



Spatiotemporal patterns of habitat quality and its topographic gradient effects of Hubei Province based on the InVEST model

Pengnan Xiao¹ · Yong Zhou¹ · Mengyao Li¹ · Jie Xu²

Received: 6 July 2021 / Accepted: 14 March 2022 / Published online: 7 April 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract

Based on the DEM (digital elevation model) data and land use data from 2000, 2005, 2010, 2015 and 2020, the spatiotemporal differentiation characteristics of habitat quality in Hubei Province were evaluated by the InVEST model (Integrated Valuation of Ecosystem Services and Tradeoffs) and GIS (Geographic Information System) spatial analysis method, and the topographic gradient effect on habitat quality was analyzed by regression analysis and terrain index. The spatial distribution of habitat quality in Hubei Province was quite different, and the overall level was high. High-quality habitats were mainly located in hilly regions and water areas, while low-level habitats are mainly distributed in agricultural areas and urban areas. From 2000 to 2020, the high-level habitats in Hubei Province tended to degenerate to low-level habitats, and the average habitat quality decreased slightly. The habitat quality in most areas of Hubei Province had no obvious change from 2000 to 2020, and the overall spatial features were "rising in the southeast and decreasing in the middle". With the elevation of the terrain grade, the number of county-level units with high-level habitat quality increased gradually, and the average habitat quality increased accordingly. From 2000 to 2020, the habitat quality of the first-class terrain improved, while the habitat quality of the other class terrain showed a downward trend. The results are helpful to discover the spatiotemporal change process of habitat quality in Hubei Province, and provide theoretical support for biodiversity conservation and land use planning in Hubei Province.

Keywords Land use change · Terrain index · InVEST model · Spatiotemporal pattern · Habitat quality

1 Introduction

Habitat quality, which is the capacity of ecosystem to support biological survival with appropriate condition, is regarded as an important characterization and reflection of regional biodiversity and ecological service level (Muyi et al. 2020; Alaniz et al., 2021; Wu, Sun, et al., 2021; Wu, Dai, et al., 2021), serving as an irreplaceable part to ensure

✉ Yong Zhou
yzhou@mail.ccnu.edu.cn

Extended author information available on the last page of the article

ecosystem security and improve mankind well-being (Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021; Thomas et al., 2021; Yuan et al., 2019). Different habitat qualities have a direct relationship with the service capacity of regional ecosystems (Caixian et al., 2020; Lee & Jeon, 2020). The pattern, intensity, and pattern of land use will lead to transform in ecosystem structure and function, which will have an important impact on habitat quality and biological diversity (Budnik et al., 2021; Tang et al., 2021; Zhang, Gao, et al., 2020; Zhang, Song, et al., 2020). Habitat quality assessments can reflect the advantages and disadvantages of regional ecosystem functions to a certain extent, due to the differences in ecosystems in different regions, resulting in spatial heterogeneity and regional differences in habitat quality (Sallustio et al., 2017; Thomas et al., 2021; Yang et al., 2021). Therefore, strengthening the research on regional differences in habitat quality is important to biodiversity protection, ecosystem service function, ecological security pattern construction, regional ecological balance, system health, and land ecological security (Hongjuan et al., 2016; Yan et al., 2018).

Research on habitat quality began in the 1960s, and earlier studies tend to study the regional differentiation characteristics of habitat conditions of species in a specific region, such as *Grus japonensis* (Zhiqiang et al., 2009), antelope (Xiaoyang et al., 2016), and wild bee (Wu, Dai, et al., 2021; Wu, Sun, et al., 2021). This type of research first analyzes the habitat requirements of the target species based on the actual survey and experimental data, determines the limiting factors affecting their population and behavior, establishes corresponding evaluation standards for each factor, and finally makes a comprehensive analysis of the habitat according to certain standards (Zhiyun et al., 2001). Although the method has high accuracy, it is relatively difficult to operate, and the evaluation results are difficult to promote and compare. Thus, this method is suitable for small-scale research serving specific targets (Lee & Jeon, 2020). After entering the twenty-first century, the development of 3S (GIS, RS, GPS) technology has made it possible to evaluate habitat quality and biodiversity in a quantitative, large-scale, long term sequence (Hongliang, 2001), and has gradually made spatiotemporal changes in habitat quality a research hotspot (Han et al., 2018; Zhifang et al., 2017). In recent years, some ecological models, such as SoLVES (Social Value of Ecosystem Services) (Brown & Brabyn, 2012; Codato et al., 2017; Sun, Jiang, et al., 2019; Sun, Xiang, et al., 2019; Zhang et al., 2018), HSI (habitat suitability index) (Lewis et al., 2019; Zhang et al., 2018; Zhiqiang et al., 2009), and the InVEST model (integrated evaluation of ecosystem services and tradeoff) (Berta Aneseyee et al., 2020; Chuanzhun et al., 2015; Petway et al., 2020), have unique advantages in the analysis and simulation of the spatial change in habitat quality and are constantly updated and improved (Tang et al., 2021). Furthermore, the evaluation results are more consistent with the urgent needs of natural reserve planning and ecological protection (Han et al., 2018). Among them, the InVEST model does not have high requirements for data, and it can use land use change data to quickly evaluate changes in habitat quality, such as, watersheds (Han et al., 2018; Paudyal et al., 2018), counties and cities (Chunfang et al., 2018; Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021; Zhang & Fang, 2021), and natural reserves (Rosas et al., 2017; Sun, Jiang, et al., 2019; Sun, Xiang, et al., 2019; Xiaoyang et al., 2016). However, at large- and medium-sized scales, there is still a lack of research on the spatiotemporal differentiation of habitat quality, and few scholars have focused on the impact of topographic gradients on habitat quality. Terrain, as an indispensable factor of the natural environment, has a significant impact on the transfer of surface materials and energy (Chang-li et al., 2017). Exploring the distribution characteristics and laws of habitat quality from the perspective of topographic gradients is

helpful for deeply understanding the correlation between land use change factors, and play an important role in deepening the understanding of land use-driven habitat quality change (Xiaoyan et al., 2021).

Hubei Province has plains, hills and mountains, making it suitable for study. However, Hubei Province has a rapid economic development momentum and strict environmental constraints, which may have a negative impact on the maintenance of biodiversity. Therefore, when considering the unique geographical conditions of Hubei Province, it is important to explore the relationship between Hubei Province's habitat quality and land use changes in an innovative combination of topographical perspectives. Based on the analysis of the habitat quality of Hubei Province using the InVEST model, this paper analyzes the impact of regional topographic conditions on the spatiotemporal distribution pattern of habitat quality with the help of the terrain index to discover the response of habitat quality to land use change and the differentiation of habitat quality at different terrain index grades. The research conclusion can provide decision support for land use layout and ecological environmental protection in Hubei Province in the future.

2 Methods and data sources

2.1 Study area

Hubei Province, as shown in Fig. 1, is located in central China, with various geomorphic types, including gangland, hills, plains, mountains, and other types. Among them, mountainous area, plain area and hilly area account for 56%, 20% and 24% of the total area of Hubei

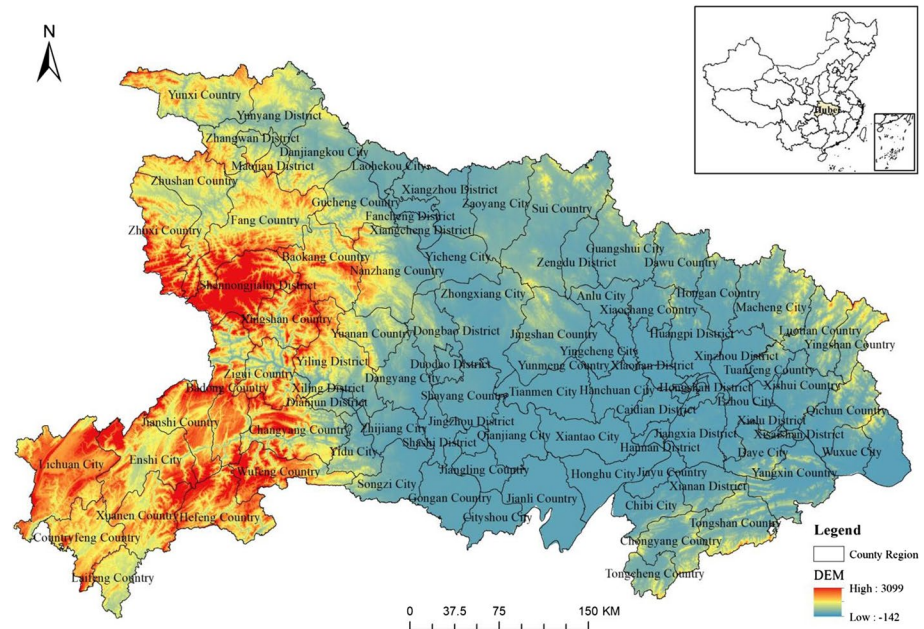


Fig. 1 Location of Hubei Province

Province, respectively (Xiao et al., 2021). Most parts of the Hubei Province have a typical subtropical monsoon climate. Its main characteristics are long frost free period, sufficient light and heat, abundant precipitation, and rain and heat in the same season (Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021). According to China's forest resources report (State Forestry and Grassland Administration, 2019), the vegetation in Hubei Province belongs to the north subtropical and middle subtropical regions, with a forest area of 736.27 hectares and a forest coverage rate of 39.61%. The total biomass of forest vegetation is 492 million tons, and the total carbon reserve is 244 million tons. The zonal soil of low mountains and hills in southeastern Hubei is brown red soil, the main zonal soil in southwestern Hubei is yellow soil, the zonal soil in central and northeastern Hubei is yellow brown soil, and the main zonal soil types in northern and northwestern Hubei are yellow cinnamon soil and yellow brown soil.

2.2 The analysis of habitat quality

2.2.1 The habitat quality module in the InVEST model

The InVEST model (Integrated Valuation of Ecosystem Services and Tradeoffs) was jointly developed by Stanford University, The Nature Conservancy (TNC) and the World Wildlife Fund (WWF) in 2007 (Dai et al., 2019; He et al., 2017; Polasky et al., 2011; Wu, Dai, et al., 2021; Wu, Sun, et al., 2021). This module can explain the impact of human production and daily life on the surrounding ecological environment and ecosystem (Zhang and Fang 2021). One of the advantages of this method is that it can replace detailed field investigation and quantitatively monitor the change of habitat quality in a short time (Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021). Linear or exponential distance attenuation function can be used to describe the spatial attenuation of threat (Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021). The stress level i_{rxy} of threat factor r in grid y to habitat grid x is calculated as follows:

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}} \right) \quad (\text{linear decay}) \quad (1)$$

$$i_{rxy} = \exp \left(- \left(\frac{2.99}{d_{rmax}} \right) \right) \quad (\text{exponential decay}) \quad (2)$$

where d_{xy} is the linear distance between grid x and grid y , and d_{rmax} is the largest impact distance of threat factor r on habitat. The total threat level of grid cell x in habitat type j (i.e., habitat degradation degree) D_{xj} can be expressed as follows:

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

where R is the number of threat factors; w_r is the weight of the threat factor r , which ranges from 0 to 1, indicating the relative destructive power of the stress factor to all habitats; Y_r is the grid number of threat factor r in the land use map; r_y is the number of stress factors on each grid in the land use map; and S_{jr} is the sensitivity of land use type j to the threat factor r , which ranges from 0 to 1. The closer the value is to 1, the more sensitive it is; β_x is the legal accessibility (or legal access degree or arrival degree) of grid unit x , which refers to the degree of land resources or ecosystem protection affected by current policies, laws,

regulations, regulations and their implementation methods, that is, the accessibility level of various threat factors to grid x . The value range is 0~1, and the closer the value is to 1, the easier it is to achieve (Yuan et al., 2019). This paper does not consider the specific land protection area of Hubei Province. The degree of protection of each land cover type in the area is equal and uniform in relation to national laws and regulations. Thus, the system will automatically assign a value of 1, that is, safe arrival. The calculation formula of the habitat quality index is as follows:

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

where Q_{xj} is the habitat quality index of grid x in land use type j ; H_j is the habitat suitability of land use type j , and the value range is 0~1, of which 1 is the most suitable. K is a semi-saturation constant, which is generally taken as half of the maximum value of habitat degradation degree D_{xj} . Value Z is a normalized constant, which is the default parameter of the model and is usually set to 2.5. The value of the habitat quality index Q_{xj} ranges from 0 to 1, and a higher value indicates better habitat quality.

2.2.2 Parameter setting of the habitat quality module

The habitat quality model is mainly composed of four factors: the relative impact of each threat, the relative sensitivity of each habitat type to each threat, the distance between the grid cell and the threat, and the level of legal protection to which the unit is protected (Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021). Other research results have found that the factors that have the greatest impact on the surrounding environment are closely related to human production and daily life (Sun et al., 2021; Wenxian et al., 2021). Cultivated land and construction land are characterized by high intensity of human activities and low biodiversity. There is basically no vegetation cover on the bare land, which will affect the richness and stability of the surrounding ecosystem. The more intense the intensity of human activities and the larger the scope of activities, the more severe the impact on the ecological security and biodiversity of the ecosystem. By collecting relevant literature (Foster et al., 2017; Terrado et al., 2016; Yang et al., 2018), referring to the user guide manual of the InVEST model (NATURAL CAPITAL PROJECT, 2021), the expert opinions of the region, and considering the special geographical environment of the research area (Fig. 2), the types, weights and habitat sensitivity distribution of threat sources in the literature are statistically analyzed, and eight threat sources are selected, namely paddy field, dry land, urban land, rural residential area, other construction land, bare land, major railways and major roads. Taking the protection of biodiversity in landscape ecology as the basic principle, the threatened sensitivity of a habitat type is determined (Yu et al., 2018). Generally speaking, the degree of sensitivity to external threat factors is natural, semi-artificial, and artificial in descending order (Han et al., 2018). The sensitivity of natural land use types such as forest and grassland is relatively high, while the sensitivity of artificial land use types such as cultivated land and construction land is relatively low. The sensitivity of the threat source is assigned a value in the range of 0 to 1, where 0 means the habitat is not sensitive to the threat factor, and 1 means it is highly sensitive. The habitat threat sources and related parameters (Table 1), habitat suitability of various land use types and sensitivity to different threat

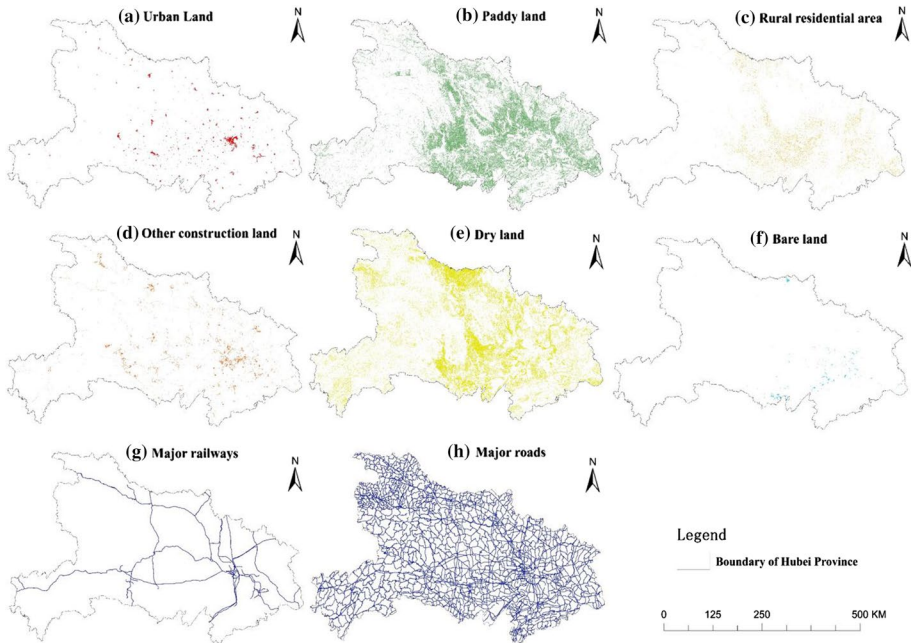


Fig. 2 Threats raster/vector

Table 1 Threat source and its weight and maximum influence distance

Threat factor	Maximum influence distance (km)	Relative weight	Types of spatial decline
Paddy land	1	0.3	Exponential decay
Dry land	1	0.3	Exponential decay
Urban land	10	1	Exponential decay
Rural residential area	5	0.6	Exponential decay
Other construction land	3	1	Exponential decay
Bare land	3	0.1	Exponential decay
Major railways	4	0.4	Linear Decay
Major roads	3	0.4	Linear Decay

sources were assigned (Table 2). The InVEST model uses the habitat quality index to represent the regional habitat quality, which ranges from 0 to 1. The higher the value, the higher the habitat quality, indicating that the better the structure and function of the corresponding ecosystem, which can help maintain biodiversity. The smaller the value, the lower the habitat quality, indicating that the worse the structure and function of the corresponding ecosystem, it cannot help the maintenance of biodiversity.

Table 2 Habitat suitability and its relative sensitivity to threat sources

Land type code	Habitat suitability	Threat factor							
		Paddy land	Dry land	Urban land	Rural residential area	Other construction land	Bare land	Major railways	Major roads
11	0.40	0	1	0.50	0.35	0.20	1	0.10	0.20
12	0.30	1	0	0.50	0.35	0.20	1	0.10	0.20
21	1	0.50	0.60	0.90	0.70	0.50	1	0.60	0.80
22	0.70	0.30	0.40	0.60	0.40	0.20	1	0.60	0.70
23	0.60	0.50	0.60	0.80	0.60	0.40	1	0.50	0.60
24	0.40	0.50	0.60	0.80	0.60	0.40	1	0.40	0.50
31	0.70	0.40	0.45	0.60	0.45	0.30	1	0.10	0.15
32	0.60	0.45	0.50	0.65	0.50	0.35	1	0.15	0.20
33	0.40	0.50	0.55	0.70	0.55	0.40	1	0.20	0.25
41	1	0.50	0.60	0.80	0.60	0.40	1	0.40	0.45
42	0.90	0.55	0.65	0.85	0.65	0.45	1	0.45	0.50
43	0.90	0.60	0.70	0.90	0.70	0.50	1	0.50	0.55
46	0.60	0.65	0.75	0.95	0.75	0.55	1	0.55	0.60
51	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0

2.3 Terrain index

The terrain index is a composite index used to analyze the elevation and slope attribute information of any point in space, and it can comprehensively reflect the spatial differentiation of topographical conditions (Chang-li et al., 2017; Güntner et al., 2004; Han et al., 2020; Yuan et al., 2019). It is calculated as follows:

$$T = \lg \left[\left(\frac{E}{\bar{E}} + 1 \right) \times \left(\frac{S}{\bar{S}} + 1 \right) \right] \quad (5)$$

where T is the terrain index; E and \bar{E} refer to the elevation value (m) and average elevation value (m) of any grid in the space respectively; and S and \bar{S} refer to the slope value of any grid in the space and the average slope value, respectively. Generally, the grid topographical index with a high elevation and slope value is larger, the grid topographical index with a low elevation and slope value is lower, and the grid topographical index with high elevation and slope value or a low elevation and high slope value is in the middle.

2.4 Data sources

The land use data of Hubei Province in 2000, 2005, 2010, 2015, and 2020 were collected from the Resource and Environmental Science Data Center of Chinese Academy of Sciences (<http://www.resdc.cn>), with a spatial resolution of 30 m. According to the characteristics of data, the land use/land cover types in the study were integrated into six first-class categories, which were mainly divided into cultivated land, woodland, grassland, water area, construction land, and unused land. The second level was mainly divided into 19 types according to the natural attributes of the land resources (as shown in Table 3). The data on administrative regions, lakes and rivers, main roads, and main railways were from the National Basic Geographic Databases (1:250,000 and 1:1,000,000). The DEM data come from the Geospatial Data Cloud (<http://www.gscloud.cn>), with a spatial resolution of 30 m. The technical flowchart of the full text is shown in Fig. 3.

3 Results

3.1 Spatiotemporal characteristics of land use change

According to the land use data of Hubei Province in 2000, 2005, 2010, 2015, and 2020 (Fig. 4), the area proportion of each land use type in five periods in Hubei Province was obtained (Table 4). The primary land use types in Hubei Province were cultivated land, woodland, cultivated land, and water area, accounting for 87% of the total area of Hubei Province. The area proportion of each land use type in Hubei Province remained relatively stable in the five stages, but there were varying degrees of changes. The area of paddy fields and dry land was in a state of fluctuation. Woodland and grassland showed a decreasing trend overall. Because of the environmental protection policies implemented in recent years, the water area was in an expanding trend. In recent years, due to the launch of the comprehensive land improvement policy, the construction land area within the city has

Table 3 Classification and description of land use types

Land use type		Detailed explanations	
Class 1	Class 2	Code	
Cultivated land	Paddy land	11	It refers to cultivated land, with a guaranteed water source and good irrigation facilities, can be irrigated normally in typical years and planting aquatic crops
	Dry land	12	It refers to cultivated land far away from irrigation water sources and irrigation facilities and can rely on natural rainfall to plant crops
	Forestland	21	It refers to natural forest and plantation with canopy density over 30%
Woodland	Shrub wood	22	It refers to the low forestland and shrub forestland with canopy density over 40% and height below 2 m
	Open woodland	23	It refers to the forestland which has 10–30% canopy density
	Other woodlands	24	It refers to the uncultivated forestland, slash land, nursery and all kinds of garden land (orchard, mulberry garden, tea garden, hot forest garden, etc.)
	High-coverage grassland	31	It refers to natural grassland, improved grassland, and mowed grassland with more than 50% coverage, which has a good water condition and a dense grass coverage
Grassland	Medium-coverage grassland	32	It refers to the natural grassland and improved grassland that coverage is more than 20–50%, which is generally lacking of water and has sparse grass coverage
	Low-coverage grassland	33	It refers to the natural grassland with 5–20% coverage, which is lacking water and has poor conditions for animal husbandry
	Canals	41	It refers to the natural or artificially excavated rivers
Water	Lake	42	It refers to the naturally formed ponding area
	Reservoir pond	43	It refers to the artificially constructed water storage area
	Shoal	46	It refers to the land in the river and lake between the water level in the normal water period and the water level in the flood period
	Urban land	51	It refers to urban land in large, medium, and small cities and counties
Construction Land	Rural residential land	52	It refers to the rural settlements that are independent of the cities and towns
	Other construction land	53	It refers to the land used for factories and mines, traffic roads, airports and special land

Table 3 (continued)

Land use type		Detailed explanations
Class 1	Class 2	
Unused land	Swamp	64 It refers to the land that is flat and low-lying, and has the characteristics of poor drainage, seasonal ponding or perennial accumulation
	Bare land	65 It refers to the land whose surface is covered with soil and vegetation coverage is less than 5%
	Bare rocky land	66 It refers to the land whose surface is rock or gravel and its coverage area is more than 5%

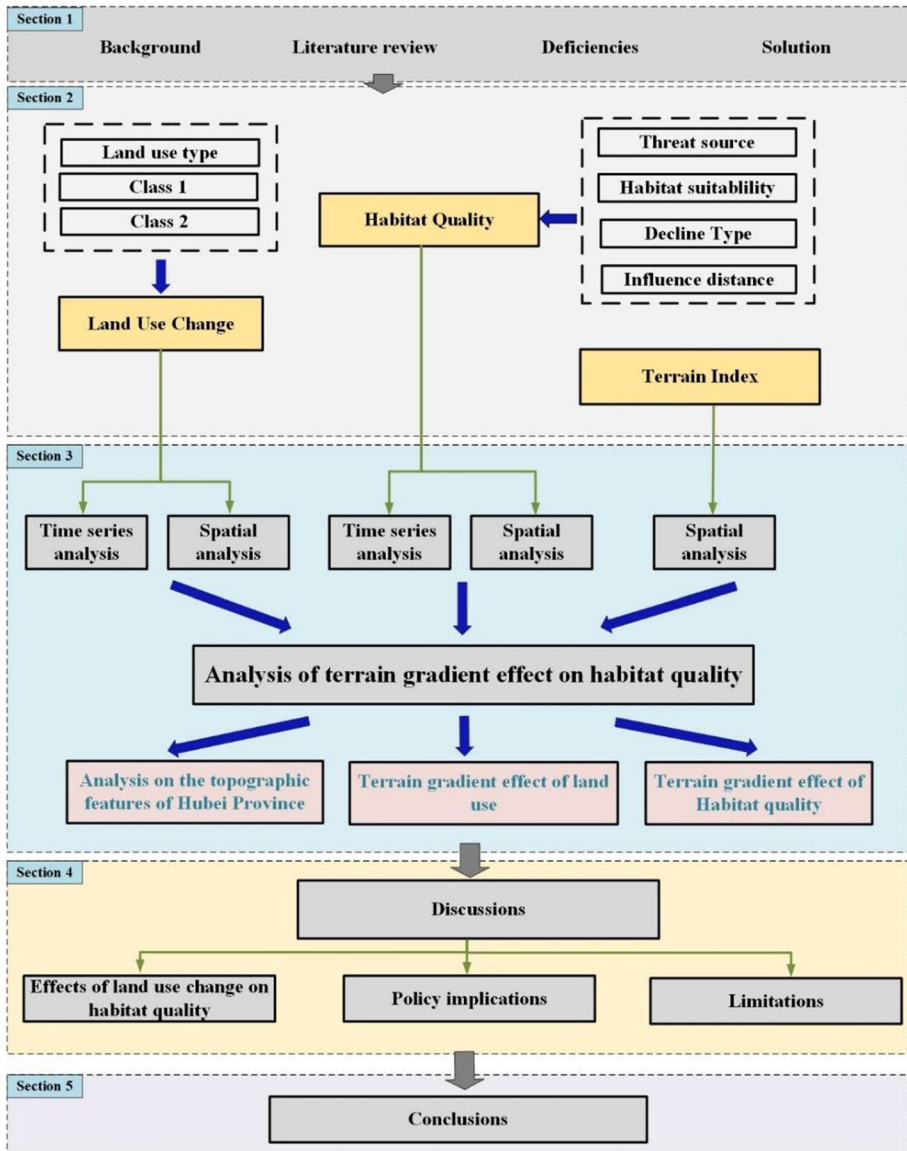


Fig. 3 Technical flowchart

promoted intensive and economical utilization, which is in a decreasing trend. The urban unused land was in a relatively stable state with little change.

The changes in land use types were analyzed based on the land use classification data of Hubei Province. In terms of change scale, the area of cultivated land decreased the most from 2000 to 2020, with a decrease of 2736.88 km². Construction land increased the most, with an increase of 2590.06 km². Woodland decreased by 565.48 km², water area increased by 878.59 km², and unused land and grassland decreased less. The

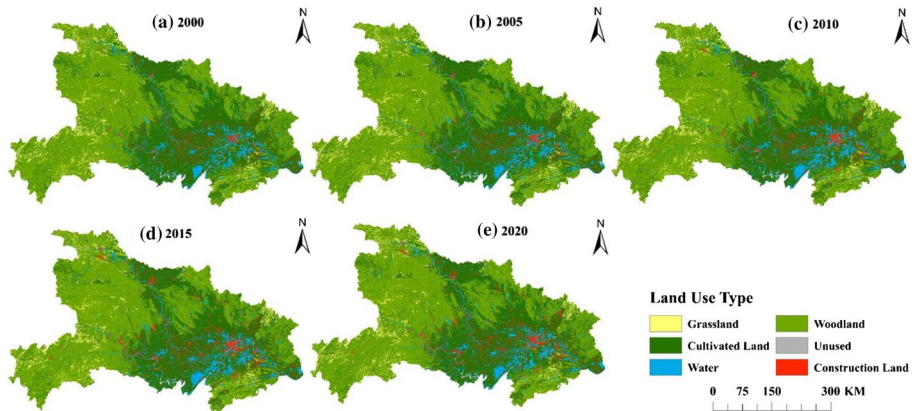


Fig. 4 Land use types of Hubei Province from 2000 to 2020

Table 4 Characteristics of land use structure in different periods

Year	Cultivated land	Woodland	Grassland	Water	Construction land	Unused land
2000	69,688.37	92,849.16	7080.08	10,792.70	5090.94	438.46
2005	68,838.16	92,717.08	7050.08	11,488.03	5418.23	429.68
2010	66,738.40	92,730.82	6943.43	12,338.78	6812.36	379.68
2015	65,878.78	92,442.28	6906.30	12,359.52	7980.21	376.43
2020	66,951.49	92,283.68	6979.03	11,671.29	7681.01	383.71
2000–2005	–850.21	–132.08	–30.00	695.33	327.28	–8.78
	–1.22%	–0.14%	–0.42%	6.44%	6.43%	–2.00%
2005–2010	–2099.76	13.74	–106.65	850.76	1394.13	–49.99
	–3.05%	0.01%	–1.51%	7.41%	25.73%	–11.63%
2010–2015	–859.62	–288.54	–37.13	20.74	1167.86	–3.26
	–1.29%	–0.31%	–0.53%	0.17%	17.14%	–0.86%
2015–2020	1072.71	–158.60	72.73	–688.23	–299.21	7.28
	1.63%	–0.17%	1.05%	–5.57%	–3.75%	1.93%
2000–2020	–2736.88	–565.48	–101.05	878.59	2590.06	–54.75
	–3.93%	–0.61%	–1.43%	8.14%	50.88%	–12.49%

change range of construction land is the largest from 2000 to 2020, with an increase of 50.88%. Unused land decreased the most, reaching 12.49%. The change rates of cultivated land, woodland, grassland, and water area were –3.93%, –0.61%, –1.43%, and 8.14%, respectively. In terms of stages, the water area and construction land area generally showed the change characteristics of "increase–decrease". Cultivated land and grassland generally showed the change characteristics of "decrease–increase". Woodland area increased only from 2005 to 2010, and decreased in other years. The unused land area only increased in 2015–2010, and decreased in other years.

3.2 Spatiotemporal variation characteristics of habitat quality

By running InVEST's habitat quality module, the spatial distribution map of Hubei Province from 2000 to 2020 was obtained. By using ArcGIS, habitat quality is divided into four levels, namely Level 1 (0.8–1.0), Level 2 (0.5–0.8), Level 3 (0.3–0.5) and Level 4 (0.0–0.3). According to the characteristics of the spatial pattern (Fig. 5), the spatial distribution difference of habitat quality in Hubei Province was obvious, and higher habitats (Level 1 and Level 2) were widely distributed.

The distribution characteristics of all kinds of habitats were different. Level 1 and Level 2 habitats were mainly located in the mountains and hills in the southwest and northwest of Hubei Province, including the Wuling Mountain Area in the southwest of Hubei Province and the Qinba Mountain Area in the northwest of Hubei Province. In addition, the habitat quality of natural lakes was at a high level, which benefits from the rich water and wetland resources, and is suitable for the survival of aquatic animals and plants. Level 3 habitats were distributed in the agricultural production area of the plain area, where the human cultivation is frequent, the ecosystem is singular, the vegetation coverage is low, and the ecological environment is fragile. Level 4 habitats were mainly concentrated in urban areas, mainly in the urban agglomerations and their surrounding areas. Among them, the lower habitats (Level 3 and Level 4) on the Jiangnan Plain were the most widely distributed. The land use structure of these places was mainly cultivated land and construction land, and the biodiversity was low. Therefore, the spatial distribution of habitat quality had a strong correlation with topography and resource endowment.

From the time scale (Table 5), the average habitat quality in 2000, 2005, 2010, 2015, and 2020 was 0.6095, 0.6107, 0.6099, 0.6060, and 0.6053, respectively. The average value of habitat quality in Hubei Province showed a trend of “increased-decreased”, and the overall average habitat quality decreased slightly. The results showed that the proportion of the Level 2 habitats was the highest, with a value of approximately 31%, and the proportion of the Level 1 and Level 2 habitats was 58%, indicating that the quality of the habitats in Hubei Province is at a higher level. From 2000 to 2020, the proportion of each level habitat area did not change much. It was obvious that the proportion of the Level 4 habitat area gradually increased, while the proportion of the Level 3 habitat area showed a declining trend, and the increase and decrease range was basically the same. This result reflects that

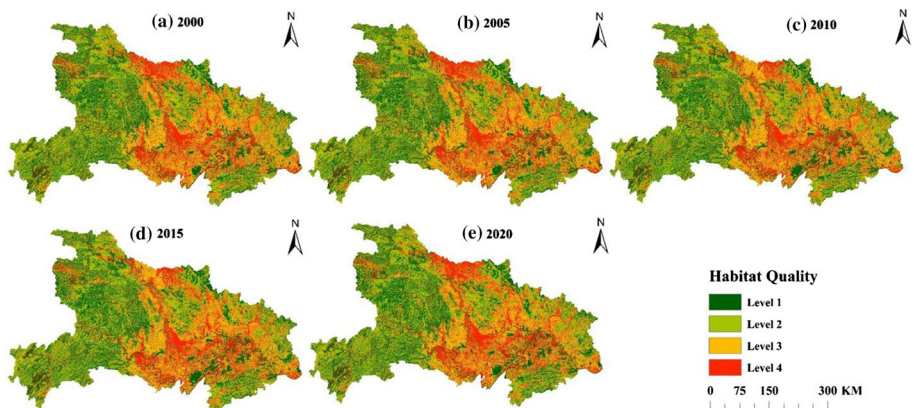


Fig. 5 Spatial distribution of habitat quality in Hubei Province from 2000 to 2020

Table 5 Characteristics of land use structure in different terrain positions

Habitat quality level	Score range	2000		2005		2010		2015		2020		Change from 2000 to 2020 (%)
		Ratio (%)	HQ _A ^a	Ratio (%)	HQ _A	Ratio (%)	HQ _A	Ratio (%)	HQ _A	Ratio (%)	HQ _A	
Level 1	0.8–1.0	27.35	0.6095	27.78	0.6107	27.94	0.6099	27.89	0.6060	27.69	0.6053	0.34
Level 2	0.5–0.8	31.83		31.64		31.77		31.54		31.44		–0.39
Level 3	0.3–0.5	21.49		21.19		21.52		21.21		20.70		–0.79
Level 4	0.0–0.3	19.33		19.39		18.77		19.37		20.17		0.84

^a HQ_A represents the average habitat quality

the higher habitats are transitioning to lower levels, and Hubei Province has a potential risk of habitat degradation.

To further explore the spatial differentiation characteristics of habitat quality, a difference analysis of the habitat quality distribution map in each year was carried out in ArcGIS. Figure 6 shows that the habitat quality in most areas of Hubei Province had no obvious change from 2000 to 2020, and the overall spatial pattern was "rising in the southeast and falling in the middle". From 2000 to 2020, the habitat quality improvement area was mainly located on Jiangnan Plain, which benefited from the increase in the aquaculture water surface driven by the economic benefits of aquaculture. The areas with declining habitat quality were mainly concentrated in Wuhan, Yichang, Xiangyang, and other cities. These cities have a high GDP, and the demand for economic development is more urgent. The expansion speed of construction land, such as urban industrial, mining and transportation is relatively fast, thus squeezing and dividing the surrounding habitat space. Additionally, the sewage, waste gas and waste gas discharged from the construction and production process, waste residue and other pollutants may cause the degradation of nearby habitats, destroy and disturb the recreational environment of surrounding species, and pose a greater threat to the maintenance of biodiversity. In 2000–2020, the improvement in habitat quality was relatively scattered, mainly due to the increase in vegetation coverage driven by the conversion of farmland to forest and afforestation, and the restoration and treatment of the water surface. The regional expansion direction of habitat quality decline matched the direction of urban spreading, and radiated from the ring to the surroundings, which indicated the acceleration of the urbanization process and also reflected the spatial agglomeration effect of habitat degradation.

3.3 Habitat quality change characteristics of different land types

Table 6 shows that the dominant habitat quality level of cultivated land, woodland, grassland, and water area was Level 3, Level 2, Level 2, and Level 1, respectively. Correspondingly, the habitat quality of woodland and water area was the highest, followed by grassland, and the habitat quality of cultivated land was the lowest. The habitat quality of cultivated land, woodland and grassland demonstrated a downward trend from 2000

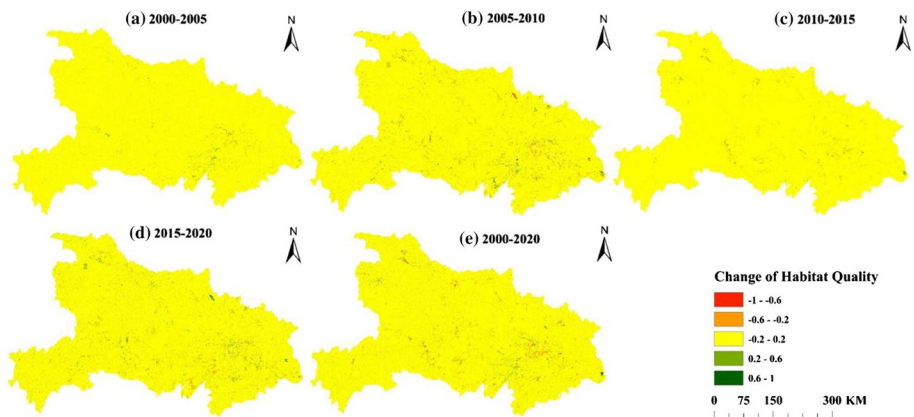


Fig. 6 Spatial variation in habitat quality in Hubei Province from 2000 to 2020

Table 6 Characteristics of land use structure in different habitat quality levels

Land type	Year	Habitat quality level				Average value of habitat quality
		1 0.8–1.0 (%)	2 0.5–0.8 (%)	3 0.3–0.5 (%)	4 0.0–0.3 (%)	
Cultivated land	2000	0.08	0.13	21.01	16.27	0.3583
	2005	0.09	0.13	20.66	16.16	0.3581
	2010	0.09	0.13	20.86	14.83	0.3603
	2015	0.08	0.13	20.45	14.60	0.3601
	2020	0.06	0.09	20.09	15.78	0.3573
Woodland	2000	22.17	27.31	0.35	0.09	0.7986
	2005	22.13	27.22	0.40	0.10	0.7983
	2010	21.94	27.30	0.52	0.10	0.7962
	2015	21.84	27.10	0.61	0.10	0.7957
	2020	22.03	27.01	0.50	0.07	0.7981
Grassland	2000	0.02	3.70	0.08	0.01	0.6546
	2005	0.02	3.68	0.08	0.01	0.6545
	2010	0.02	3.62	0.09	0.01	0.6542
	2015	0.02	3.60	0.09	0.01	0.6540
	2020	0.01	3.66	0.08	0.00	0.6543
Water	2000	5.07	0.68	0.02	0.01	0.8843
	2005	5.53	0.60	0.03	0.02	0.8904
	2010	5.88	0.70	0.03	0.02	0.8865
	2015	5.93	0.68	0.03	0.02	0.8875
	2020	5.58	0.67	0.02	0.01	0.8888

to 2020. The habitat quality of the water area improved by 0.0045. As can be seen from Table 6, the high-level habitats of woodland and water area degenerate to lower-level habitats in a fluctuating way, which was mainly attributed to human activities such as deforestation for farmland, steep slope reclamation, and lake reclamation. In conclusion, woodland and water areas contributed the most to the habitat quality of Hubei Province, and the degradation of the two habitats was the main factor for the decrease in regional habitat quality.

3.4 Topographic gradient effect of habitat quality

3.4.1 Topographic features of Hubei Province

The terrain index of Hubei Province, based on the DEM data, was calculated according to Formula (5). The result range was $-0.351-3.76$. It was divided into five grades (Fig. 7): grade 1 (<0.54), grade 2 ($0.54-1.09$), grade 3 ($1.09-1.71$), grade 4 ($1.71-2.27$), and grade 5 ($2.27-3.76$). The topographical position of Hubei Province is low in the middle and high in the southwest and northwest, and the terrain index can fully describe the distribution of the regional topography. Figure 8 shows that the terrain grade of the Hubei Province was mainly grade 1 (more than 30%), followed by grade 2, grade 3, and grade 4 (each approximately 18%), and grade 5 was the lowest (only 12%).

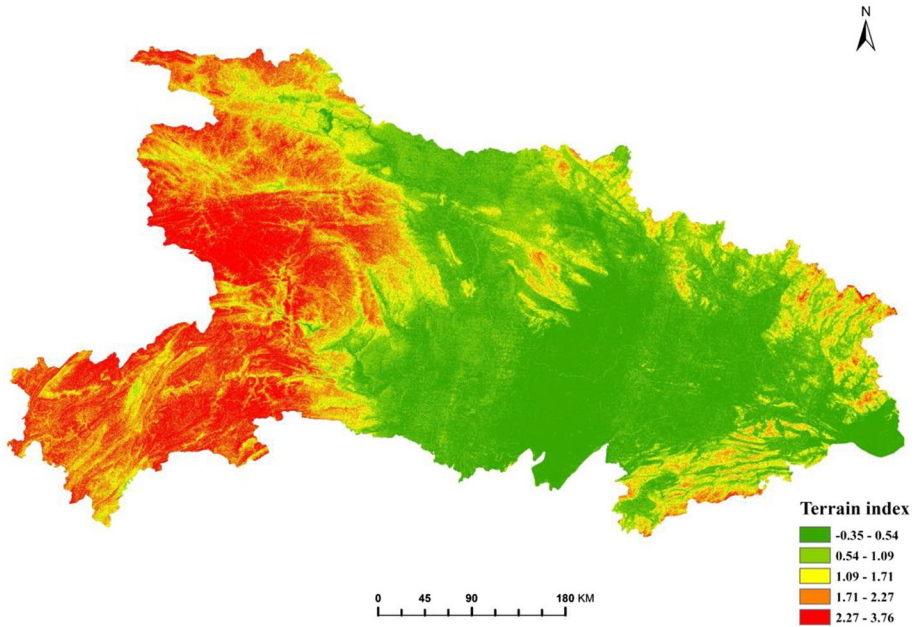


Fig. 7 Spatial distribution of terrain index values in Hubei Province

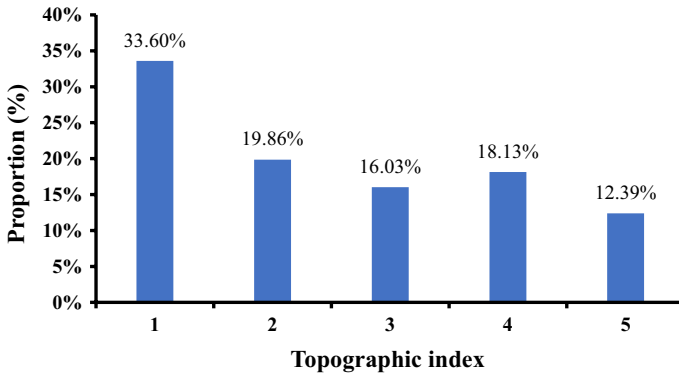


Fig. 8 Proportion of topographic index

3.4.2 Topographic gradient effect of land use

The intensity of human activities and the vertical differentiation of climate make the land use structure have an obvious terrain gradient effect. As can be seen from Table 7, the most important land use types in Hubei Province are cultivated land and water areas. Cultivated land is the main land use type in the grade 1 terrain, accounting for more than 20%, and woodland is the principal land use type of terrain above grade 1. With the increase in terrain grade, the proportions of cultivated land, construction land, water area, and unused land decreased sharply, while the proportions of woodland and grassland increased

Table 7 Characteristics of land use structure in different terrain grade

Terrain Index Grade	Land use type											
	Cultivated Land		Woodland		Grassland		Water		Construction Land		Unused Land	
	2000 Ratio (%)	V ^a (%)	2000 Ratio (%)	V (%)	2000 Ratio (%)	V (%)	2000 Ratio (%)	V (%)	2000 Ratio (%)	V (%)	2000 Ratio (%)	V (%)
1	23.31	-1.15	3.42	-0.08	0.16	-0.01	4.44	0.35	2.13	0.91	0.19	-0.02
2	9.02	-0.29	8.77	-0.14	0.34	-0.01	1.14	0.10	0.56	0.34	0.03	0.00
3	2.61	-0.03	12.36	-0.10	0.82	-0.01	0.18	0.03	0.05	0.10	0.01	0.00
4	2.01	0.00	14.82	-0.02	1.25	-0.01	0.02	0.01	0.01	0.03	0.00	0.00
5	0.61	-0.01	10.52	0.02	1.22	-0.01	0.00	0.00	0.00	0.01	0.00	0.00

^aVariation (V) represent change in proportion from 2000 to 2020

Table 8 The number of county-level units of habitat quality in each topographic position in Hubei Province

Habitat quality level	Year	Topographical index grade				
		1	2	3	4	5
Level 1	2000	0	0	0	0	1
	2005	0	0	0	0	1
	2010	0	0	0	0	1
	2015	0	0	0	0	1
	2020	0	0	0	0	1
Level 2	2000	8	25	13	17	0
	2005	7	25	13	17	0
	2010	4	24	13	17	0
	2015	3	21	13	17	0
	2020	4	22	13	17	0
Level 3	2000	27	6	0	0	0
	2005	28	6	0	0	0
	2010	30	7	0	0	0
	2015	31	10	0	0	0
	2020	31	9	0	0	0
Level 4	2000	4	0	0	0	0
	2005	4	0	0	0	0
	2010	5	0	0	0	0
	2015	5	0	0	0	0
	2020	4	0	0	0	0

significantly. The proportion of water area and construction land is increased, and the proportion of cultivated land, woodland, grassland and unused land is decreased during the research period, which indicated that the problem of extensive land use is still prominent (Table 8). Moreover, the higher the terrain grade is, the smaller the change range is. This is because the lower the terrain grade is, the greater the intensity of human activities and the stronger the interference of human factors is on land use. In contrary, adverse climate and natural disasters have a greater impact on land use change in high-lying areas. Compared with natural factors, human factors have a more significant impact on land use in the short term (Fig. 9).

3.4.3 Topographic gradient effect of habitat quality

Human activities can change the surface structure, thus affecting the regional habitat quality. The intensity of human activities is usually consistent within an administrative region, and the county is the smallest unit in the formulation and implementation of ecological policies. Therefore, taking county as the basic unit, this paper analyzes the impact of terrain gradient effect on habitat quality. The correlation between the terrain index and habitat quality was discussed by regression analysis. As can be seen from Fig. 10, the habitat quality of Hubei Province showed an upward trend with the increase of terrain index. There was a significant correlation between the two, but the correlation had a decreasing trend. The curve fitting degree (R^2) was greater than 0.7, indicating that the logarithmic function could describe the relationship between the two.

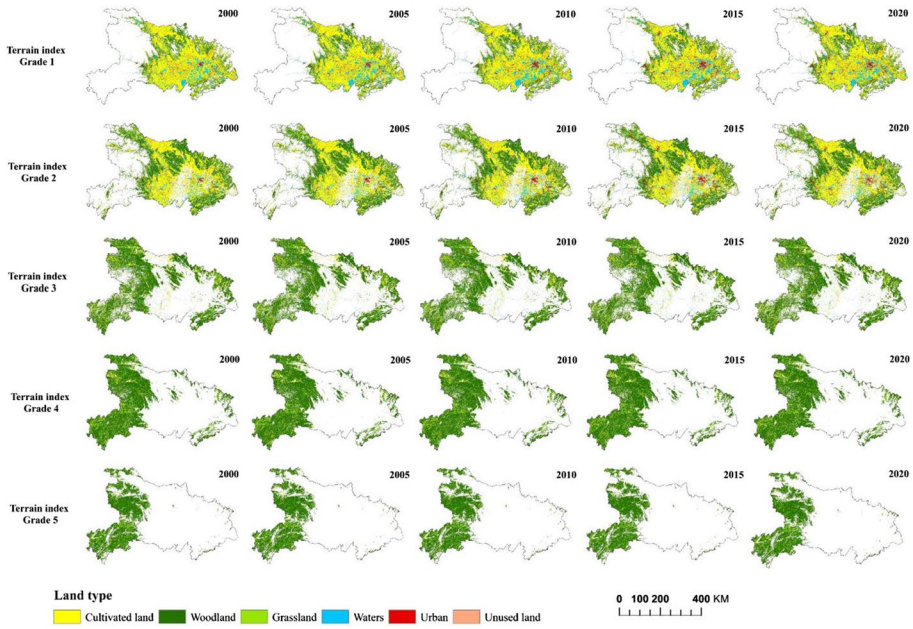


Fig. 9 Land use type shown for each terrain index grade in Hubei Province from 2000 to 2020

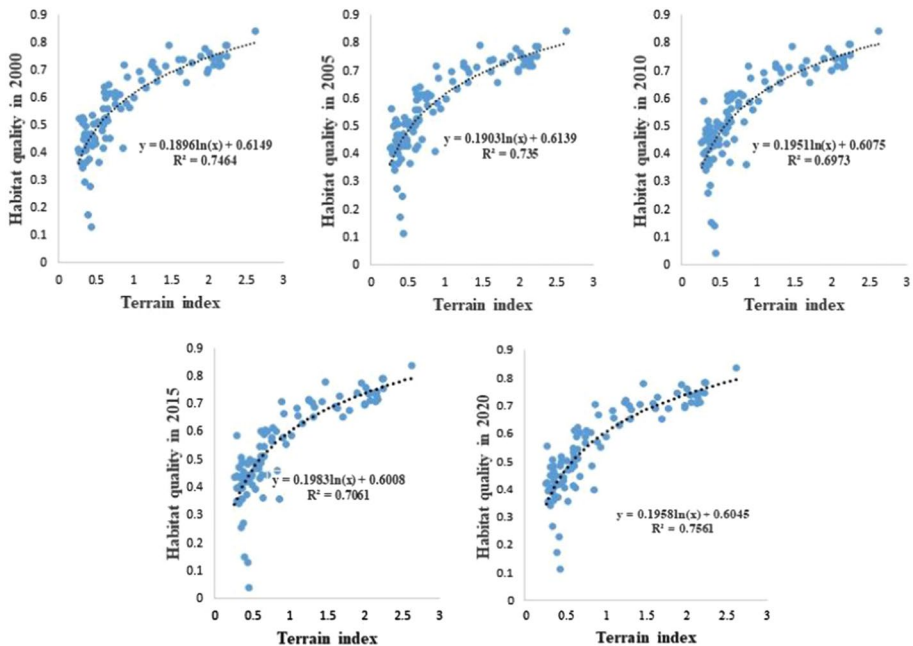


Fig. 10 Relationships between topographical index and habitat quality

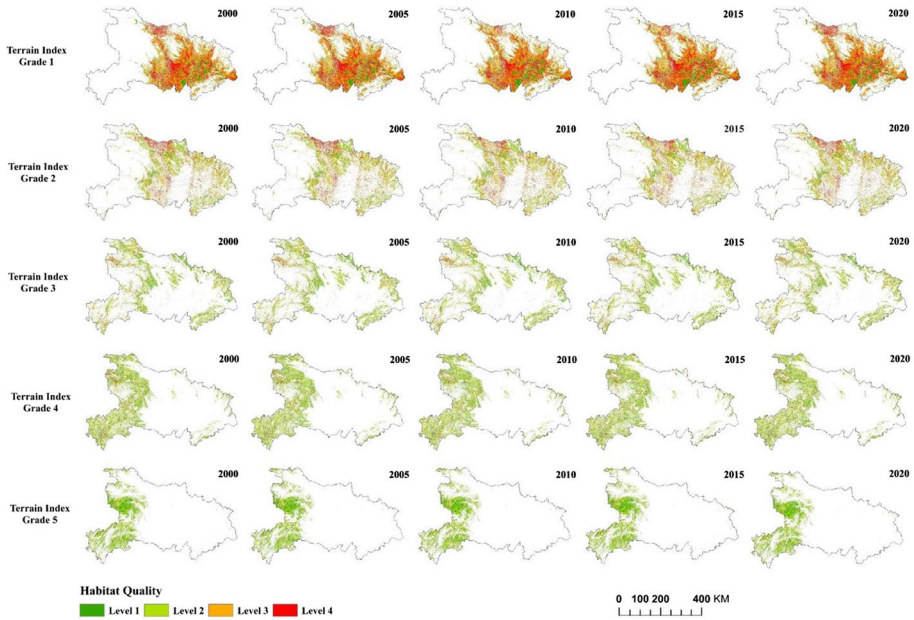


Fig. 11 Habitat quality for each terrain index grade in Hubei Province from 2000 to 2020

According to the number of counties with different levels of habitat quality in Hubei Province from 2000 to 2020 (Table 8), there was only one county with Level 1 habitat quality. The dominant range of grade 1 terrain was Level 3 habitat, and the dominant range of second-, third-, and fourth-grade terrain was Level 2 habitat (Fig. 11). From the perspective of habitat quality, the counties in the Level 1 habitat were the lowest, only distributed in the grade 5 terrain. The number of level 2 habitats was the largest, and they were mainly distributed in the terrain of grade 1, grade 2, grade 3, and grade 4. The number of counties in Level 3 habitat is relatively large, mainly in the terrain of grade 1 and grade 2. The habitat of Level 4 was distributed only on the terrain of grade 1.

The average habitat quality on different terrain index grade range from 2000 to 2020 was calculated. According to Table 9, as the terrain index grade increases, the average value of habitat quality increases accordingly. In 2015, the average habitat quality of the grade 5 terrain was 1.80 times that of the grade 1. But the rising rate of habitat quality

Table 9 Average habitat quality of different topographical sites in Hubei Province

Topographical index Grade	Average habitat quality					Change in 2000–2020
	2000	2005	2010	2015	2020	
1	0.4435	0.4469	0.4465	0.4407	0.4384	−0.0051
2	0.5610	0.5619	0.5600	0.5542	0.5540	−0.0070
3	0.7184	0.7181	0.7169	0.7134	0.7132	−0.0052
4	0.7476	0.7472	0.7467	0.7456	0.7458	−0.0018
5	0.7930	0.7928	0.7928	0.7921	0.7931	0.0001

was increasingly lower, which indicated that the gradient effect of habitat quality was more obvious when the terrain was gentle. The average habitat quality of all terrain sites fluctuated, and the average habitat quality of grade 1, grade 2, grade 3, and grade 4 terrain had a downward trend. The reason was that the quantity of forest and grassland decreased continuously, which led to the general decrease of habitat quality, while the growth of cultivated water surface, lake reservoir and wetland in the first grade terrain made the habitat quality increase without decreasing.

4 Discussion

This study fully describes the spatiotemporal differentiation characteristics of habitat quality in Hubei Province, and analyzes the distribution characteristics of habitat quality from the perspective of terrain index. The results may provide theoretical support for biodiversity conservation policies with spatial differentiation. However, the factors that affect habitat quality are complex, and there is no in-depth analysis of the influence mechanism of each factor on its distribution formation, which is a direction of future research.

Resource endowments limit the overall level of habitat quality, while industrial development and land use patterns determine the change trend, resulting in differences in habitat quality distribution and change level. However, unreasonable human activities, such as rapid expansion of urban and rural and deforestation, have seriously damaged the original ecological structure, resulting in a decline in habitat quality. On the contrary, Hubei Province has a large proportion of cultivated land and a low level of habitat quality, but the promotion of green development awareness and the protection of water resources have had a positive influence on the maintenance of biodiversity. In the flat area of Hubei Province, the contribution of water area to habitat quality is greater, and human activities are relatively frequent. Therefore, it is very important to effectively limit the occupation and pollution of cultivated land and urban land to the water area to improve the habitat quality of water resources. In mountainous areas, the contribution of forest and grass resources is greater. We must strengthen the protection, breeding and restoration of important forests and grasslands, prevent the degradation of forests and grasses, and vigorously promote the planting of trees and grasses. The habitat quality of cultivated land is low, but its role in ensuring food security cannot be ignored. The development of ecological agriculture should be encouraged, and the usage of chemical fertilizers and pesticides that threaten the survival of animals and plants should be reduced to gradually improve the biodiversity level of cultivated land.

4.1 Influence of land use change on habitat quality

Studies have shown that disordered urban expansion could easily lead to the reduction of land with critical natural habitat functions (such as wetlands, waters, and other) and the decline of habitat quality and biodiversity (Li et al., 2018; Zhu et al., 2020). From 2005 to 2015, the construction land in Hubei Province grew rapidly and showed the characteristics of rapid urbanization, resulting in the serious occupation of natural habitats. Tables 2 and 3 show that urban land and traffic road were identified as the main threat sources. First, rapid urban expansion has caused the destruction of natural environment, which hinders the connection of ecological corridor. Second, human activities caused by urban expansion have a significant negative spatial correlation with habitat quality (Ting et al., 2021; Zhang, Gao,

et al., 2020; Zhang, Song, et al., 2020). With the increase in human activity intensity, habitat quality has been severely disturbed.

Hubei Province is a major agricultural province in China, and its cultivated land area shows a "decrease-increase" trend, while its construction land shows a "increase-decrease" change feature. The emergence of this phenomenon is largely related to the special policies implemented by China, that is, "balance of arable land occupation and compensation" and "comprehensive land consolidation" (Wu et al., 2017). The core measure of the policy is that if urban construction occupies cultivated land, cultivated land of the same quantity and quality must be supplemented. Cultivated land, which is differ from construction land, has some certain ecological service functions, such as food production, water conservation, and biodiversity protection (Swinton et al., 2007).

As can be seen from Table 6, the dominant habitat quality level of cultivated land, woodland, grassland and water area was Level 3, Level 2, Level 2, and Level 1, respectively. Accordingly, the woodland and water area' habitat quality were the highest, followed by grassland, and the habitat quality of cultivated land was the lowest. The reduction in water area, woodland, and grassland is an important factor influencing the decline of habitat quality. Therefore, the government should adjust the relationship between economic prosperity and ecosystem health through a series of methods, such as revitalizing urban stock land and protecting high-quality habitat, so as to achieve sustainable development.

The contribution of water area to the habitat quality is greater, and human activities are relatively frequent. Therefore, it is very important to effectively limit the occupation and pollution of cultivated land and construction land to the water area to improve the habitat quality of water resources. In mountainous areas, the contribution of forest and grass resources is greater. We must strengthen the protection, breeding and restoration of important forests and grasslands, prevent the degradation of forests and grasses, and vigorously promote the planting of trees and grasses. The habitat quality of cultivated land is low, but its role in ensuring food security cannot be ignored. The development of ecological agriculture should be encouraged, and the use of chemical fertilizers and pesticides that threaten the survival of animals and plants should be reduced to gradually improve the biodiversity level of cultivated land.

4.2 Policy implications

The continuous social-economic progress of Hubei Province and the rapid changes in land use have led to declining habitat quality. In order to protect the biodiversity of Hubei Province and achieve sustainable development, corresponding land management measures and ecological protection strategies can be carried out based on the regional heterogeneity of habitat quality. In the southwest and northwestern mountains of Hubei Province, the land use types are mainly woodland and grassland, which are key habitat aggregation areas with high habitat quality levels (Level 1 and Level 2). In these areas, urban expansion and the occupation of ecological land need to be strictly controlled, and a series of protection projects should be implemented to maintain extremely significant habitat patches and ecological reserves such as lakes, forests, and rivers (Lee & Jeon, 2020; Li, He, et al., 2021; Li, Sun, et al., 2021; Li, Zhou, et al., 2021). Government actions and policies, such as delimitation ecological protection zones and national parks, can limit the intensity of human activities and the disturbance to these areas, so as to strengthen the protection of the above-mentioned areas with high-level habitat quality (Gao, 2019).

Cultivated land is the land use type that accounts for a large proportion in the area with Level 3 habitat quality. Although the habitat quality in these areas is not high, cultivated land, as the most important carrier of agricultural production, plays a significant role in ensuring food production and food security. In order to ensure food security and maintain the effective operation of society, for a populous country like China, the sufficient quantity and good quality of cultivated land must be effectively guaranteed. The Jiangnan Plain in Hubei Province is one of the most important grain production bases in China. In the future, it is important to focus on reducing the occupation of cultivated land during urban expansion. The balance of occupation and compensation policy and the implementation of comprehensive land improvement projects being implemented in China can effectively stabilize agricultural land and reduce the loss of essential agricultural land resources. In addition, Hubei Province should designate the high-quality farmland resources within terrain index grade 1 and grade 2 as permanent basic farmland protection areas, so as to improve the level of cultivated land resources protection.

In the area with Level 4 habitat quality, construction land was the land use type that accounts for a large proportion. It is necessary to optimize land use allocation on the premise of protecting biodiversity and ecological corridors for these areas. Delimiting the urban growth boundary is an efficient way to control the disorderly spread of cities and curb the decline of biodiversity. Follow-up research can study the urban growth boundary from the perspective of ecosystem services, construct the delimitation method of the urban growth "ecological boundary" based on the concept of "ecological priority" to explore the urban expansion path under the situation of minimizing the impact on habitat quality, and provide scientific support for the urban sustainable development of the Wuhan urban circle and other similar regions in the country (Jiansheng et al., 2017).

4.3 Limitations and future research directions

At present, there are two types of habitat quality assessment methods: one is to obtain habitat quality parameters through field investigation in the study area, and construct evaluation indicators on the basis of field sample investigations to comprehensively evaluate habitat quality (Qiang et al., 2014, 2019). For example, Liu et al. investigated and evaluated the biodiversity and habitat quality of Dunhuang West Lake Nature Reserve (Minxia, 2009). Liu et al. investigated and analyzed the habitat quality of rivers in the Yixing area of Taihu Lake basin (Hua et al., 2012). Yang et al. investigated the habitat quality of Laizhou Bay (Jianqiang et al., 2014). However, the methods of field survey sampling used to evaluate habitat quality tend to study the habitat environment of small geographical ranges or of a single species, and these methods are limited by time and labor consumption, making it especially difficult to carry out long term data analysis.

Second, based on land use data, multiple software models are applied to evaluate the habitat quality of the study area (Xiaoyan et al., 2021), such as the habitat quality evaluation module of the InVEST model (Xueru et al., 2020), the biodiversity evaluation module of the SoLVES model (Yu et al., 2016) and IDRISI software (Shanthala et al., 2016). Among them, the habitat quality assessment module of the InVEST model is widely used because of its convenient parameter acquisition and accurate result analysis. For example, Huang et al. discussed the spatiotemporal evolution of habitat quality in the Dabie Mountains of western Anhui (Muyi et al. 2020). Han et al. studied the impact of land use change on habitat quality in the Qinghai Lake basin (Yanli et al., 2019). Zheng et al. assessed the habitat quality and landscape pattern of Changli County (Yu et al., 2018). Some scholars

have also combined the InVEST model and land use change simulation model to study the changes in habitat quality in historical and future periods (Kang et al., 2019; Xueru et al., 2020). As can be seen from the previous research results, the InVEST model, which combines the advantages of RS and GIS, is capable of carrying out habitat quality assessments on different geospatial scales and time dynamics, providing a feasible method for habitat quantitative estimation. However, due to data limitations, this study considered only the influence of habitat quality on land use change. Future research can be combined with other types of ecosystem service function evaluation modules to comprehensively evaluate the ecological effects of land use change, so as to provide scientific guidance for ecosystem health and economic and social sustainable development in Hubei Province.

5 Conclusions

Based on the InVEST model, DEM data, and land use data from 2000 to 2020, this study analyzed and discussed the spatiotemporal change characteristics of habitat quality in Hubei Province, and studied the impact of terrain gradients effect on habitat quality. The conclusions are as follows:

(1) The land use types in Hubei Province are mainly cultivated land, woodland, grassland, and water area, which is 87% of the total area of Hubei Province. The proportion of each land use type in Hubei Province remained relatively stable during the research period, but there were varying degrees of changes. From 2000 to 2020, the habitat quality of each land use type in Hubei Province fluctuated little, and the distribution of habitat quality was basically consistent with that of land use type. The habitat quality of water area and woodland was the highest, followed by the habitat quality of grassland and cultivated land. During the research period, the habitat quality of cultivated land, woodland, and grassland decreased slightly, but the habitat quality of water area improved. Woodlands and water surfaces contributed the most to the habitat quality of Hubei Province. The main factors for the decline in the regional habitat quality were the increase in construction land and the change of cultivated land.

(2) The distribution characteristics of all kinds of habitats were different. High level habitats (Level 1 and level 2) were mainly distributed on the mountains and hills in the southwest and northwest of Hubei Province. Level 3 habitat quality was mainly distributed on the Jiangnan Plain of Hubei Province, with frequent disturbance by human activities and a fragile ecological environment. Level 4 habitats were mainly distributed on urban areas, three urban agglomerations, and their surrounding areas. The average habitat quality in 2000, 2005, 2010, 2015, and 2020 was 0.6095, 0.6107, 0.6099, 0.6060, and 0.6053, respectively, showing the change characteristics of “increase–decrease”. This result reflects that the higher habitats are degrading to lower levels, and Hubei Province has a potential risk of habitat degradation.

(3) The topographic index in Hubei Province ranged from -0.351 to 3.76 and was divided into five grades, which could describe the characteristics of regional topography; that is, the topographic position of Hubei was lower in the middle, and higher in the southwest and northwest. The terrain level of the region was mainly grade 1 (more than 30%), followed by grade 2, grade 3, grade 4 (each approximately 18%), and grade 5 was the lowest (only 12%). The spatial distribution of habitat quality at different levels in Hubei Province was quite different on the terrain gradient. In addition, terrain level played a key role in the spatial distribution pattern of habitat quality. With the increase in topography,

the average habitat quality increased, but the increase gradually decreased. In addition, the effect of terrain gradient on habitat quality was more significant. From 2000 to 2020, the habitat quality of all terrain levels showed a downward trend, and the number of forests and grasslands continued to decrease, resulting in a general decline in habitat quality.

Acknowledgements The author is very grateful to Mengyao Lu, Li Wang, and Muhtar-AMAT for their great contributions to this paper. We would like to thank the anonymous reviewers for their helpful comments and suggestions, which improved the quality greatly of this paper.

Author contribution Yong Zhou and Pengnan Xiao contributed to conceptualization; Pengnan Xiao, mengyao Li contributed to methodology; Jie Xu and Pengnan Xiao contributed to software; Pengnan Xiao contributed to writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

Funding This work was financial supported by two projects: Special Foundation for National Science and Technology Basic Research Program of China (2021FY100505) and Study on temporal and spatial response mechanism of cultivated land quality change and grain productivity in Lianghu Plain in the past 40 years (42171061).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The manuscript was not submitted to more than one journal for simultaneous consideration.

Consent for publication The submitted works are original and have not been published elsewhere in any form or language. The study was not divided into several parts to increase the number of submissions and submitted to various journals or one journal over time. All authors have read and agreed to the published version of the manuscript.

Human or animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

References

- Alaniz, A. J., Carvajal, M. A., Fierro, A., Vergara-Rodríguez, V., Toledo, G., Ansaldo, D., Moreira-Arce, D., Rojas-Osorio, A., & Vergara, P. M. (2021). Remote-sensing estimates of forest structure and dynamics as indicators of habitat quality for magellanic woodpeckers. *Ecological Indicators*, *126*, 107634. <https://doi.org/10.1016/j.ecolind.2021.107634>
- Berta Aneseyee, A., Noszczyk, T., Soromessa, T., & Elias, E. (2020). The invest habitat quality model associated with land use/cover changes: a qualitative case study of the Winike watershed in the Omo-gibe basin, Southwest Ethiopia. *Remote Sensing-Basel*, *12*(7), 1103. <https://doi.org/10.3390/rs12071103>
- Brown, G., & Brabyn, L. (2012). The extrapolation of social landscape values to a national level in new zealand using landscape character classification. *Applied Geography*, *35*(1–2), 84–94. <https://doi.org/10.1016/j.apgeog.2012.06.002>
- Budnik, R. R., Conroy, J. D., Zweifel, R. D., Ludsin, S. A., & Marschall, E. A. (2021). Projecting future habitat quality of three midwestern reservoir fishes under warming conditions. *Ecology of Freshwater Fish*, *30*(1), 31–47. <https://doi.org/10.1111/eff.12561>
- Caixian, X., Jie, G., Yan, L., Lingling, Y., & Bingli, G. (2020). Spatial distribution characteristics of typical ecosystem services based on terrain gradients of bailongjiang watershed in gansu. *Acta Ecologica Sinica*, *40*(13), 4291–4301.
- Chang-Li, Z., Ji-Fei, Z., Yu-Luan, Z., & Chun-Yan, L. (2017). Topographic gradient effects of typical watershed ecosystem services in the eastern tibetan plateau—a case study of the upper reaches of minjiang river. *Resources and Environment in the Yangtze Basin*, *26*(10), 1687–1699.

- Chuanzhun, S., Lin, Z., Chao, W., Jie, H., & Bingzhen, D. (2015). Biodiversity simulation of poyang lake wetlands by invest model under different scenarios. *Resources and Environment in the Yangtze Basin*, 24(07), 1119–1125.
- Chunfang, L., Chuan, W., & Licheng, L. (2018). Spatio-temporal variation on habitat quality and its mechanism within the transitional area of the three natural zones: A case study in yuzhong county. *Geographical Research*, 37(02), 419–432.
- Codato, D., Pappalardo, S. E., & de Marchi, M. (2017). Participatory gis in mapping ecosystem services: Two case studies from high-biodiversity regions in Italy and Peru. *GI Forum*, 1, 78–96. https://doi.org/10.1553/giscience2017_02_s78
- Dai, L., Li, S., Lewis, B. J., Wu, J., Yu, D., Zhou, W., Zhou, L., & Wu, S. (2019). The influence of land use change on the spatial-temporal variability of habitat quality between 1990 and 2010 in northeast china. *Journal of Forestry Research*, 30(6), 2227–2236. <https://doi.org/10.1007/s11676-018-0771-x>
- Forestry, S., & Administration, G. (2019). *China forest resources report (2014–2018)*. China Forestry Publishing House.
- Foster, E., Love, J., Rader, R., Reid, N., & Drielsma, M. J. (2017). Integrating a generic focal species, meta-population capacity, and connectivity to identify opportunities to link fragmented habitat. *Landscape Ecology*, 32(9), 1837–1847. <https://doi.org/10.1007/s10980-017-0547-2>
- Gao, J. (2019). How china will protect one-quarter of its land. *Nature*, 569(7757), 457. <https://doi.org/10.1038/d41586-019-01563-2>
- gradient in wujiang river basin. *Ecological Science*, 35(05): 154–159.
- Güntner, A., Seibert, J., & Uhlenbrook, S. (2004). Modeling spatial patterns of saturated areas: An evaluation of different terrain indices. *Water Resources Research*. <https://doi.org/10.1029/2003WR002864>
- Han, R., Feng, C., Xu, N., & Guo, L. (2020). Spatial heterogeneous relationship between ecosystem services and human disturbances: A case study in chuandong, China. *Science of the Total Environment*, 721, 137818. <https://doi.org/10.1016/j.scitotenv.2020.137818>
- Han, R., Jingjing, Z., Wenbo, Z., Liyuan, W., Lijuan, Z., & Lianqi, Z. (2018). Impact of land use change on habitat in the qihe river basin of taihang mountains. *Progress in Geography*, 37(12), 1693–1704.
- He, J., Huang, J., & Li, C. (2017). The evaluation for the impact of land use change on habitat quality: A joint contribution of cellular automata scenario simulation and habitat quality assessment model. *Ecological Modelling*, 366, 58–67. <https://doi.org/10.1016/j.ecolmodel.2017.10.001>
- Hongjuan, G., Huiqing, H., Hongyan, Y., & Moran, H. (2016). Distribution characteristic of important ecosystem services in terrain gradient in Wujiang river Basin. *Ecological Science*, 35(05), 154–159.
- Hongliang, Z. (2001). The prospect of gis application in wildlife habitat studies. *Chinese Journal of Ecology*, 03, 52–55.
- Hua, L., Ying, C., Mengqiu, Y., Leiting, G., & Shuqing, A. (2012). Assessment of river habitat quality in yixing district of taihu lake basin. *Chinese Journal of Ecology*, 31(05), 1288–1295.
- Jianqiang, Y., Yonggui, Z., Wenpeng, S., Juan, Z., Longjun, Z., & Xianxiang, L. (2014). The eco-environmental evaluation based on habitat quality and ecological response of laizhou bay. *Acta Ecologica Sinica*, 34(01), 105–114.
- Jiansheng, W., Jiaying, M., Qian, L., & Jiacheng, L. (2017). Urban growth boundary based on the evaluation of habitat quality: Taking the yangtze river delta as an example. *Scientia Geographica Sinica*, 37(01), 28–36.
- Kang, H., Wenyuan, D., Wanli, H., Hui, O., & Hangxiao, H. (2019). Impacts of land use change evaluation on habitat quality based on ca-markov and invest models—taking fuzhou new district of fujian province as an example. *Bulletin of Soil and Water Conservation*, 39(06), 155–162.
- Lee, D., & Jeon, S. W. (2020). Estimating changes in habitat quality through land-use predictions: Case study of roe deer (*capreolus pygargus tianschanicus*) in Jeju Island. *Sustainability-Basel*, 12(23), 10123. <https://doi.org/10.3390/su122310123>
- Lewis, N. S., Fox, E. W., & Dewitt, T. H. (2019). Estimating the distribution of harvested estuarine bivalves with natural-history-based habitat suitability models. *Estuarine, Coastal and Shelf Science*, 219, 453–472. <https://doi.org/10.1016/j.ecss.2019.02.009>
- Li, D., Sun, W., Xia, F., Yang, Y., & Xie, Y. (2021). Can habitat quality index measured using the invest model explain variations in bird diversity in an urban area? *Sustainability-Basel*, 13(10), 5747. <https://doi.org/10.3390/su13105747>
- Li, F., Wang, L., Chen, Z., Clarke, K. C., Li, M., & Jiang, P. (2018). Extending the sleuth model to integrate habitat quality into urban growth simulation. *Journal of Environmental Management*, 217, 486–498. <https://doi.org/10.1016/j.jenvman.2018.03.109>
- Li, M., Zhou, Y., Xiao, P., Tian, Y., Huang, H., & Xiao, L. (2021). Evolution of habitat quality and its topographic gradient effect in northwest hubei province from 2000 to 2020 based on the invest model. *Land*, 10(8), 857. <https://doi.org/10.3390/land10080857>


- Li, S., He, Y., Xu, H., Zhu, C., Dong, B., Lin, Y., Si, B., Deng, J., & Wang, K. (2021). Impacts of urban expansion forms on ecosystem services in urban agglomerations: a case study of Shanghai-Hangzhou bay urban agglomeration. *Remote Sensing-Basel*, *13*(10), 1908. <https://doi.org/10.3390/rs13101908>
- Minxia, L. (2009). Biodiversity characters and eco-environment quality evaluation on nature reserve of xihu in dunhuang. *Journal of Arid Land Resources and Environment*, *23*(03), 171–175.
- Muyi, H., Wenzhe, Y., Shaoru, F., & Jiahui, Z. (2020). Spatial-temporal evolution of habitat quality and analysis of landscape patterns in dabie mountain area of west anhui province based on invest model. *Acta Ecologica Sinica*, *40*(09), 2895–2906.
- NATURAL CAPITAL PROJECT, (2021) Invest 3.2.0 user's guide_chinese version_20171008. <https://naturalcapitalproject.stanford.edu/software/invest> (accessed 2021.10.1).
- Paudyal, K., Baral, H., & Keenan, R. J. (2018). Assessing social values of ecosystem services in the Phewa Lake Watershed, Nepal. *Forest Policy and Economics*, *90*, 67–81. <https://doi.org/10.1016/j.forpol.2018.01.011>
- Petway, J. R., Lin, Y., & Wunderlich, R. F. (2020). A place-based approach to agricultural nonmaterial intangible cultural ecosystem service values. *Sustainability (basel, Switzerland)*, *12*(2), 699. <https://doi.org/10.3390/su12020699>
- Polasky, S., Nelson, E., Pennington, D., & Johnson, K. A. (2011). The impact of land-use change on ecosystem services, biodiversity and returns to landowners: A case study in the state of minnesota. *Environmental and Resource Economics*, *48*(2), 219–242. <https://doi.org/10.1007/s10640-010-9407-0>
- Qiang, W., Xingzhong, Y., Hong, L., Xu, P., Zhijian, W., & Yaoguang, Z. (2014). Stream habitat assessment of dong river, china, using river habitat survey method. *Acta Ecologica Sinica*, *34*(06), 1548–1558.
- Qiang, W., Xu, P., Xiuming, L., Zhijian, W., Xingzhong, Y., & Yaoguang, Z. (2019). Assessment method for the influence of hydroelectric dams on the physical habitat quality and longitudinal connectivity of rivers: A case study of the wubu and zaodu rivers. *Acta Ecologica Sinica*, *39*(15), 5508–5516.
- Rosas, Y. M., Peri, P. L., Huertas Herrera, A., Pastore, H., & Martínez Pastur, G. (2017). Modeling of potential habitat suitability of hippocamelus bisulcus: Effectiveness of a protected areas network in Southern Patagonia. *Ecological Processes*. <https://doi.org/10.1186/s13717-017-0096-2>
- Sallustio, L., De Toni, A., Strollo, A., Di Febraro, M., Gissi, E., Casella, L., Geneletti, D., Munafò, M., Vizzarri, M., & Marchetti, M. (2017). Assessing habitat quality in relation to the spatial distribution of protected areas in Italy. *Journal of Environmental Management*, *201*, 129–137. <https://doi.org/10.1016/j.jenvman.2017.06.031>
- Shanthala, D. B. S., Murthy, M. S. R., Bijan, D., & Jha, C. S. (2016). Identification of potential habitat patches for connectivity using weighted linear combination (wlc) and integral index of connectivity (iic) at east Godavari district, Andhra Pradesh, India. *Journal of the Indian Society of Remote Sensing*, *44*(3), 385–394. <https://doi.org/10.1007/s12524-015-0508-7>
- Sun, F., Xiang, J., Tao, Y., Tong, C., & Che, Y. (2019). Mapping the social values for ecosystem services in urban green spaces: Integrating a visitor-employed photography method into solves. *Urban Forestry Urban Greening*, *38*, 105–113. <https://doi.org/10.1016/j.ufug.2018.11.012>
- Sun, X., Jiang, Z., Liu, F., & Zhang, D. (2019). Monitoring spatio-temporal dynamics of habitat quality in nansihu lake basin, eastern china, from 1980 to 2015. *Ecological Indicators*, *102*, 716–723. <https://doi.org/10.1016/j.ecolind.2019.03.041>
- Sun, X., Yu, Y., Wang, J., & Liu, W. (2021). Analysis of the spatiotemporal variation in habitat quality based on the invest model- a case study of Shangri-la city, northwest Yunnan, China. *Journal of Physics: Conference Series*. <https://doi.org/10.1088/1742-6596/1961/1/012016>
- Swinton, S. M., Lupi, F., Robertson, G. P., & Hamilton, S. K. (2007). Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. *Ecological Economics*, *64*(2), 245–252. <https://doi.org/10.1016/j.ecolecon.2007.09.020>
- Tang, F., Fu, M., Wang, L., Song, W., Yu, J., & Wu, Y. (2021). Dynamic evolution and scenario simulation of habitat quality under the impact of land-use change in the huaihe river economic belt, china. *PLoS ONE*, *16*(4), e249566. <https://doi.org/10.1371/journal.pone.0249566>
- Terrado, M., Sabater, S., Chaplin-Kramer, B., Mandle, L., Ziv, G., & Acuna, V. (2016). Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. *The Science of the Total Environment*, *540*, 63–70. <https://doi.org/10.1016/j.scitotenv.2015.03.064>
- Thomas, E., Jansen, M., Chiriboga-Arroyo, F., Wadt, L., Corvera-Gomringer, R., Atkinson, R. J., Bonser, S. P., Velasquez-Ramirez, M. G., & Ladd, B. (2021a). Habitat quality differentiation and consequences for ecosystem service provision of an amazonian hyperdominant tree species. *Frontiers in Plant Science*, *12*, 621064. <https://doi.org/10.3389/fpls.2021.621064>
- Ting, Z., Wanxu, C., Jiangfeng, L., & Jiale, L. (2021). Spatial relationship between human activities and habitat quality in shennongjia forest region from 1995 to 2015. *Acta Ecologica Sinica*, *15*, 1–12.

- Wenxian, Y., Shihua, L., Shuangyun, P., Yingxin, L., Shoulou, Z., & Lidan, Q. (2021). Identification of important biodiversity areas by invest model considering topographic relief: A case study of Yunnan Province, China. *Chinese Journal of Applied Ecology*. <https://doi.org/10.13287/j.1001-9332.202112.004>
- Wu, L., Sun, C., & Fan, F. (2021). Estimating the characteristic spatiotemporal variation in habitat quality using the invest model—a case study from guangdong–hong kong–macao greater bay area. *Remote Sensing-Basel*, 13(5), 1008. <https://doi.org/10.3390/rs13051008>
- Wu, P., Dai, P., Wang, M., Feng, S., Olhnuud, A., Xu, H., Li, X., & Liu, Y. (2021). Improving habitat quality at the local and landscape scales increases wild bee assemblages and associated pollination services in apple orchards in china. *Frontiers in Ecology and Evolution*. <https://doi.org/10.3389/fevo.2021.621469>
- Wu, Y., Shan, L., Guo, Z., & Peng, Y. (2017). Cultivated land protection policies in china facing 2030: Dynamic balance system versus basic farmland zoning. *Habitat International*, 69, 126–138. <https://doi.org/10.1016/j.habitatint.2017.09.002>
- Xiao, P., Zhao, C., Zhou, Y., Feng, H., Li, X., & Jiang, J. (2021). Study on land consolidation zoning in hubei province based on the coupling of neural network and cluster analysis. *Land*, 10(7), 756. <https://doi.org/10.3390/land10070756>
- Xiaoyan, Z., Yiyi, H., Xin, H., & Miaomiao, Z. (2021). Topographic gradient effects of habitat quality and its response to land use change in hubei section of the three gorges reservoir. *Transactions of the Chinese Society of Agricultural Engineering*, 37(11), 259–267. <https://doi.org/10.11975/j.issn.1002-6819.2021.11.029>
- Xiaoyang, S., Wenming, S., Huawei, W., Peng, H., & Gang, L. (2016). Dynamic monitoring of tibetan antelope habitat suitability in the hoh xil nature reserve using remote sensing images. *Resources Science*, 38(08), 1434–1442.
- Xueru, Z., Jie, Z., & Mengmei, L. I. (2020). Analysis on spatial and temporal changes of regional habitat quality based on the spatial pattern reconstruction of land use. *Acta Geographica Sinica*, 75(1), 160–178. <https://doi.org/10.11821/dlxb202001012>
- Yan, S., Wang, X., Cai, Y., Li, C., Yan, R., Cui, G., & Yang, Z. (2018). An integrated investigation of spatiotemporal habitat quality dynamics and driving forces in the upper basin of miyun reservoir, north china. *Sustainability-Basel*, 10(12), 4625. <https://doi.org/10.3390/su10124625>
- Yang, S., Zhao, W., Liu, Y., Wang, S., Wang, J., & Zhai, R. (2018). Influence of land use change on the ecosystem service trade-offs in the ecological restoration area: Dynamics and scenarios in the Yanhe Watershed, China. *The Science of the Total Environment*, 644, 556–566. <https://doi.org/10.1016/j.scitotenv.2018.06.348>
- Yang, Z., Wang, S., Guo, M., Tian, J., & Zhang, Y. (2021). Spatiotemporal differentiation of territorial space development intensity and its habitat quality response in northeast China. *Land*, 10(6), 573. <https://doi.org/10.3390/land10060573>
- Yanli, H., Kelong, C., & Deyong, Y. (2019). Evaluation on the impact of land use change on habitat quality in qinghai lake basin. *Ecology and Environment Sciences*, 28(10), 2035–2044.
- Yu, W., Bitian, F., Yongpeng, L., Kai, Y., & Yue, C. (2016). Assessment of the social values of ecosystem services based on solves model: A case study of wusong paotaiwan wetland forest park, shanghai, china. *Chinese Journal of Applied Ecology*, 27(06), 1767–1774.
- Yu, Z., Pengtao, Z., Feng, T., Li, Z., & Xu, Z. (2018). The effect of land use change on habitat quality in changli county based on invest model. *Chinese Journal of Agricultural Resources and Regional Planning*, 39(07), 121–128.
- Yuan, L., Yong, Z., & Yuetian, D. (2019). Study on the spatio-temporal patterns of habitat quality and its terrain gradient effects of the middle of the yangtze river economic belt based on invest model. *Resources and Environment in the Yangtze Basin*, 28(10), 2429–2440.
- Zhang, C., & Fang, S. (2021). Identifying and zoning key areas of ecological restoration for territory in resource-based cities: A case study of huangshi city, china. *Sustainability-Basel*, 13(7), 3931. <https://doi.org/10.3390/su13073931>
- Zhang, H., Sun, T., Xue, S., Yang, W., & Shao, D. (2018). Habitat-mediated, density-dependent dispersal strategies affecting spatial dynamics of populations in an anthropogenically-modified landscape. *Science of the Total Environment*, 625, 1510–1517. <https://doi.org/10.1016/j.scitotenv.2018.01.065>
- Zhang, T., Gao, Y., Li, C., Xie, Z., Chang, Y., & Zhang, B. (2020). How human activity has changed the regional habitat quality in an eco-economic zone: Evidence from poyang lake eco-economic zone, China. *International Journal of Environmental Research and Public Health*, 17(17), 6253. <https://doi.org/10.3390/ijerph17176253>
- Zhang, X., Song, W., Lang, Y., Feng, X., Yuan, Q., & Wang, J. (2020). Land use changes in the coastal zone of china's hebei province and the corresponding impacts on habitat quality. *Land Use Policy*, 99, 104957. <https://doi.org/10.1016/j.landusepol.2020.104957>

- Zhifang, L., Lina, T., Quanyi, Q., Lishan, X., Tong, X., & Li, Y. (2017). Temporal and spatial changes in habitat quality based on land-use change in Fujian province. *Acta Ecologica Sinica*, *37*(13), 4538–4548.
- Zhiqiang, W., Zhichao, C., & Chengyuan, H. (2009). Breeding habitat suitability evaluation of red-crown crane in Zhalong National Nature Reserve by the method of habitat suitability index. *Wetland Science*, *7*(03), 197–201.
- Zhiyun, O., Jianguo, L., Han, X., Yincun, T., & Heming, Z. (2001). An assessment of giant panda habitat in Wolong Nature Reserve. *Acta Ecologica Sinica*, *11*, 1869–1874.
- Zhu, C., Zhang, X., Zhou, M., He, S., Gan, M., Yang, L., & Wang, K. (2020). Impacts of urbanization and landscape pattern on habitat quality using OLS and GWR models in Hangzhou, China. *Ecological Indicators*, *117*, 106654. <https://doi.org/10.1016/j.ecolind.2020.106654>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Pengnan Xiao¹ · Yong Zhou¹  · Mengyao Li¹ · Jie Xu²

Pengnan Xiao
maikedang@mails.cnu.edu.cn

Mengyao Li
limengyao@mails.cnu.edu.cn

Jie Xu
201901110800086@stu.hubu.edu.cn

¹ College of Urban and Environmental Sciences, Central China Normal University, Wuhan 430079, China

² Faculty of Resources and Environmental Science, Hubei University, Wuhan 430062, China