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Research on Temporal and Spatial Evolution of Habitat Quality and Terrain Gradient Effect in Hilly Areas: A Case Study of Changsha-Zhuzhou-Xiangtan Urban Cluster

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ABSTRACT

Habitat quality is an important manifestation of the service functions and biodiversity in an ecological service system. Hilly areas have complex terrain and sensitive and diverse ecological environment characteristics. This study describes the spatiotemporal evolution of habitat quality in the Changsha-Zhuzhou-Xiangtan urban cluster from 2010 to 2020 based on the InVEST model, and explores its spatial differentiation and change characteristics under different topographic gradients. The results show that the habitat quality in the Changsha-Zhuzhou-Xiangtan urban cluster is showing a downward trend, with a spatial pattern of 'middle loss and high, surrounding loss low', and has obvious spatial cluster characteristics. The habitat quality in areas with a topographic gradient of 1 is the worst, while the habitat quality in areas with a topographic gradient of 5 is the best. The habitat quality and topographic gradient show a positive growth trend. Based on the investigation of the spatio-temporal evolution characteristics of the habitat quality in the Changsha-Zhuzhou-Xiangtan urban cluster and the effect of topographic gradient, it provides a theoretical basis and scientific basis for the protection of ecological space and the optimization of the spatial structure of land use in hilly areas, which is of great significance for promoting the sustainable ecological development of hilly urban clusters.

KEYWORDS

Habitat quality; Gradient effect; Changsha-Zhuzhou-Xiangtan urban cluster; InVEST model; Hilly area.

1. INTRODUCTION

Biodiversity is an important foundation for the harmonious development of human society and ecology, and can be regarded as the fundamental guarantee for the harmonious development of society and the stable ecological balance[1]. However, with the rapid advancement of urbanization and the development of large-scale and unplanned construction and other high-intensity human activities, the spatial land structure and utilization methods have become unreasonable. The contradiction between the disorderly and large-scale development and construction of human society and the natural ecological space has become increasingly acute[2]. Habitat is the sum of environmental resources that organisms rely on to maintain normal life activities[3]. In order to strengthen the protection and restoration of ecological space, promote sustainable development, and solve problems such as habitat degradation, it is particularly important to conduct in-depth research on the spatiotemporal evolution characteristics of regional habitats, which will provide a key basis for maintaining the stability and balance of the ecosystem.

Topographic features are key factors influencing regional ecological structure, changes in ecological function, and spatial differentiation of development[4], and they directly affect the dynamic changes in ecosystem service functions[5]. Among them, the ecological environment in hilly areas has a more complex structure. Therefore, from the perspective of the topographic gradient effect, studying the spatiotemporal evolution of habitat quality in hilly areas is of great significance for promoting the effective protection and sustainable development of ecosystems in hilly areas[6].

2. LITERATURE REVIEW

Habitat quality (HQ) is a key indicator reflecting the level of ecosystem services and regional biodiversity within the study area. It is an important indicator for quantifying the function of the ecological service system[7]. An economic development model that comes at the expense of the environment is a major factor restricting the sustainable development of cities. Early impact studies based on habitat quality mainly investigated the establishment of a habitat quality assessment index system through field research, but this was limited to small spatial scales, and it was difficult to conduct long-term evolutionary research on habitat quality[8]. However, with the widespread use of big data, the spatiotemporal evolution of habitat quality is studied using various ecological assessment models such as the InVEST model[9], ARIES model[10], Maxent model[11], HIS model[12], and SoLVES model for quantitative evaluation[13, 14]. Among them, the InVEST model has been widely used due to its applicability, ease of operation and spatialization[15]. Hu Feng et al.[16] quantified the evolution characteristics of land use and habitat quality in the Yellow River Basin and simulated its changing trends based on the PLUS model and the InVEST model. Wang et al. [17]quantified various ecosystem indicators such as water conservation, carbon storage and biodiversity in Shaoguan City based on the InVEST model and quantified the impact factors of ecological service functions based on the Geographical Detector method. Liu et al. [18] quantified the temporal evolution of habitat quality in the Wanjiang Urban Belt from 2000 to 2020 and used the MGWR model to explore the impact of urbanization and landscape patterns on habitat quality. Related research focuses on the relationship between land use and habitat quality, the factors affecting habitat quality, and the degree of human activity interference, while there is less research on the spatial differentiation characteristics between habitat quality and topographic elements. Exploring the impact of topographic characteristics on the spatial and temporal differentiation of habitat quality in ecosystems, and exploring the spatial differentiation characteristics of the topographic gradient in ecosystems, emphasizes the important role of developing ecological space governance zoning and management in accordance with local conditions.

The research on the effect of terrain gradient on habitat quality has mainly focused on the exploration of a single topographic factor, such as elevation, slope, and topographic variance, while the research on the spatiotemporal evolution characteristics of habitat quality with multiple topographic factors is still lacking[19]. Moreover, the research perspective is mostly limited to the county[20], city[21], provincial[22] and watershed[23] scales, and there is less research on the topographic gradient changes of ecological quality in hilly areas. Hilly areas are characterized by complex ecological environments and rich biodiversity. At the same time, compared with plain areas, the quality of their habitats is more highly influenced by topographic factors. Therefore, it is of great significance to explore the spatio-temporal differentiation mechanism of habitat quality based on topographic gradients and ecosystem governance in hilly urban areas from the perspective of topographic characteristics.

This paper uses the InVEST model system to analyze the spatiotemporal evolution of habitat quality and habitat degradation in the Changsha-Zhuzhou-Xiangtan urban cluster (hereinafter referred to as C-Z-X urban cluster) from 2010 to 2020. It also constructs the topographic gradient of habitat quality in hilly areas from the perspective of multiple topographic factors such as elevation, slope, topographic variance and topographic roughness. topographic gradient of habitat quality in hilly areas, and analyze the mechanism of changes in habitat quality and its spatial differentiation under the effects of different topographic gradients from the multiple perspectives of the whole region, the city, and the county. This is an important basis for promoting the optimization of land use structure and rationalization of land use methods in hilly areas, and for achieving effective protection of biodiversity in hilly cities.

3. STUDY DESIGN

3.1. Study area

The C-Z-X urban cluster has typical hilly landform characteristics. It covers the urban centers of Changsha, Zhuzhou and Xiangtan and the surrounding counties and cities, including Ningxiang, Liuyang and Changsha County in Changsha City, Ling County, You County and Yanling County in Zhuzhou City, and Liling City. Xiangxiang City, Shaoshan City and Xiangtan County in Xiangtan City govern a total of 13 districts, 5 counties and 5 county-level cities.

The eastern side of the C-Z-X urban cluster is connected to Yichun City, Pingxiang City, and Ji'an City in Jiangxi Province, the southern side is close to Hengyang City and Chenzhou City in Hunan Province, and the western side is connected to Yiyang City. The three cities of the C-Z-X urban cluster are adjacent to each other in a “pin” shape along the Xiangjiang River, with the urban areas close to each other and a compact organizational structure[24]. Among them, the green heart of the C-Z-X urban cluster serves as an ecological barrier between the three cities. Its ecological protection has a significant impact on the ecological environment quality of the entire urban cluster. Therefore, it is of great research significance to explore the spatiotemporal evolution characteristics of habitat degradation and quality in hilly areas from the perspective of the C-Z-X urban cluster.

3.2. Data and preprocessing

The data for this study were obtained from the Center for Resource and Environmental Sciences at the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences. The land use status (LULC) of the C-Z-X urban cluster in 2010, 2015 and 2020 was obtained using raster extraction and reclassification in ArcGIS software to quantify the temporal and spatial differentiation of habitat quality and habitat degradation. The C-Z-X urban cluster DEM data was obtained based on the geospatial data cloud, and relevant data such as terrain, elevation, terrain relief, and terrain position index were obtained quantitatively using ArcGIS software.

3.3. Research Methods

3.3.1. Quantitative evaluation of habitat quality

The habitat quality (HQ) module in the InVEST model can calculate the habitat quality in the study area based on the land use pattern of the area and the threat factor weights and sensitivity allocations of the LULC type, that is, the status of biodiversity maintenance capacity[25, 26]. The calculation formula is as follows:

$$\mathrm{HQ}_{ij} = \mathrm{H}_j \times \left[1 - \frac{D_{ij}^Z}{D_{ij}^Z + K^Z}\right] \quad (1)$$

where HQ_{ij} is the habitat quality of land use type j in cell i, Dij is the degree of habitat degradation, H_j is the suitability of the habitat for land use type j, and K is the half-saturation constant. Z is the model parameter. Both K and Z are set to the default values for the model, which in this study are set to 0.5.

$$D_{xi} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{W_r}{\sum_{r=1}^{R} W_r} \right) \times r_y \times i_{rxy} \times \beta_x \times S_{jr} \tag{2}$$

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}} \right) \tag{3}$$

$$i_{rxy} = exp\left(-\left(\frac{2.99}{d_{rmax}} \right) d_{xy} \right) \tag{4}$$

where R is the number of stress factors; W_r is the weight; Y_r is the number of grid cells; r_y is the number of stress factors on the grid cell; β_x is the accessibility level of grid x; S_{jr} indicates the sensitivity of landscape j to stress factors; and i_{rxy} is the influence distance of stress factors. d_{xy} is the straight-line distance between two grids, and d_{rmax} is the maximum influence distance of the stress factor r.

This study refers to relevant studies[27, 28] and combines the current situation of socio-ecological factors in the C-Z-X urban cluster to obtain the spatial attenuation types of different threat factors, threat factor weights and sensitivity (Table 1), and set the parameters required for the calculation (Table 2). Habitat suitability (HABITAT) refers to the degree to which each land use type provides habitat for biodiversity, which is directly related to the quality of the habitat. Habitat suitability ranges from 0 to 1, with 1 representing the highest suitability. Spatial decay types are divided into exponential and linear types, and the preservation path is the raster path of each threat factor.

Table 1 Maximum distance, weight and attenuation type of stress factors in the C-Z-X urban cluster

Stress factor	Maximum distance/km	Weight	Attenuation type
Farm land	1	0.5	Linear
Urban land	10	0.9	Index
Rural residential area	5	0.6	Index
Other buildable land	8	0.7	Index
Unused land	1	0.4	Linear

Table 2 Sensitivity of stress factors in the C-Z-X urban cluster

Land use type			Stress factors				
Category	Subcategory	Habitat suitability	Farm land	Urban land	Rural residential area	Other buildable land	Unused land
Farm land	/	0.5	0	0.8	0.6	0.7	0.3
Forest land	Forest land	1	0.8	0.9	0.8	0.7	0.4
	Shrubland	0.9	0.6	0.7	0.6	0.7	0.4
	Wooded area	0.7	0.6	0.8	0.7	0.8	0.3
	Other forest	0.6	0.7	0.8	0.7	0.8	0.3
Meadom	High coverage grassland	0.8	0.4	0.6	0.7	0.5	0.3
	Coverage grassland	0.7	0.5	0.7	0.7	0.6	0.4
	Ground coverage grassland	0.6	0.6	0.8	0.7	0.6	0.4
Water area	Rivers and streams	0.9	0.3	0.8	0.6	0.8	0.1
	Lakes	1	0.3	0.8	0.6	0.8	0.1
	Reservoirs ponds	1	0.5	0.8	0.5	0.5	0.2
	Tidal flat	0.7	0.6	0.8	0.7	0.7	0.3
Buildable land	Urban land	0	0	0	0	0	0
	Rural residential area	0	0	0	0	0	0
	Other buildable land	0	0	0	0	0	0
Unused land	/	0.2	0.3	0.5	0.4	0.5	0

To quantify the temporal and spatial changes in habitat quality and degradation degree of the C-Z-X urban cluster, the difference in habitat quality over a period of 5 years was calculated. The changes in habitat quality and degradation degree reflect the changes in the C-Z-T urban agglomeration from 2010 to 2020. The evaluation criteria are shown in Table 3.

Table 3 Evaluation of the change in habitat quality and degradation in the C-Z-X urban cluster

Change	$\Delta>0$	$\Delta=0$	$\Delta<0$
Habitat quality change	Gain	No change	Loss
Habitat degradation change	Deterioration	No change	Optimization

3.3.2. Topographic position index and topographic relief calculation

The study introduces various elements such as topographic position index and topographic relief, emphasizing the spatial differentiation characteristics of the topographic conditions of the C-Z-X urban cluster from the perspective of multiple topographic elements. Based on the perspective of topographic position index and topographic relief, an in-depth analysis of the hilly landform characteristics of the C-Z-X urban cluster is carried out. The calculation formulas for the two are as follows:

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

$$A = A_{MAX} - A_{MIN} \quad (6)$$

Among them, T is the topographic position index, E and $E_{average}$ are the elevation and mean elevation in a certain area, S and $S_{average}$ are the slope and mean slope in a certain area; A is the topographic relief; A_{MAX} and A_{MIN} are the maximum and minimum values of the elevation in a certain area.

Based on the topographic factors of the C-Z-X urban cluster, such as elevation, slope, topographic position index and topographic relief, and using the ArcGIS software to divide the terrain of the C-Z-X urban cluster into five categories using the natural breakpoint method, the specific classification criteria are shown in Table 4.

Table 4 Grading standard for topographic gradient in the C-Z-X urban cluster

Level	Elevation/m	Slope/degrees	Topographic relief/m	Topographic position index
1	<173	0-3.26	0-41	0.0385-0.2923
2	173-375	3.26-7.71	41-90	0.2923-0.5319
3	375-672	7.71-13.19	90-148	0.5319-0.8350
4	672-1119	13.19-20.22	148-224	0.8350-1.1662
5	1119-2073	20.22-43.70	224-585	1.1662-1.8358

3.3.3. Spatial autocorrelation

Spatial autocorrelation analysis can be used to quantitatively describe the spatial dependence of things. In this study, data on habitat quality in the Changsha-Zhuzhou-Xiangtan urban agglomeration was extracted to analyze the overall spatial correlation and its degree of difference, in order to measure its spatial dependence and degree of agglomeration. Moran's I Moran's I is based on the concept

Global Moran's I is used to measure the spatial autocorrelation of the entire dataset to assess whether there is significant agglomeration of high and low habitat quality in Jiangxia District. The calculation formula is as follows:

$$\mathrm{I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\,(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad (6)$$

Where w_{ij} is the element value of the spatial weight matrix. The value of I ranges from -1 to 1. I > 0 indicates a positive correlation; a value close to 1 indicates that similar attributes are clustered together (i.e., high values are adjacent to high values, and low values are adjacent to low values). values are adjacent, and low values are adjacent to low values); I is less than 0 for negative correlation, and a value close to -1 indicates that attributes with different values are clustered together; a value close to 0 indicates that the attributes are randomly distributed or there is no spatial autocorrelation. When the P value corresponding to the Z value is lower than the given significance level (usually 0.05), it is considered that the observations are significantly correlated spatially.

After it is found that there is obvious data clustering through the global Moran's index, Local Moran's I needs to be used for further calculation. Local Moran's I is used to measure the spatial autocorrelation between a specific area and its neighboring areas, and can provide a more detailed pattern of spatial autocorrelation. The calculation formula is as follows:

$$I_i = \frac{(x_i - \bar{x}) \sum_{j=1}^{n} x_j - \bar{x}}{S^2} \quad (7)$$

A positive I_i indicates that a high value is surrounded by high values (high-high), or that a low value is surrounded by low values (low-low). A negative I i indicates that a low value is surrounded by high values (low-high), or that a high value is surrounded by low values (high-low).

4. RESULT

4.1. Spatial and temporal changes in habitat quality of the C-Z-T urban cluster

Quantify the habitat quality of the Changsha-Zhuzhou-Xiangtan urban agglomeration during the period 2010–2020 based on the InVEST model. The average habitat quality of the Changsha-Zhuzhou-Xiangtan urban agglomeration in 2010, 2015 and 2020 is 0. 6522, 0.6398, and 0.6353, respectively, indicating that the overall habitat quality of the Changsha-Zhuzhou-Xiangtan urban agglomeration is showing a year-on-year decline, with the habitat quality declining more sharply between 2010 and 2015. Based on ArcGIS software, the habitat quality of each year was divided into five levels through reclassification. The higher the level, the higher the habitat quality, which is classified as follows: V-level habitat quality (0–0.2), IV-level habitat quality (0.2–0.4), III-level habitat quality (0.4–0.6), II-level habitat quality (0.6–0.8) and I-level habitat quality (0.8–1). As shown in Tables 2–4, the habitat quality in the Changsha–Zhuzhou–Xiangtan urban agglomeration from 2010 to 2015 was mainly Class III, with an area proportion of more than 33.80%. The area proportion of Class I habitat quality decreased from 36.16% in 201 36.16% in 2010 to 34.16% in 2020, while the area proportion of habitat quality from II to IV showed an increasing trend from 2010 to 2015, and then decreased in 2020. From 2010 to 2020, the proportion of area with habitat quality of class V increased from 4.19% to 5.84%, indicating that with the intensification of urbanization in the Changsha-Zhuzhou-Xiangtan urban agglomeration, the overall habitat quality is showing a trend of continuous degradation.

Table 5 Proportion of area with different levels of habitat quality in the Changsha-Zhuzhou-Xiangtan urban agglomeration

Year	Average Habitat Quality Index	Level V	Level IV	Level III	Level II	Level I
2010	0.6522	4.19%	7.51%	33.87%	18.27%	36.16%
2015	0.6398	4.97%	8.22%	33.96%	18.42%	34.43%
2020	0.6353	5.84%	7.63%	33.88%	18.30%	34.36%

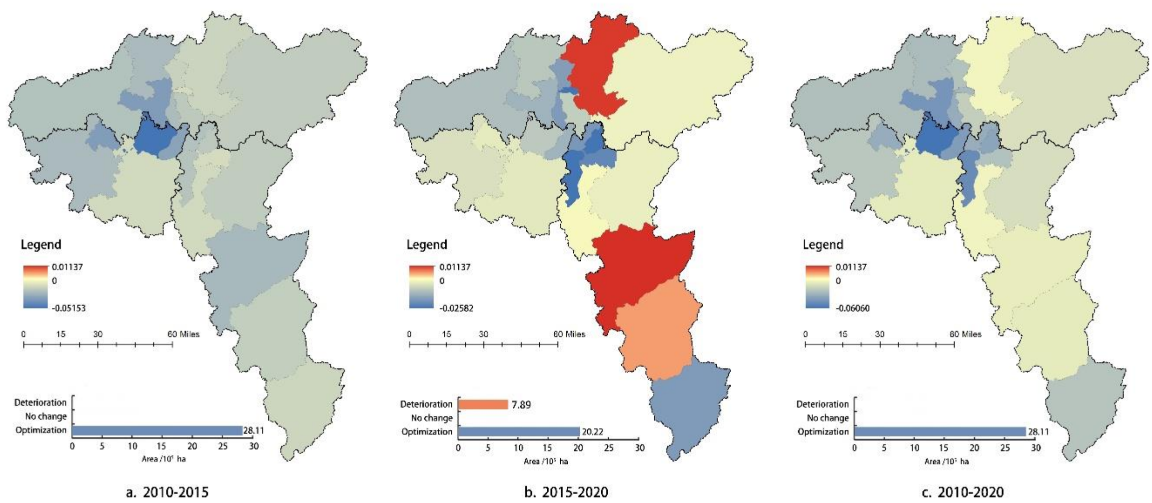

Figure 1 Spatial distribution map of habitat quality index changes in the C-Z-X urban cluster from 2010 to 2020

The overall trend of habitat quality change in the C-Z-X urban cluster from 2010 to 2020 showed a downward trend, with the loss area far greater than the gain area. From 2010 to 2015, the overall habitat quality decreased at the county scale, with a loss area of 28.11 × 105 hectares, among which Yuhua District, Yuelu District and other areas had the largest habitat loss. During the period of 2015-2020, the habitat quality of some counties showed an upward trend, such as You County, Chaling County and Changsha County, with an overall habitat quality gain area of 7.89 × 105 hectares; while in Tianyuan District, Hetang District and other areas mainly in the urban area of Zhuzhou City, the habitat quality decreased. The habitat quality change in the C-Z-X urban cluster from 2010 to 2020 generally showed the characteristics of "high loss in the central part and low loss in the surrounding areas". The most significant habitat quality changes were mainly concentrated in the urban areas of Changsha City, Zhuzhou City and Xiangtan City.

4.2. Temporal and spatial variation characteristics of habitat degradation in the C-Z-T urban cluster

The habitat degradation degree of the C-Z-T urban cluster from 2010 to 2020 was reclassified using the natural breakpoint method through ArcGIS, dividing ecological degradation into three categories: mild, moderate, and severe degradation. The overall habitat degradation degree of the C-Z-T urban cluster is mainly characterized by moderate degradation, with the area of degraded land accounting for more than 42%. The average habitat degradation degree increased from 0.2113 in 2010 to 0.2163 in 2015, and then decreased to 0.2142 in 2020. Among them, the proportion of mild degradation area decreased from 32.95% in 2010 to 31.64% in 2020; the proportion of severe degradation area showed an upward trend from 2010 to 2015 before starting to decline, but the overall area proportion showed a growth trend. Overall, the habitat degradation degree of the C-Z-T urban cluster exhibited a significant increase followed by a slight decline, reflecting the requirements for practicing ecological-friendly concepts in the new era.

Table 6 Area Proportion of Habitat Quality Degradation at Different Levels in the C-Z-X urban cluster

Year	Average Habitat Degradation Index	Mild degeneration (0-0.15)	Moderate degeneration (0.15-0.30)	Severe degeneration (>0.30)
2010	0.2113	32.95%	43.05%	24.00%
2015	0.2163	31.69%	42.42%	25.89%
2020	0.2142	31.64%	43.40%	24.95%

The area of habitat degradation in the C-Z-X urban cluster increased from 1.16 million hectares in 2010 to 1.65 million hectares in 2020; while the area of habitat optimization decreased from 1.65 million hectares to 1.16 million hectares. By 2020, the area of habitat degradation was far greater than that of optimization, showing an overall downward trend in habitat degradation. The degree of habitat degradation was mainly concentrated in the Yuetang District, Tianyuan District, and Yuelu District, primarily within the urban areas of Changsha, Zhuzhou, and Xiangtan. The areas with a relatively high degree of habitat optimization were mainly in parts of You County, Xiangxiang City, and Shaoshan City.

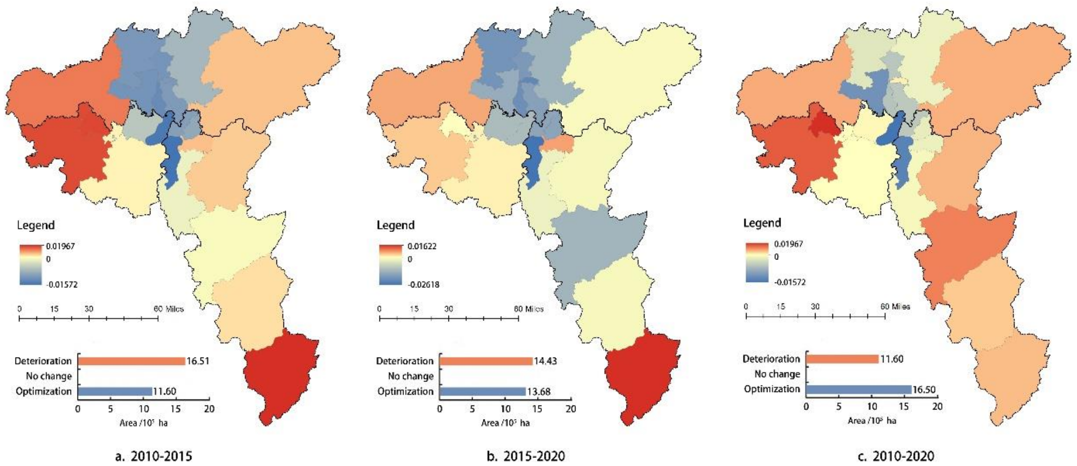

Figure 2 Spatial distribution map of habitat degradation changes in the C-Z-X urban cluster from 2010 to 2020

4.3. Cluster analysis of the quality of the habitat in the C-Z-X urban cluster

Using ArcGIS software to calculate the Moran's I index of the overall habitat quality of the C-Z-T urban cluster from 2010 to 2020, the results show that at a 95% confidence level, the overall Moran's I indices for 2010, 2015, and 2020 are 0.7973, 0.8054, and 0.8091, respectively, indicating that the habitat quality of the C-Z-T urban cluster has significant spatial correlation, with a trend of aggregation among different regions.

As shown in Figure 3-3, the habitat quality of the C-Z-X urban cluster from 2010 to 2020 shows obvious agglomeration characteristics. In general, the spatial clustering of habitat quality is mainly dominated by the two types of "H-H" and "L-L", and the clustering types of "H-L" and "L-H" are less distributed. Among them, the "H-H" agglomeration area of habitat quality is mainly concentrated in the core area of the study area, that is, the urban area of the C-Z-X urban cluster, while the "L-L" is mainly concentrated in the southern part of Zhuzhou City and the east side of Changsha City. The "H-L" and "L-H" show a trend of scattered distribution during the period of 2010-2020.

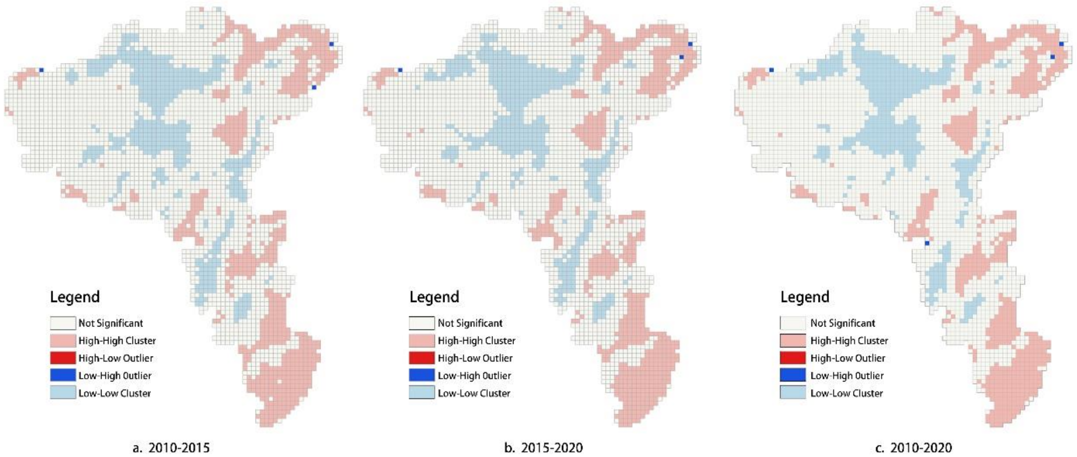

Figure 3 LISA Distribution Map of Habitat Quality in C-Z-X urban cluster from 2010 to 2020

4.4. Gradient Effect Differentiation of Habitat Quality in the C-Z-T Urban cluster

The habitat quality of the C-Z-X urban cluster showed an increasing trend with the rise in slope from 2010 to 2020. As the elevation increased, it exhibited a growth trend from level 1 to level 4, followed by a slight decline. The overall topographic relief of the C-Z-X urban cluster ranges from 0 to 585m, and the overall habitat quality shows an upward trend with the increase in topographic relief. The average habitat quality at level 1 topographic relief is the lowest, mainly due to the land use types in this area being primarily construction land and arable land, resulting in a relatively flat terrain suitable for urban expansion. In contrast, areas with level 5 topographic relief have higher habitat quality, with land use primarily consisting of forest land. The topographic position index of the C-Z-X urban cluster ranges from 0.0385 to 1.8358, indicating that certain local areas have characteristics of steep slopes and high elevations. The overall habitat quality improves with the increase in the topographic position index, although the growth shows a continuous slowing trend. Areas with a lower topographic position index have lower habitat quality, mainly concentrated in urban development zones. Overall, it indicates that as the elevation, slope, topographic relief, and topographic position index increase, the degree of human intervention in the natural ecological environment decreases, leading to an improvement in habitat quality levels.

Under different terrain gradients, the area of habitat quality change from 2010 to 2020 is mainly dominated by gain areas. With the increase in elevation, the change area of habitat quality gain zones shows a slight decline from level 1 to level 2, while it shows a growth trend from level 2 to level 5. In terms of slope and terrain undulation, the proportion of habitat quality gain area from 2010 to 2020 shows a declining trend as these factors increase, with the highest degree of habitat quality degradation occurring at slope and terrain undulation level 5, where the degradation area proportions are 44.12% and 41.95%, respectively. The proportion of gain area in habitat quality at terrain position index levels 1 to 3 declines, while it shows an upward trend from levels 3 to 5.

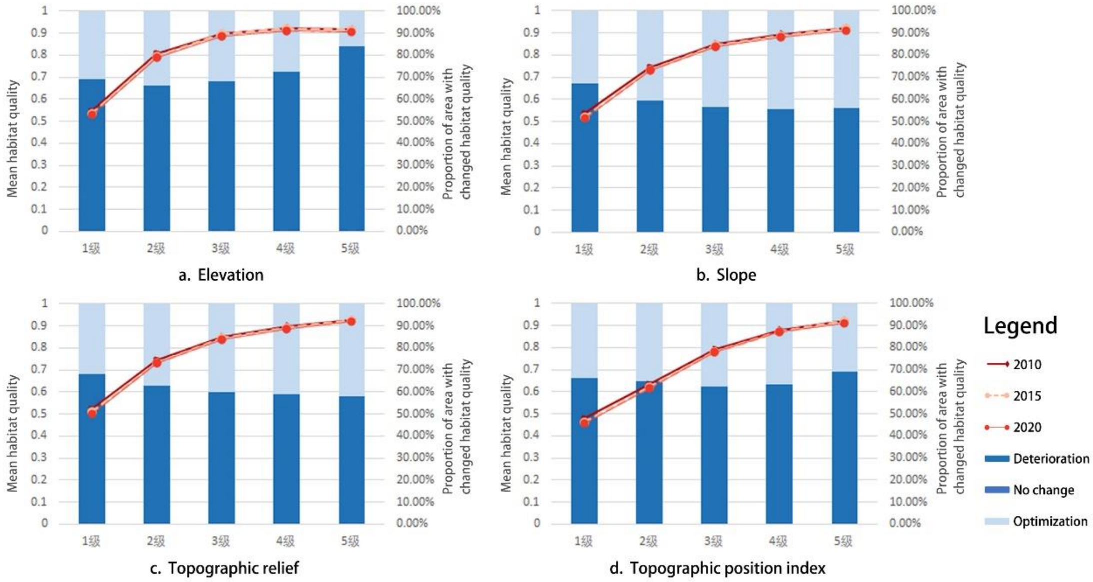

Figure 4 Proportion of area with varying habitat quality and area change in different topographic gradient classes in the C-Z-X urban cluster

Overall, as the terrain gradient increases, the habitat quality index shows an upward trend with its increase, and is generally in a state of gain. The change in habitat quality increases with elevation and terrain position index, with the gain area continuously expanding, while slope and terrain undulation show the opposite trend.

5. DISCUSSION AND CONCLUSION

5.1. Discussion

Based on the concept of "dual carbon", the urban cluster has gradually become an important spatial carrier for improving the high-quality development of the region and enhancing the competitiveness at home and abroad. In order to improve the ecological safety level and sustainable development of the ecological environment quality of the C-Z-X urban cluster, ecological protection and quality improvement measures are proposed for the ecological green heart space of the C-Z-X urban cluster, and the development concept of "green waters and green mountains are金山银山" is implemented. This is consistent with the gradual slowdown of habitat quality loss in this study during the period of 2010-2020, emphasizing that the measures for the remediation and restoration of the ecological quality of the C-Z-X urban cluster have certain benefits in habitat governance, but emphasizing that the ecological governance of the C-Z-X urban cluster needs to be further improved and perfected.

The spatiotemporal differentiation characteristics of habitat quality are constrained by multiple factors from both natural and human activities. Overall, the Chang-Zhu-Tan and Chengdu urban cluster showed a declining trend in habitat quality from 2010 to 2020, with a slowing rate of decline from 2015 to 2020. This indicates that the ecological environment quality of the C-Z-X urban cluster is gradually improving and enhancing, but the habitat quality in some local areas remains fragile and shows a trend of degradation. In the urban areas of Changsha, Zhuzhou, and Xiangtan, rapid urbanization and fast urban construction have caused serious damage to habitats. Notably, from 2010 to 2015, there was significant habitat degradation in the urban area of Xiangtan, and from 2015 to 2020, significant degradation occurred in the urban area of Zhuzhou. Overall, from 2010 to 2020, the habitat quality in the urban center areas of the C-Z-X urban cluster has significantly deteriorated, while the habitat quality in the surrounding counties has degraded less and even improved in some cases. Therefore, it is necessary to strengthen ecological protection efforts in the urban center areas of the Chang-Zhu-Tan region, emphasizing the coordinated protection and sustainable development of the green core areas of the C-Z-X urban cluster, and to create a good ecological restoration green barrier.

Habitat quality shows an upward trend with the increase of grade, except for the altitude factor on each grade terrain gradient. The areas with high terrain gradient are mainly forest land types, with high habitat quality level, while the areas with poor habitat quality are mainly located in the areas with relatively flat terrain, small slope and low overall terrain index, that is, in the areas of level 1 terrain index, which are mainly construction land and cultivated land. The terrain gradient level 1 area is relatively flat and open, easy to build and expand, and is an important area suitable for urbanization construction in hilly areas. It is mainly the central urban area, with high population concentration and rapid expansion of construction land, leading to obvious damage to the ecosystem and habitat quality. However, the general county areas of C-Z-X urban cluster are mainly located in the areas of terrain index level 1 and level 2, with low development level and weak overall habitat quality loss. The areas above terrain gradient level 3 are mainly characterized by large slope and high altitude, with relatively sparse population, low degree of human activity interference and high forest coverage rate. Therefore, the habitat quality shows an upward trend with the increase of terrain gradient. However, with the rapid construction of urbanization, a large number of trees are cut down and reclaimed for construction, and the rapid development and construction of relatively flat areas lead to a high degree of habitat quality loss. Therefore, it is emphasized that C-Z-X urban cluster should strengthen the organic balance between urban construction and ecological sustainable development, strictly implement the delineation of "three zones and three lines" of national land space, promote the compact and intensive development and construction of the central urban area, and attach importance to the ecological restoration and improvement of Changzhutan green heart area, and explore new paths and new models for urban green transformation and development. At the same time, strengthen the restoration and reshaping of ecological space in surrounding counties and districts, improve, maintain and improve the overall habitat quality.

5.2. Conclusion

This study takes the typical hilly area - C-Z-X urban cluster as an example to explore the spatial-temporal evolution pattern characteristics of habitat quality in the C-Z-X urban cluster from 2010 to 2020, and based on the spatial differentiation of habitat quality and the proportion of change area under different topographic gradients, the conclusions are as follows:

1) The habitat quality mean values of C-Z-X urban cluster in 2010, 2015 and 2020 were 0.6522, 0.6398, and 0.6353, respectively, showing a downward trend overall. From the perspective of districts and counties, the habitat quality mean values of all districts and counties showed a decreasing trend, especially in the central urban area, where the decrease was the highest, with significant spatial heterogeneity, and the overall distribution pattern was "high in the middle and low around".

2) The degree of habitat degradation shows a trend of first increasing and then decreasing, but overall presents an increasing trend. The average habitat degradation index during the period from 2010 to 2020 was 0.2113, 0.2163, and 0.2143, respectively. From the perspective of districts and counties, the C-Z-X urban cluster is mainly characterized by moderate ecological degradation, with the area of ecological degradation far exceeding the area of optimization. Habitat degradation is mainly concentrated in areas such as Yuetang District, Yuelu District, and Tianyuan District.

3) The habitat quality of land types such as forests and grasslands in the C-Z-X urban cluster is high, while the habitat quality of land types such as arable land and construction land is relatively low. Habitat quality shows a high correlation with topographic gradients, where the areas with the lowest habitat quality are mainly located in the first-level topographic gradient, while the best habitat quality is found in the fourth-level elevation areas and the fifth-level areas of slope, topographic undulation,

and topographic position index. Moreover, under different topographic gradients, the area of habitat quality change from 2010 to 2020 is predominantly in the gain zone.

This study takes the C-Z-X urban cluster as the research object for the spatiotemporal differentiation characteristics of habitat quality in hilly areas and the spatial differentiation of topographic gradients. It provides theoretical support for improving habitat quality in urban clusters in hilly areas and optimizing land use structure and patterns. This research quantifies the habitat quality of the Chang-Zhu-Tan Chengdu agglomeration from 2010 to 2020 based on the InVEST model. However, some threat factors and weight selections are somewhat subjective, and the study only explores within the single scope of the C-Z-X urban cluster, neglecting the impact of surrounding land use on habitat quality. Therefore, the exploration of habitat quality should be based on multiple perspectives and a broader view to enhance the scientific and practical significance of the research.

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