Urban and rural residential areas and other construction land are treated as non-habitat (with a habitat appropriateness value of 0). Major roadways (national highways, expressways), railroads, irrigated fields, dry farming fields, urban and rural residential areas, and other construction land are all potential threat source. Combined with the actual situation in CELR, relevant parameters were determined, and the maximum influence distance and weight of threat sources (Table 2), the sensitivity of various habitats to threat sources and their own habitat suitability (Table 3) were formulated.

Table 2
Threat factor weighting table.

Threat factors	The maximum influence distance/km	Weights	Decreasing distance rate
Irrigated field	4	0.5	Linear
Dry farming field	4	0.5	Linear
Urban construction land	8	0.9	Exponential
Rural construction land	5	0.6	Exponential
Other construction land	8	0.5	Linear
Major highway(national highways, expressways)	3	0.4	Linear
Railway	4	0.4	Linear

Table 3
Threat factor sensitivity table.

Land use type	Habitat suitability	Irrigated field	Dry farming field	Urban construction land	Rural construction land	Other construction land	Railway	Major highway
Irrigated field	0.5	0	1	0.5	0.35	0.3	0.1	0.2
Dry farming field	0.3	1	0	0.5	0.35	0.3	0.1	0.2
Closed forest land	1	0.5	0.6	0.9	0.7	0.5	0.6	0.8
Shrub land	1	0.3	0.4	0.6	0.4	0.8	0.6	0.7
Sparse wood land	1	0.5	0.6	0.8	0.6	0.8	0.5	0.6
Other forest land	0.8	0.5	0.6	0.8	0.6	0.8	0.4	0.5
Grassland with high coverage	0.8	0.5	0.55	0.7	0.55	0.4	0.2	0.25
Grassland with middle coverage	0.6	0.45	0.5	0.65	0.5	0.4	0.15	0.2
Grassland with low coverage	0.5	0.4	0.45	0.6	0.45	0.4	0.1	0.15
Water body	1	0.55	0.65	0.85	0.65	0.5	0.45	0.5
Reservoir lake	0.8	0.6	0.7	0.9	0.7	0.1	0.5	0.55
Bench land	0.7	0.65	0.75	0.95	0.75	0.1	0.55	0.6
Urban construction land	0	0	0	0	0	0	0	0
Rural construction land	0	0	0	0	0	0	0	0
Other construction land	0	0	0	0	0	0	0	0

2.5.2. Ecological sensitivity evaluation

Located at the junction of the plateau lakes and mountains, the CELR has dual characteristics of lake and mountain ecosystems and is also disturbed by human beings due to its particular ecological and tourism values. Using seven distinct indicators of 4 aspects, human activities, topography and geomorphology, the natural environment, and ecosystems, we developed the ecological sensitivity evaluation index system (Table 4).

By choosing the 7 factors in the ecological sensitivity evaluation index system as evidence for ecological sensitivity evaluation of CELR, we divided single-factor evaluation results into 5 levels as extremely high sensitive, high sensitive, moderate sensitive,low sensitive and non-sensitive, and their corresponding scores are 5, 4, 3, 2 and 1, respectively [48]. Ultimately, the ecological sensitivity score for CELR was computed by averaging the 7 factors listed above.

Table 4
Ecological sensitivity evaluation index

Target layer	Index layer	Factor layer
Ecological sensitivity	Topography and geomorphology sensitivity	Elevation
		Slope
	Natural circumstance sensitivity	Vegetation coverage
		Water environment
	Ecosystems sensitivity	Land use
	Human activities sensitivity	Road
		Night-time light

2.6. Species protection key spaces identification

The probability map of the potential distribution of species output by the Maxent model range from 0 (unsuitable environment) to 1 (highly suitable habitat). Using current species distribution data and pertinent environmental variables, the MaxEnt is a general method for making predictions or drawing conclusions from incomplete information.

We predicted the potential distribution hotspots of key species in the CELR using the MaxEnt 3.4.4 model. In the beginning load the environmental data and the important species distribution data (.csv file) into the model. Following that, a random selection of 25% of the data was made to serve as the test data. Bootstrap was utilized for verification, with 1,000 iterations and 10 repetitions. Last but not least, determine the significance of environmental elements using the Jackknife approach. The receiver operating characteristic curve (ROC) and the area under the curve (AUC) were used to assess the model prediction's accuracy. The region under the ROC curve, or AUC, is a graphical tool used to assess a binary classification model's performance. AUC values range from 0 to 1, with 0.75 to 0.85 indicating good accuracy and 0.85 to 1 showing great accuracy [49].

3. Results and Discussion

3.1. Result of green spaces identification

Based on FVC, the GSs of the study area was divided, as shown in Fig. 4. The GSs makes up roughly 1085.64 km^2, or 69.37% of the CELR's total area. Those that follow are the features of green spaces distribution.

- The GSs has the following features such as "less distribution in the middle, more distribution in the surround, scattered distribution in the waterfront, and concentrated distribution in the mountainous" ;
- The GSs within the built-up area are mainly urban parks and waterfront GSs, mainly concentrated in Erhai Moon Wetland Park, Hai She Ecological Park and Erhai Ecological Corridor;
- Outside of the urban built-up area, the GSs is primarily found in the form of forest parks and natural woodlands, among which are Cangshan Global Geopark, Canglang Peak, Zhemo Mountain.

3.2. Result of key spaces for ecosystem protection

3.2.1. Result of habitat quality evaluation

The results of the InVEST model show that the HQ in CELR is between 0 and 1, and HQ grades are extremely high (0.8–1), high (0.6–0.8), medium (0.4–0.6), relatively low (0–0.4), and low (0). Figure 5 displays the spatial distribution of HQ, whereas Table 5 displays the statistical results of the area and proportion of habitats at each level. According to the results, the HQ is high, and the high HQ areas were significantly more than the other three types. From the perspective of spatial pattern distribution, the HQ presents a spatial pattern of high in the east and low in the west, with the extremely high HQ areas mainly concentrated in ecological conservation area namely Cangshan mountain region and the northeast side of the CELR.

Overall, the farmland surrounding the built-up region reduces the ecological impact of urban construction by acting as a beneficial buffer for the ecosystem integrity of grassland and forest land. However, this area continued to experience significant issues with habitat degradation and landscape fragmentation as a result of the impact of Dali's tourism boom, which included the reclamation of forest land, the occupancy of farmed land, and the construction of residential building. However, habitat degradation will be more threatened if urban land expansion is not controlled and planning and development guidelines are not followed. As a result, GSs should be planned sensibly and scientifically in order to improve the protection of HQ [50, 51].

Table 5
Area and proportion of each habitat level of habitat quality.

Habitat quality level	[illegible]	[illegible]	[illegible]	[illegible]
Area/km^2	763.87	300.64	371.47	129.02
Proportion/%	48.81%	19.21%	23.74%	8.24%

3.2.2. Result of ecological sensitivity evaluation

The single-factor ES assessment is shown in Fig. 6. After superposition, the comprehensive ES assessment result of the Erhai Lake area is obtained (Fig. 7). The ES of the study area is mainly extremely high ES and high ES. The total area of non-ES area is 137.22 km^2, the low ES area is 229.34 km^2, the total area of medium ES area is 327.44 km^2, and the total area of high ecological sensitivity area is 399.35 km^2. The total area of extremely high ES areas was 471.64 km^2, which made up 8.7%, 14.65%, 20.92%, 25.52%, and 30.14% of the study area's total area, respectively .

From the perspective of spatial distribution, the comprehensive ecological sensitivity and the single-factor sensitivity are basically consistent. The distribution characteristics of ES in the CELR could be summed up as follows, the dividing line is 2170 meters above sea level, and the ES above it is high, while the ES below it is somewhat low. While lesser ES is found in the southern Erhai Lake, extremely high and high sensitivity area are primarily found in high-altitude woods. Furthermore, medium sensitive zones are dispersed throughout the area between high and low sensitivity, while low-sensitivity areas are primarily arranged in a circle with Erhai Lake at its core. Overall, extremely high sensitivity areas make up 30.1% of the CELR, followed by high sensitivity area. Non sensitivity areas only cover 137.22 km^2, with a proportion of up to 8.7%.

3.2.3. Result of key spaces for ecosystem protection

We picked an extremely high HQ area and extremely high ES area based on the results of the HQ and ES evaluation, and superimposed these two regions to obtain the key space for ecosystem protection, which has a total area of 1029.54 km^2 and 65.78% of the CELR (Fig. 8). The key spaces for ecosystem protection in CELR are mainly distributed in mountainous regions such as Qiaoding Mountain, Diancang Mountain, and Zhonghe Peak, as well as along the Erhai Lake from Wenbi Village to Xiaoputuo to Changyu Village and from Shuanglang Village to Beihai Guanyin Pavilion.

According to the Dali National Land Space Master Plan (2021–2035), the northeast, southwest, and southeast sides of the CELR, which were the ecological conservation areas of the Jinsha River Basin, Lancang River Basin, and Hainan Mountain, respectively, are largely protected and have seen less exploitation and utilization. Cangshan Mountain and Erhai Lake constitute significant national nature reserves. As a result, these locations are mostly home to important spaces for ecological protection. It is pertinent to note that, despite being both coastal areas of Erhai Lake, there are very few significant regions for ecosystem protection on the lake's west and south banks, whereas there are numerous significant locations for ecosystem protection spread out from the east bank to the north bank. This is most probably due to the dense residential areas in Dali Town, Xiaguan Town, and Fengyi Town, as well as the ecological restoration that has begun and the yearly decline in the development and intensity of occupancy of the eastern mountain of Erhai Lake.

3.3. Result of key spaces for species protection

Based on 26 environmental variables, we predicted the potential distribution areas of key species in CELR under current climate conditions. During model validation, MaxEnt simulations yielded a mean AUC of 0.870 over 10 iterations, confirming high predictive performance for reconstructing keystone species distributions with substantial reliability. These results demonstrate robust simulation capabilities suitable for subsequent studies. The ROC is shown in Fig. 9.

According to the results of the Jackknife test (Fig. 10), we found that the environmental variables with the greatest gain when used alone were: NDVI, bio7,bio2and NL, which indicates that these environmental factors contain some information that other environmental factor variables do not contain. Considering comprehensively, these are the 4 most important environmental factors affecting the spatial distribution of key species in CELR.

The contribution of each environmental variable to the MaxEnt model (Table 6) indicates that BIO17 is the main limiting factor for the potential distribution of key species in CELR, with a single-factor contribution rate of 25.6%. Next come BIO7,NDVI, NL, and LC. The combined contribution rate of these 5 environmental factors is 71.2%. Permutation importance values are random substitutions of the value of each environmental factor on the background training presence data, where larger values indicate greater dependence on that particular variable. In terms of permutation importance values, BIO7, BIO3, BIO12, BIO6 and NDVI are the 5 most important environmental variables. Overall, climate are important factors influencing the prediction model of the distribution of key species in the CELR. Table 7 shows the classification criteria of suitable areas and the statistical results of various types of suitable areas.

The following traits of "more in the west and less in the east" and concentration in mountain and lakeshore regions characterize the distribution of key species in the CELR (Fig. 11).

- Concentrated area of highly and moderately suitable areas for key species are found in the CanGSshan-Erhai National Nature Reserve on the west shore of Erhai Lake;
- The highly suitable areas have formed three key species distribution hotspots in Xiaguan Town, Dali Town and Xizhou Town respectively, accounting for approximately 1.75% of the total area in CELR;
- The moderately suitable areas are mainly distributed in the lower-altitude lakeside areas of five towns, namely Xiaguan Town, Dali Town, Yinqiao Town, Wanqiao Town and Xizhou Town, as well as the peripheral areas of the high-suitable areas, accounting for approximately 4.81% of the total area in CELR;
- The proportion of unsuitable areas in CELR is about 93.44%. In the eastern part of the study area, it is basically an unsuitable zone for key species, with only small areas of suitable zones for key species sporadically distributed along the eastern coast of Erhai Lake.

Table 6
Contribution (%) and permutation importance of environmental factors affecting the distribution of key species.

Environmental variables	Percent contribution (%)	Permutation importance (%)
Bio17	25.6	0.1
Bio7	15.1	40.7
NDVI	12.6	6.9
NL	10.6	1.6
LC	7.3	1.3
DW	6.4	4
ASPECT	4.5	2.7
Bio6	3.5	7.7
Bio4	2.9	5.5
Bio3	1.9	10.8
Bio12	1.8	9.2
SLOPE	1.5	0.7
ELEVATION	1.4	2.3
Bio15	1	2
Bio2	0.8	0.5
Bio13	0.7	0.7
Bio16	0.6	1.6
Bio10	0.5	0.7
Bio14	0.4	0.2
Bio9	0.2	0
Bio18	0.2	0.4
Bio5	0.1	0.1
Bio11	0.1	0.2
Bio19	0.1	0
Bio8	0.1	0
Bio1	0	0

Table 7
Suitable areas classification criteria.

Probability/%	Suitable areas classification	Area/km^2	Proportion/%
80–100	Highly suitable areas for key species	27.45	1.75
60–80	Moderately suitable areas for key species	75.18	4.81
0–60	Non-suitable distribution area for key species	1462.37	93.44

3.4. Spatial characteristics of biodiversity in Erhai Lake

In this study, we superimposed the HQ index, ES index and key species distribution index using the grid calculator in ArcGIS to obtain the comprehensive biodiversity index (Fig. 12) and quantitatively analyzed the DPOB in the CELR.

The results show that the areas with a high CELR comprehensive biodiversity index are mainly concentrated in the mountainous areas of the west and northeast. Among them, the overall level of biodiversity in Shuanglang Town, Xizhou Town and Wanqiao Town is significantly higher than that in other towns. These areas are all high-altitude mountainous regions far from the city center and have a relatively high forest coverage rate. But we also noticed that the biodiversity along the coast of Erhai Lake is at a low level, especially in the southeast, south and southwest of Erhai Lake. The land use types in areas with low biodiversity levels are mainly construction land and cultivated land, and thus are more severely affected by human activities.

3.5. Distribution pattern of biodiversity in green spaces

In this study, extremely high and high HQ areas (HQ 0.6-1) and extremely high ES areas were superimposed to generate the key space for ecosystem conservation. The area with a distribution probability of key species greater than 0.6 was defined as the key space for species protection. The next step is to superimpose the key spaces for ecosystem conservation, species protection and GSs to obtain the DPOB in GSs in CELR. The classification methods of various types of GSs are shown in the Fig. 13.

The core GSs were 13.21 km^2, accounting for only 1.21% of the GSs area, which were mainly distributed in CanGSshan National Geopark. The GSs with high quality ecosystem were 842.37km^2, accounting for 77.6% of the GSs area, which were mainly distributed in the high-altitude mountain forest. The GSs suitable for key species were 20.98 km^2, covering for 19.34% of the green spaces area, which were found to be mainly distributed in flat area on the west bank of Erhai Lake. The GSs of non suitable area were 201.73 km^2, accounting for 18.59% of the GSs area,showing a highly fragmented distributing characteristics in the CELG (Fig. 14).

4. Discussion

4.1. Distribution pattern of biodiversity

Based on the above studies, it can be found that most of the GSss in CELR is green spaces with high quality ecosystem, which is mainly distributed in the mountain forest area in the west and northeast of the study area. The distribution of green spaces suitable for key species and core green spacess is relatively small, with a linear distribution on the west side of the study area. The core green spaces is only 13.21 km2. Meanwhile, there is still a considerable area of green spaces without suitable habitat, accounting for as high as 18.59%.

An analysis of its distribution pattern reveals that the majority of the core green spacess are located in areas far from the built-up areas of cities and are forestlands with relatively rich plant layers. The distribution area of green spaces with high quality ecosystem is evenly distributed over a large area in the high-altitude areas around Erhai Lake, indicating that the overall HQ of the GSss is relatively high.It is worth noting that the core GSs and the GSs suitable for key species not only relatively small in areas, but also highly concentrated in the west side of Erhai Lake, while these two types of GSs have not been found in the eastern area of Erhai Lake. These findinGSs suggest that the region between CanGSshan and Erhai Lake is crucial for future DPOB optimization.

By comparing and analyzing the distribution pattern of biodiversity in the green spaces around Erhai Lake with the "Territorial Spatial Master Plan of Dali (2021–2035)"(TSMP), we found that: The green spaces with high quality ecosystem is basically consistent with the protection areas of the CanGSshan Natural Ecological Reserve, the Jinsha River Basin Ecological Conservation Area, the Lancang River Basin Ecological Conservation Area and the Hainan Mountain Ecological Conservation Area as stipulated in the TSMP. The core green spaces is basically located within the ecological protection red line, and the green spaces without suitable habitat is located within the urban development boundary and the permanent basic farmland. Although both are part of the Erhai Lake coastal area, there are basically no green spaces with high quality ecosystem on the west and south coasts of Erhai Lake. However, there are many distributions from the east to the north coasts of Erhai Lake. This situation is related to the dense residential areas in Dali Town, Xiaguan Town and Fengyi Town, while the mountain in Haidong has been recovering year by year.

Overall, the research results on the DPOB that combines ecosystems and species are basically consistent with the conservation goals of TSMP. Moreover, the GSs for biodiversity conservation has been further divided, and conservation gaps and core conservation areas have been identified, indicating that this research method has high accuracy and feasibility.

4.2. Suggestions for the restoration and management of green spacess

Based on the research results of the DPOB in GSs, we have proposed suggestions for graded restoration and management of GSs.

- Although the core green spaces has the dual advantages of high-quality ecosystems and suitability for key species, from the perspective of ecological networks, biodiversity consistently declines in fragmented habitat islands[52].
- Numerous studies have proved that the construction of ecological corridors plays an important role in promoting biological exchange and maintaining ecological balance [53,54]. Therefore, we suggested building ecological corridors between core green spacess, such as planting native tree species and shrubs between Haise Park and CanGSshan Mountain to form green corridors. Secondly, by making use of the existing natural terrain and vegetation, an ecological corridor network should be planned and constructed to connect different nature reserves. The core green spaces can be connected with the surrounding wetlands and forests through ecological corridors, effectively promoting the diffusion and exchange of species among different habitats and enhancing the stability of the regional ecosystem.
- In green spaces with high quality ecosystem, we suggested creating a diverse habitat by increasing the complexity of forest layers and structures. In addition, based on the previous review of key species in the Erhai Lake area, we have also proposed a strategy for building key species. By fully utilizing the high-quality habitat and ecosystem of the region, adopting a "recruitment and attraction" strategy for key local species, and implementing habitat creation measures such as planting foodborne plants and providing safe shelter areas, we aim to attract species with strong migratory abilities to settle here. At the same time, through scientific and artificial introduction, we aim to introduce species with weaker migratory abilities or smaller wild populations into the region.
- For green spaces suitable for key species, we should focus on the protection and management of key species within the region, establish a database of key species protection information, and integrate and manage information on land use changes, dynamic distribution of key species, and the effectiveness of protection measures. Within the built-up area, it is recommended to plan and set up ecological buffer zones on the periphery, strictly control human interference, and avoid negative impacts on key species.

- Green spaces without suitable habitat have great potential for improving habitat quality and biodiversity. With their wide distribution range, low ecological sensitivity, and rich and diverse terrain and landforms, they have become the most suitable type of GSs for creating harmonious coexistence between humans and nature, and between humans and organisms. We suggest using artificial plant communities, biological attraction, ecological restoration, and the establishment of ecological parks to transform green spaces without suitable habitat into ecologically suitable and biologically diverse oases.

4.3. Limitations

The limitations of this study lie in the following: Firstly, the key species distribution data adopted in this study rely on digital herbarium. The collected data may have deviations compared with the species data collected in the field, or some of them may not be available due to reasons such as confidentiality and sensitivity, resulting in incomplete data collection and deviations in the research results of the MaxENT model. Future research can solve this problem by collecting more species data on the field. Although numerous scholars' research has confirmed that the MaxENT model can accurately predict the distribution of species, in this study, we also found that in some densely populated human activity areas and high-altitude areas where the distribution of key species is lacking, the simulation results show that there is still potential for species distribution in these areas. To mitigate this deviation between MaxEnt predictions and reality, future simulations could be refined by excluding habitat definitively assessed as unsuitable. This approach serves to enhance the accuracy of identifying potential distribution areas.

5. Conclusions

In this study, the simulation results of HQ, ES, and potential distribution were used as alternative measures of biodiversity in order to clarify the DPOB in GSs in CELR. The research framework accurately depicted the geographical heterogeneity of biodiversity in CELR and reflected the various aspects that human and natural factors affect biodiversity.

The main finding of this research are as follows: BIO17, BIO7, and NDVI were the most important environmental factors affecting the habitat distribution of CELR key species. Among them, BIO17 exhibited the most considerable influence, with a contribution rate of 25.6%. In terms of spatial distribution, the GSs of unsuitable areas are numerous and dispersed, the core GSs and the GSs with key species are few and concentrated, and the GSs with high-quality ecosystem are numerous and uniform. On the western side of the CELR, Four types of green spaces were distributed,as well as large areas of non-green spaces. This area has a great deal of spatial an heterogeneity because of the complicated topography and frequent human activity. The GSs in the research area's north, east, and south is distinguished by the mosaic distribution of both high-quality ecosystem and green spaces of unsuitable areas. It is indisputable that as cities grow, they are continuously encroaching on natural biological areas, turning grasslands and forests into cultivated land or construction land.

In summary, this study offers valuable information for revealing the DPOB in GSs in CELR. It is suggested that targeted planning be carried out according to different types of GSs to enhance the protection of biodiversity and ecosystems, thereby promoting the sustainable development of high-altitude lake cities.

Author: Conceptualization, P.L.; Data curation, P.L., Y.L. and H.X. ; Methodology, P.L.; Software, P.L.; Writing—original draft, P.L.; Writing—review & editing, Y.L., Y.S. and H.X..; P.L. performed the data analysis and wrote the manuscript; P.L., Y.L., H.X., and Y.S.. corrected our manuscripts. All authors have read and agreed to the published version of the manuscript.

Declarations

Conflicts of Interest:

The authors declare no conflicts of interest.

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Author Contribution

Conceptualization, P.L.; Data curation, P.L., Y.L. and H.X. ; Methodology, P.L.; Software, P.L.; Writing—original draft, P.L.; Writing—review & editing, Y.L., Y.S. and H.X..; P.L. performed the data analysis and wrote the manuscript; P.L., Y.L., H.X., and Y.S.. corrected our manuscripts. All authors have read and agreed to the published version of the manuscript.

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Data Availability

Data will be made available on request. If you have any questions, please contact the only corresponding author, “Yuhong Song”.

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Figures

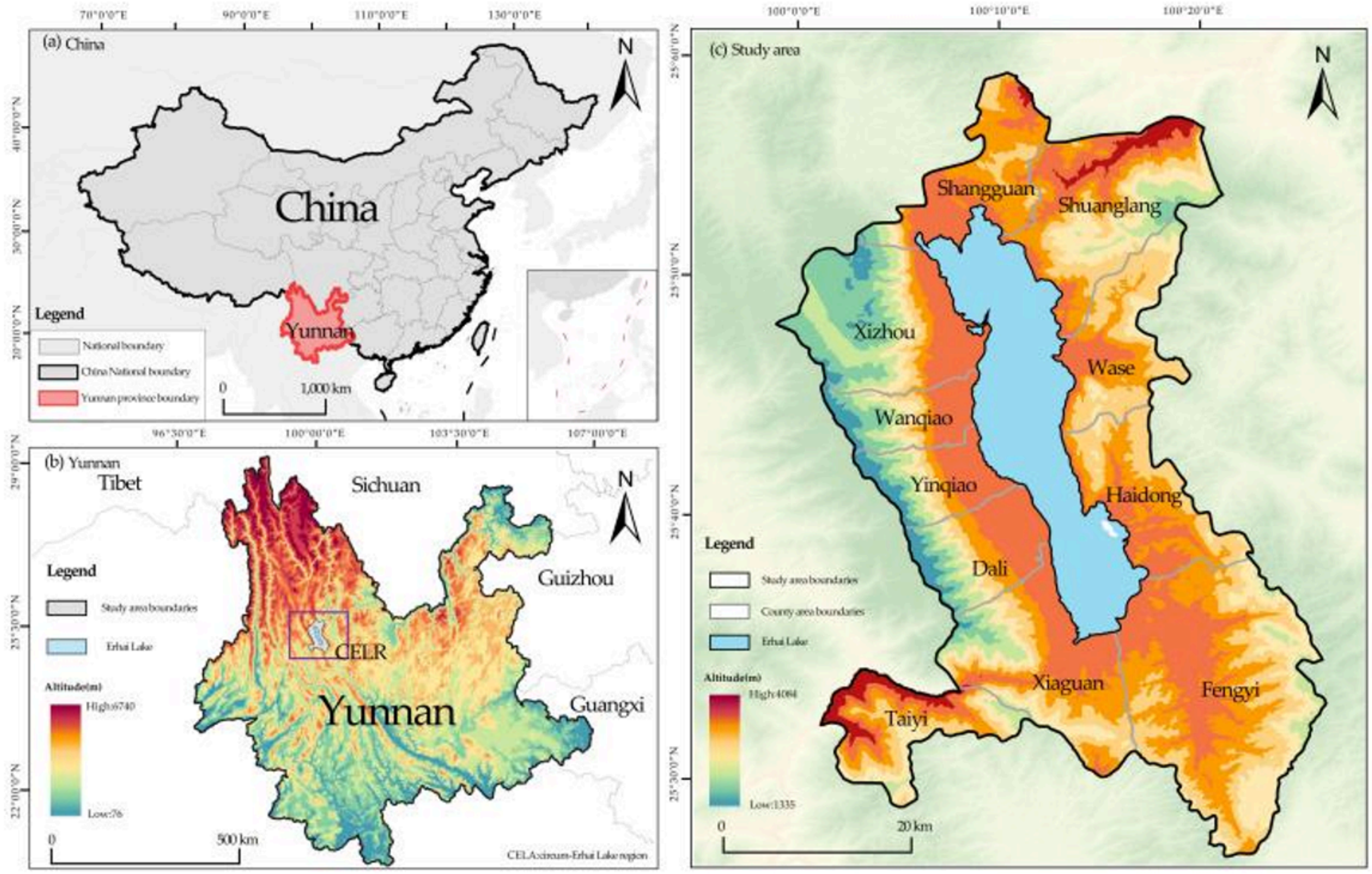

Figure 1

Geographical location of study area.

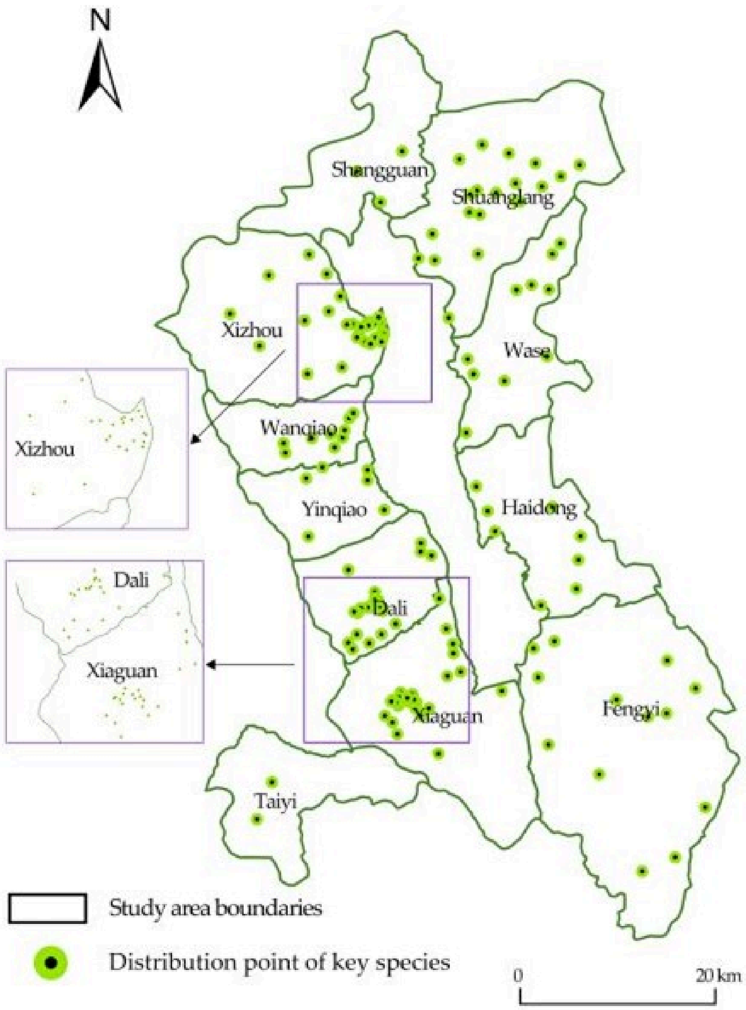

Figure 2

Distribution record of key species.

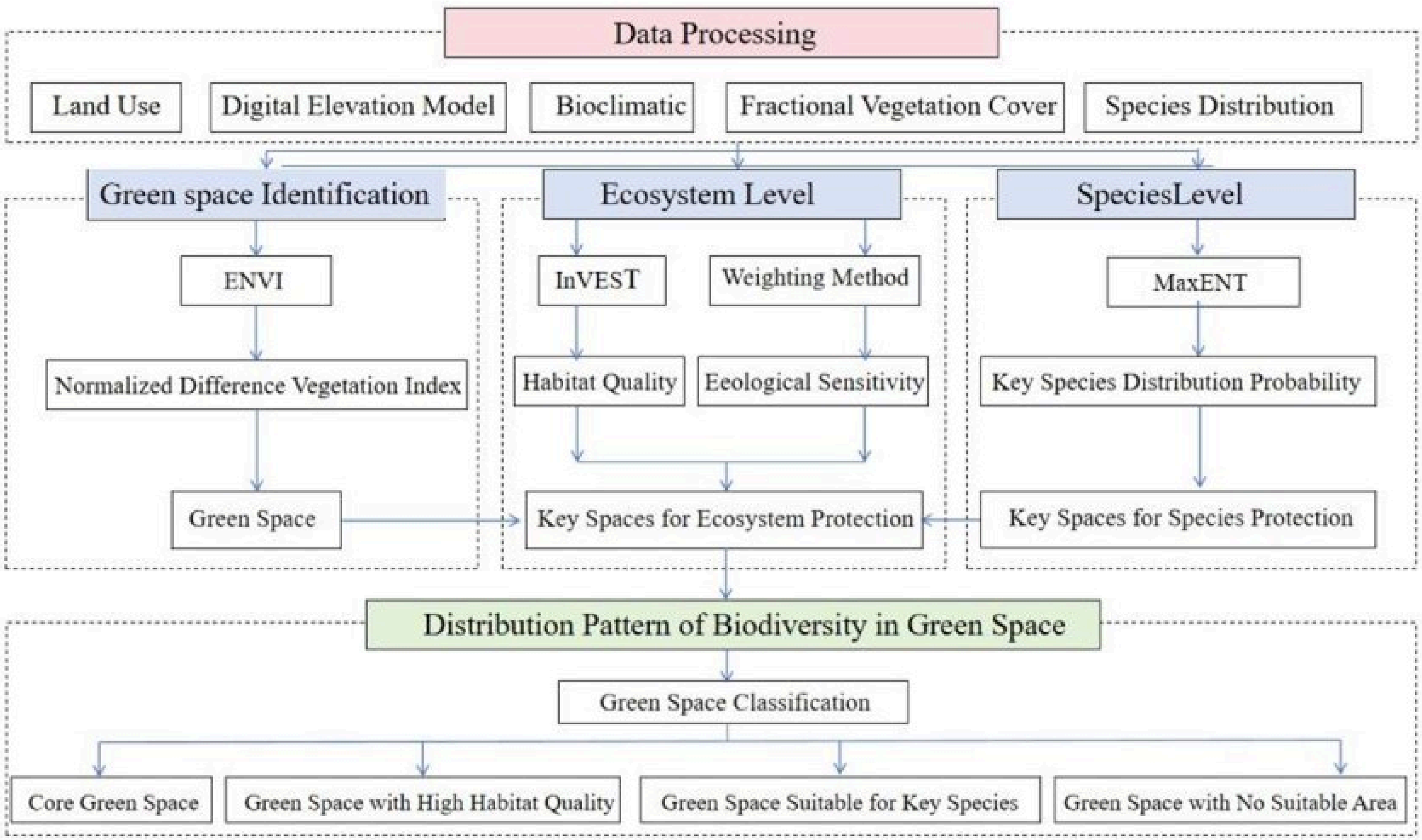

Figure 3

Workflow.

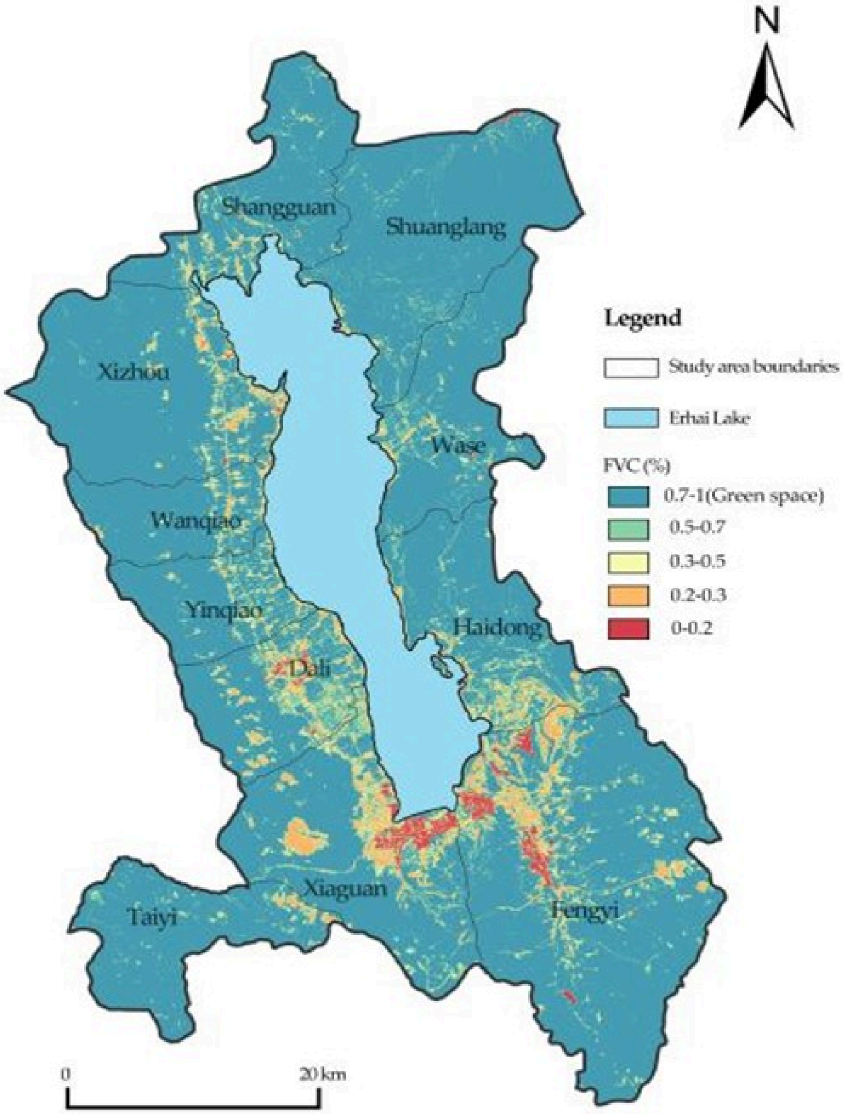

Figure 4

Distribution of green spaces.

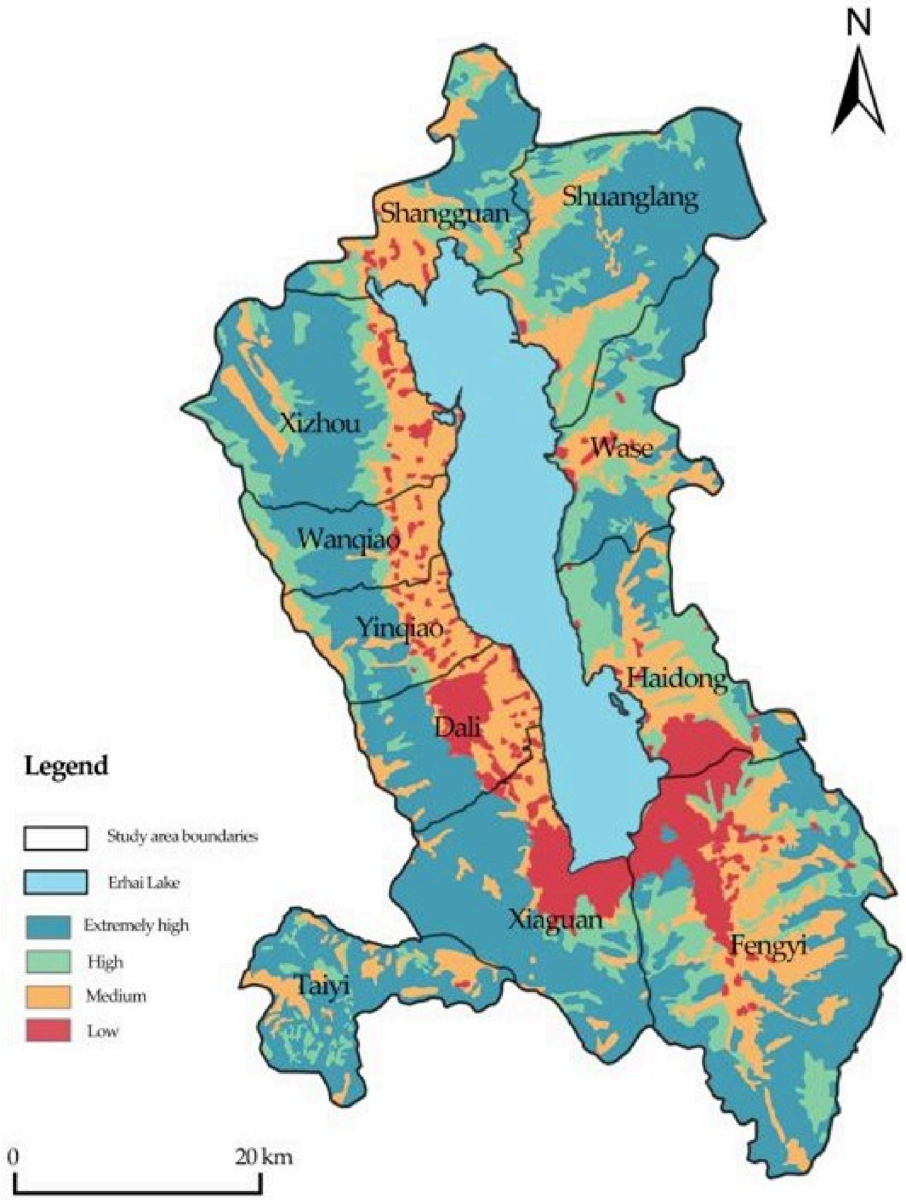

Figure 5

InVEST habitat quality map

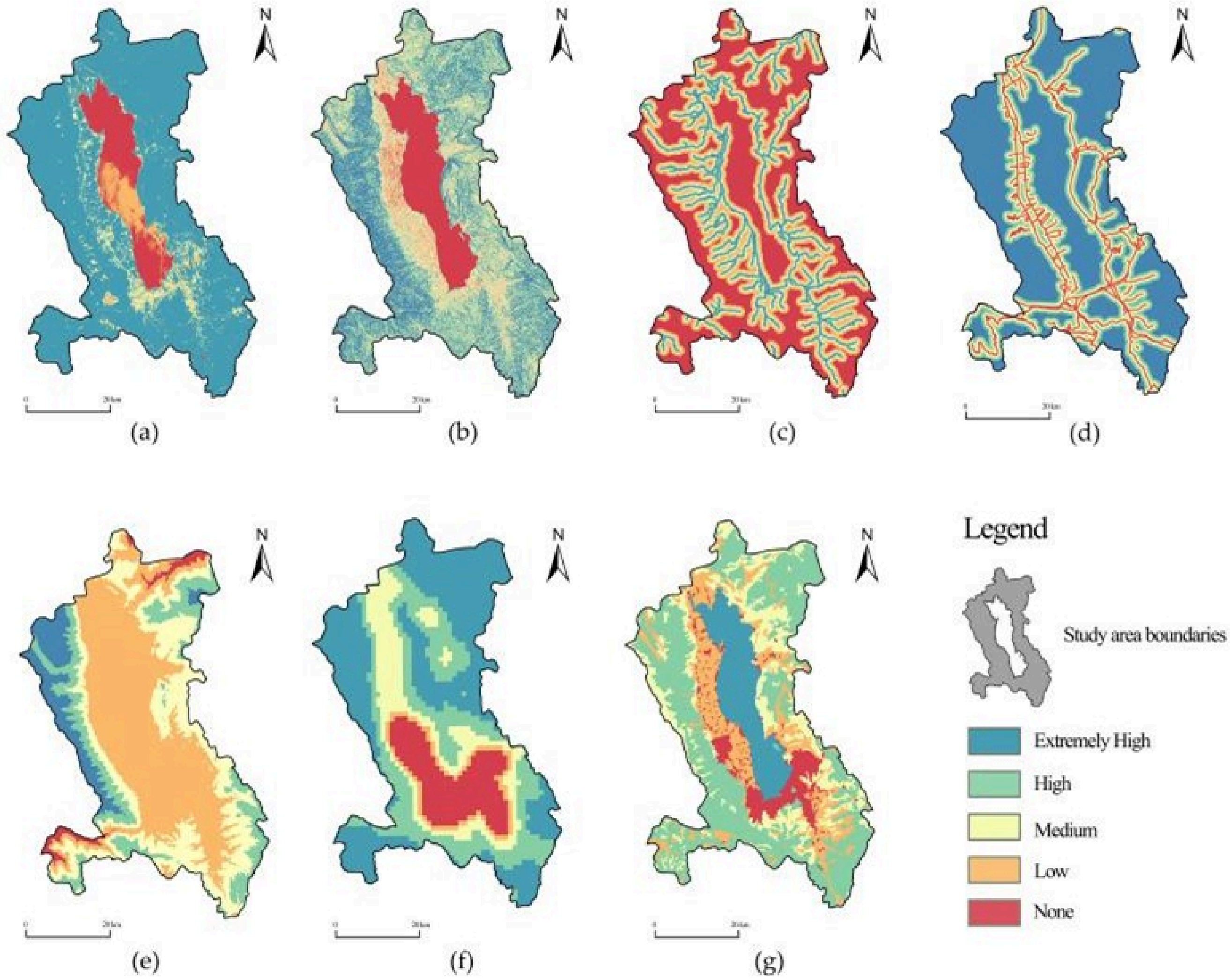

Figure 6

(**a**) Vegetation coverage; (**b**) Slope; (**c**) Water environment; (**d**) Road; (**e**) Elevation; (**f**) Night-time light; (**g**) Land use.

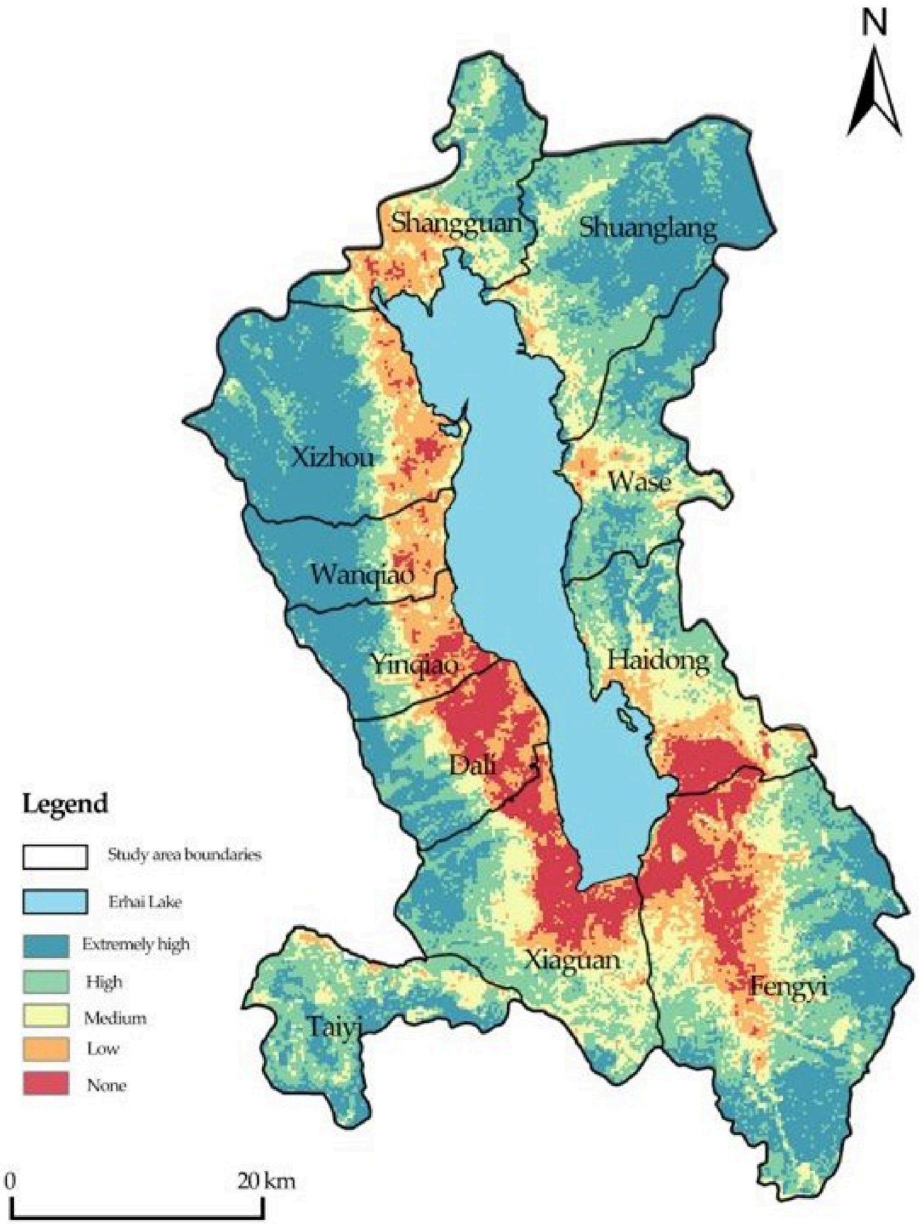

Figure 7

Comprehensive ecological sensitivity map.

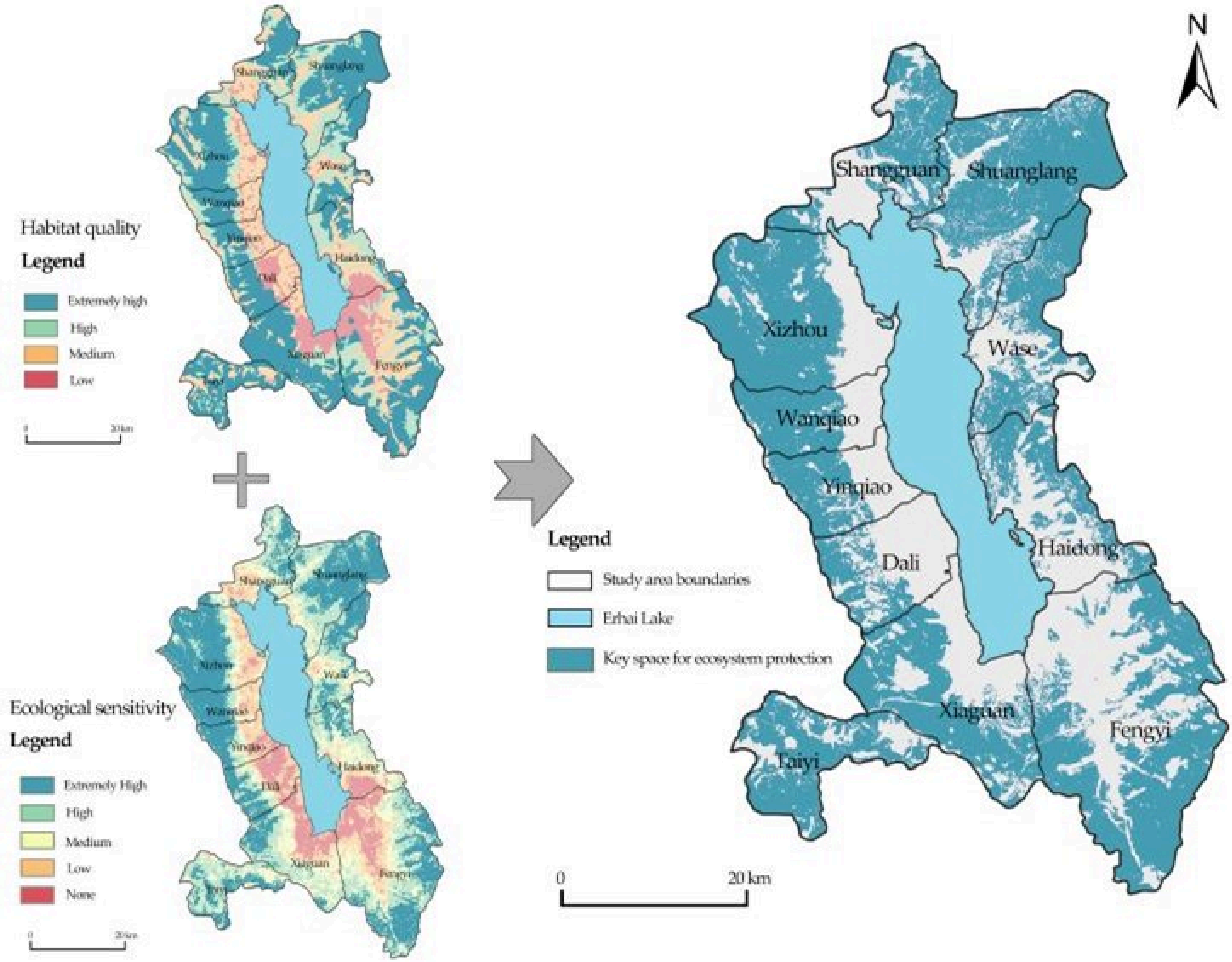

Figure 8

Key space for ecosystem protection mapping by habitat quality and ecological sensitivity overlays.

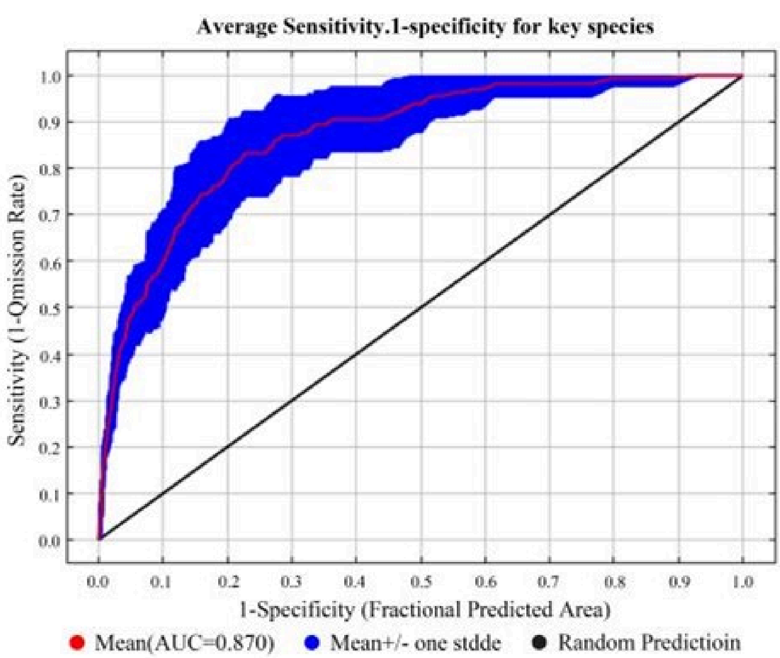

Figure 9

ROC test of the MaxENT result.

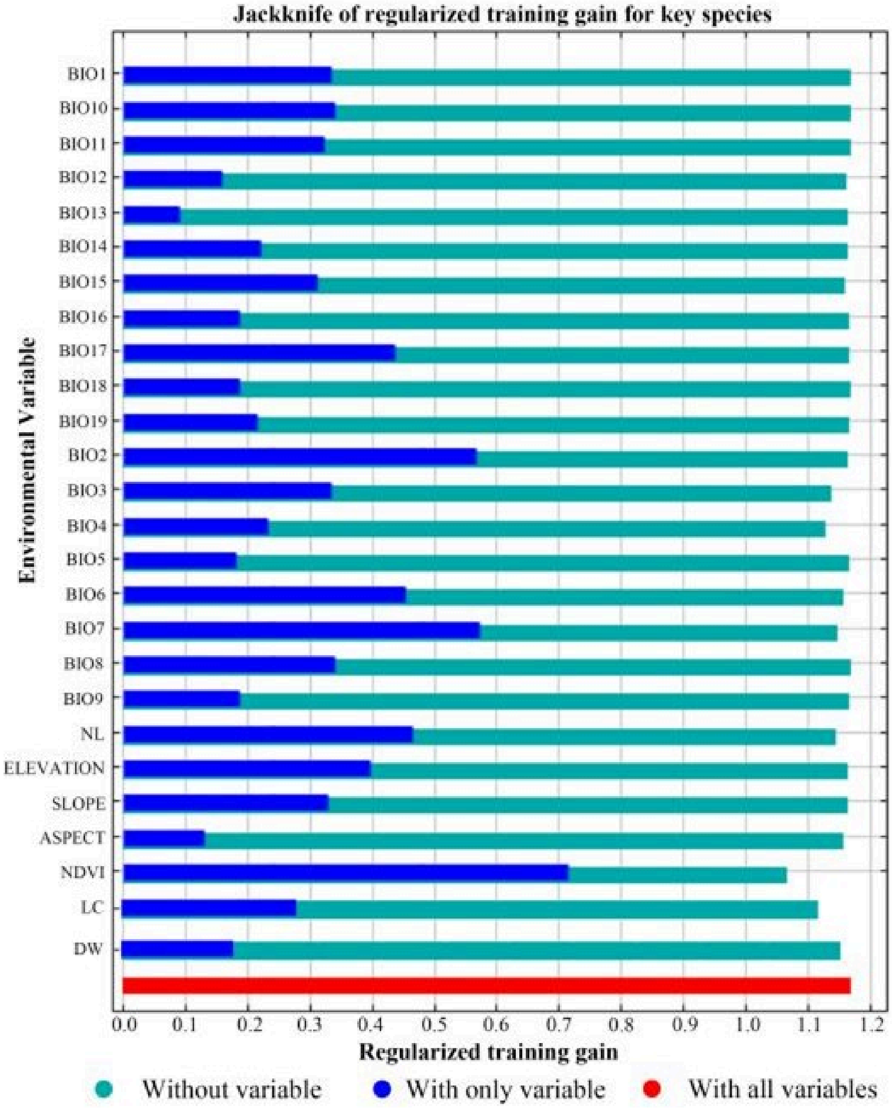

Figure 10

The jackknife test result for the environmental factors.

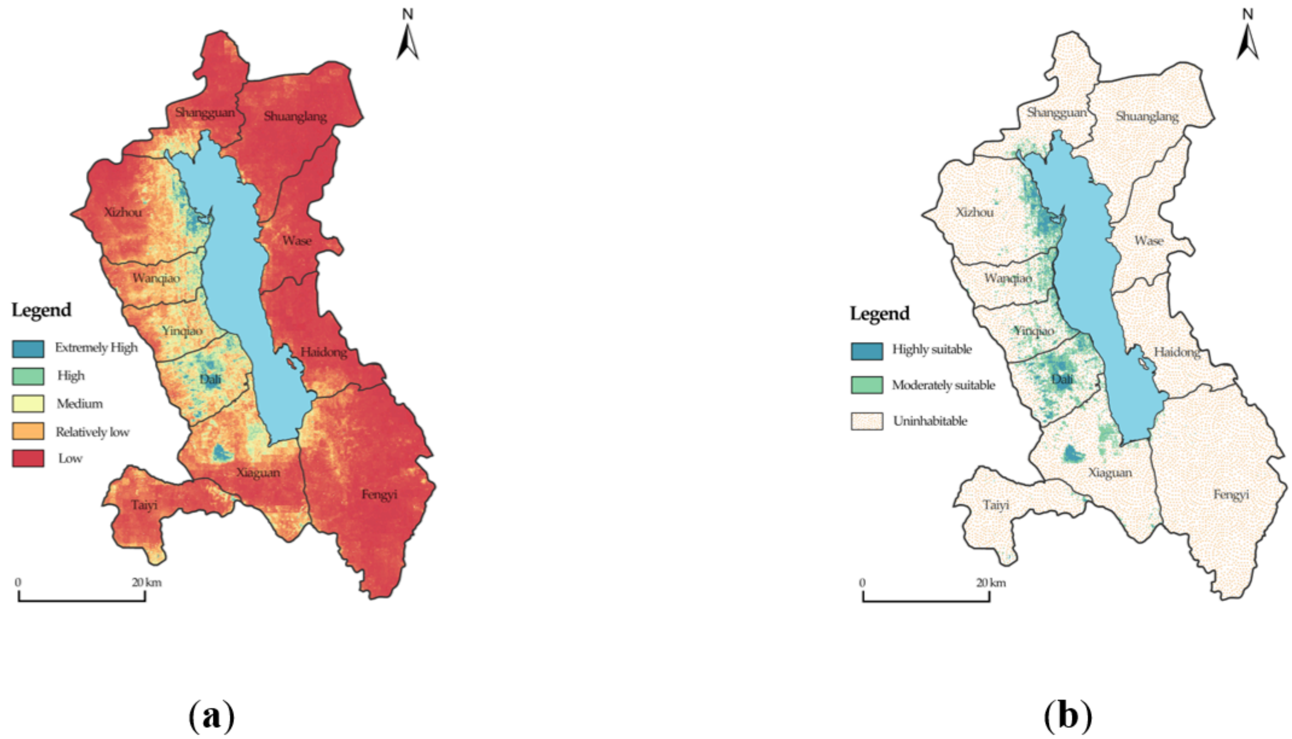

Figure 11

(**a**) Results of key species distribution probability; (**b**) Key space for species protection.

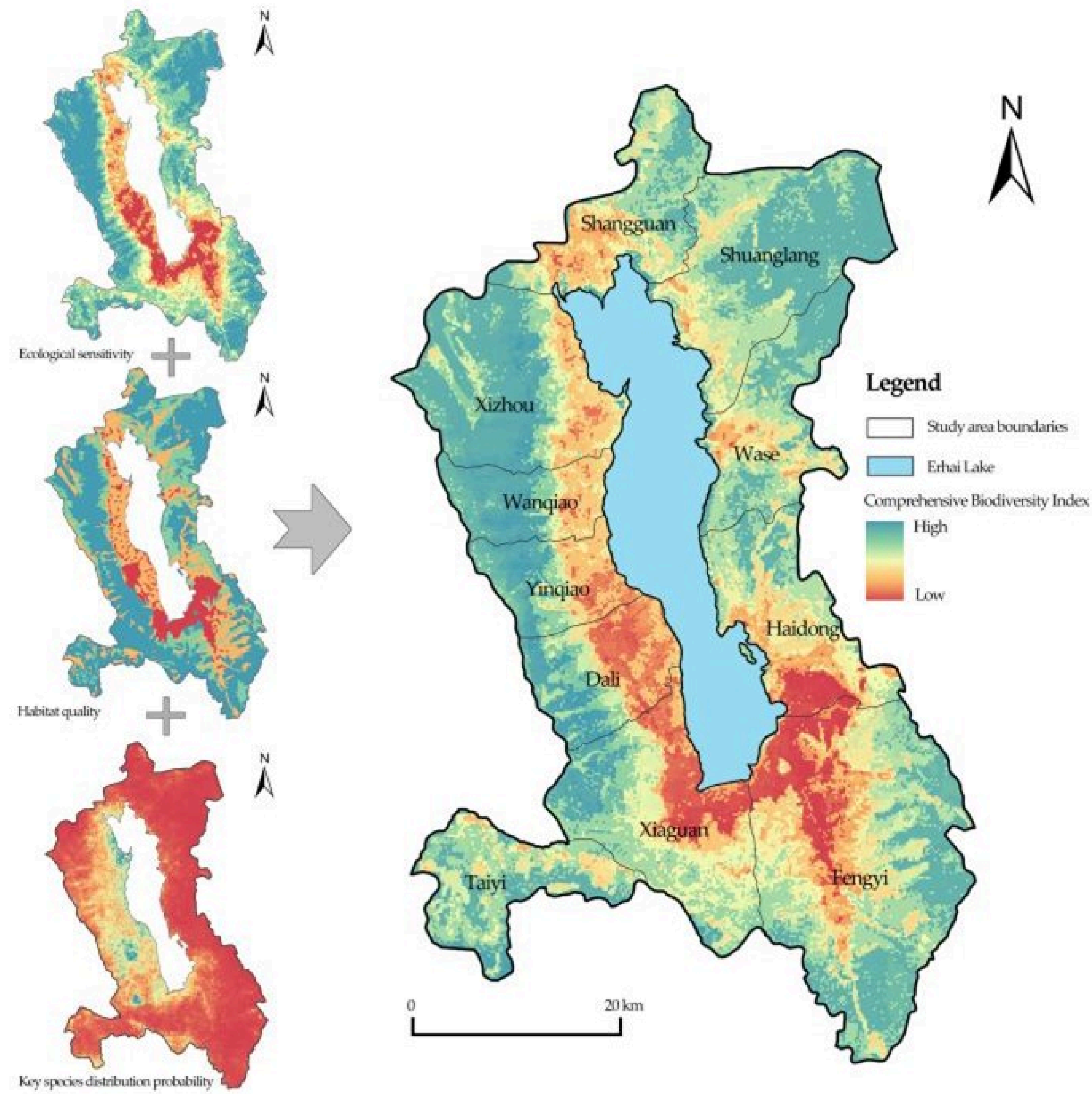

Figure 12

Comprehensive biodiversity index map.

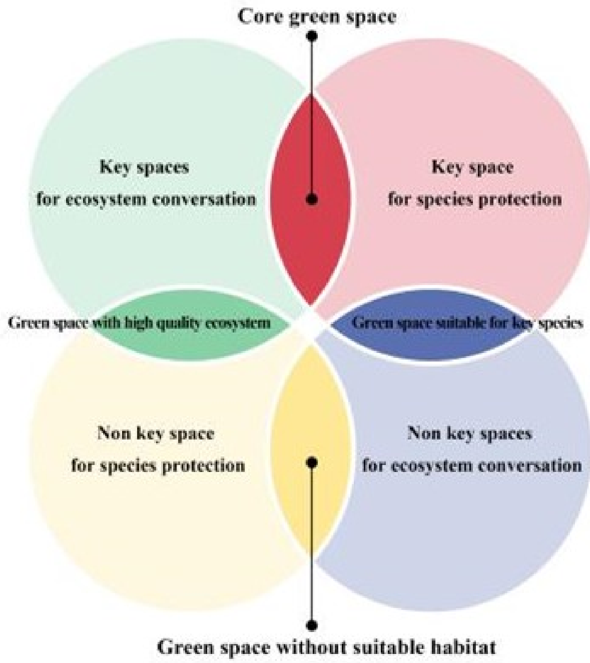

Figure 13

Classification methods of green spaces.

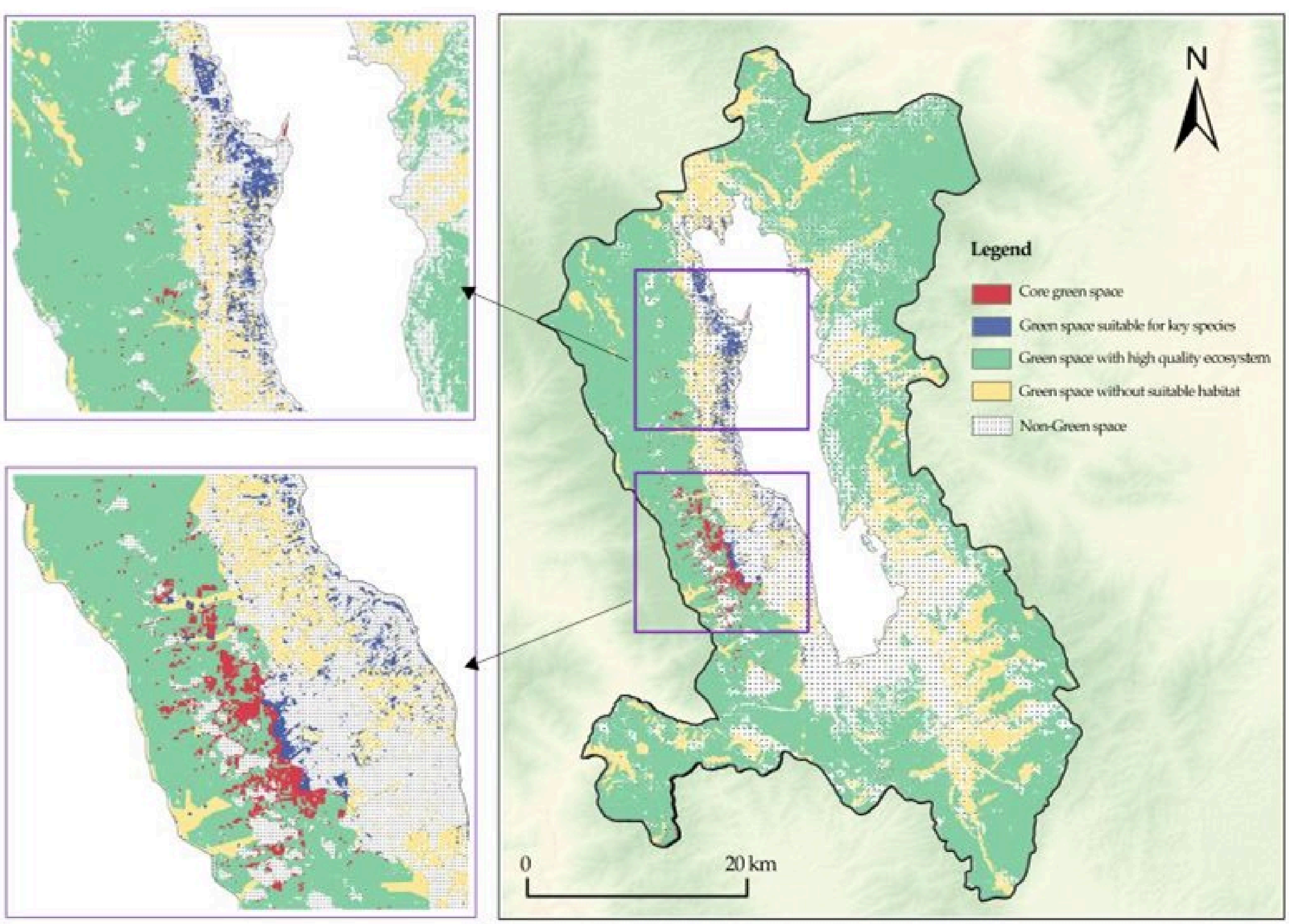

Figure 14

Distribution of different types of green spacess.