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Comprehensive Evaluation of Island Habitat Quality Based on the Invest Model and Terrain Diversity: A Case Study of Haitan Island, China

He Huang [1,2], Yanzhi Xiao [1], Guochang Ding [1,2], Lingyun Liao [1], Chen Yan [1,2], Qunyue Liu [3], Yaling Gao [3,*] and Xiangcai Xie [1,2,*]

[1] College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, Fuzhou 350002, China; fafuhh@fafu.edu.cn (H.H.); xyzhi@fafu.edu.cn (Y.X.); fjdgc@fafu.edu.cn (G.D.); liaolingyun@fafu.edu.cn (L.L.); etanyan@fafu.edu.cn (C.Y.)
[2] National Center for Water Conservancy Scenic Area Research, Fuzhou 350002, China
[3] School of Design Straits College of Engineering, Fujian University of Technology, Fuzhou 350118, China; fjlqy@fjut.edu.cn
* Correspondence: gaoyal@fjut.edu.cn (Y.G.); fjlxyxxc@126.com (X.X.)

Abstract: The assessment of habitat quality is instrumental in preserving regional species diversity and ecosystem health, thereby forming the theoretical foundation for sustainable urban development. While the Invest model is a commonly employed tool for habitat quality evaluation, it fails to consider the terrain. This study, centered on Haitan Island, introduces the terrain diversity index to rectify the Invest model's lack of terrain evaluation. The terrain diversity index, encompassing indices for terrain slope, undulation, and humidity, combined with the Invest model, was applied for a comprehensive assessment of the study area's habitat quality. Furthermore, the distribution characteristics of habitat quality on Haitan Island, China, were examined using Moran's I and LISA indices. The research indicates that forest land is the primary land cover type on Haitan Island, with blue-green space comprising forests, farmland, water bodies, and grassland, making up 66.8% of the island's area, thus implying a positive overall ecological base. Habitat quality distribution within the study area displays spatial heterogeneity, with regions of superior habitat quality primarily found in the northeast areas such as Junshan. Compared to the standalone Invest model, the combined method considering terrain and vegetation cover types yields a more sensitive impact on habitat quality evaluation and improves the precision of identifying superior habitat quality by 56.7%. Spatial autocorrelation analysis revealed that the comprehensive habitat quality index in the study area exhibited clustered distribution. Hotspots were mainly identified in areas like Junshan and the western mangrove wetland, regions with a high concentration of habitat quality values, while low-value clusters were mostly found in the central city and southwestern plains. This study offers a novel methodology for habitat quality evaluation, compensating for the traditional Invest model's neglect of terrain factors, and enriching the research on island habitat quality. It can provide fresh approaches and references for future habitat-related studies.

Keywords: island; habitat quality evaluation; invest model; terrain diversity index; ecosystem services

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1. Introduction

Habitat quality encompasses the capacity of an ecosystem to offer suitable living and reproductive conditions for species within specific temporal and spatial boundaries [1,2]. It is a comprehensive reflection of ecological suitability, species diversity, and ecosystem health within a region [3,4]. Generally, habitat objects encompass all landscape types, and their quality is not only associated with species diversity, but also positively correlated with ecosystem service capacity. Consequently, habitat quality is essential for human sustainable development and has become a prevalent topic in international research. Nevertheless, rapid urban economic development and continuous urban expansion have doubled construction land, encroached upon ecological land, and diminished high-quality habitats such as wetlands and forests in recent years [5]. These habitats are often replaced by low-quality, low-ecological service construction land. Urbanization exacerbates ecosystem and habitat interference, posing significant threats to animal and plant habitats. In this context, habitat quality assessment is crucial for maintaining regional species diversity, preserving ecosystems, providing a theoretical foundation for sustainable urban development, and offering practical guidance for regional planning, urban environmental assessment, and other related fields.

As public concern for ecosystem and species diversity protection grows [6,7], researchers worldwide have conducted extensive studies on habitat quality assessment. The spatial scope of this research has expanded from micro to macro scales. Initially, micro-scale studies predominantly utilized plot surveys to examine the influence of factors such as vegetation [8], land-use types [9] terrain [10], light [11], soil, and species density on the habitat quality of specific species [12]. Early research on habitat quality focused on small-scale and suburban areas, since species and habitat protection were in their infancy and urbanization had a lesser impact on habitats. Additionally, technological limitations made it challenging to represent urban and larger-scale regional habitats. However, advancements in remote sensing and geographic information systems, along with environmental issues arising from global urbanization, have led researchers to shift their focus to mid-to-macro-scale urban spaces. At this scale, scholars employ 3S technologies (Remote Sensing, Geographic Information System, and Global Positioning System) and associated models to achieve research goals. For instance, researchers use remote sensing data and GIS platforms in combination with the GUMBO model [13], IDRISI biodiversity [14,15], Maxent model [16,17], CLIMEX model [18], habitat suitability model HIS [19], SoIVES model [20], C-Plan model [21], and Invest model [21–23] to obtain significant results in evaluating ecosystems and habitat quality. The Invest model encompasses an autonomous habitat quality evaluation module [24], recognized for its prompt analysis and evaluation pace, and the availability of pertinent data. Consequently, it has gained popularity as a preferred method for regional habitat quality assessment.

Terrain is a crucial factor influencing habitat and biodiversity. For instance, Stuart discovered that varying slopes significantly impact butterfly development and reproduction [25]. Dunbar assessed the effects of habitat conditions on gibbons' feeding and energy consumption in different terrains [26]. Chen et al. examined the grassland habitat in Nagqu, Tibet, and identified altitude as an essential factor affecting grassland habitats. They classified grasslands into types based on altitude, such as alpine meadows, alpine desert, and high-altitude grasslands [27]. Zhang et al. investigated red bamboo forest habitat conditions and determined that altitude and slope are the primary factors affecting red bamboo distribution in Qu County [28]. James et al. discovered during his research on the wedge-tailed eagle in Tasmania that they have a preference for steep and undulating terrains, as such topography offers superior vertical aerodynamic advantages during flight [29]. Consequently, terrain significantly impacts hydrological processes, material flow, and energy distribution in ecosystems [23], and is closely related to habitat quality. Recent research has seen extensive application of the Invest model in evaluating habitat quality. Notably, this model overlooks topographic factors. For instance, Qing et al. employed the Invest model to investigate habitat quality differences across various terrains in the upper reaches of China's Minjiang River, without incorporating terrain factors in their evaluation [30]. Similarly, Yongge et al. examined the driving factors behind shifts in habitat quality at different scales, determining that, in addition to land cover types, topographic elements such as slope and undulation significantly influence habitat quality [31]. In Yang's research on Yunnan Province's biodiversity using the Invest habitat quality model, he noted the model's disregard for topography [32].

To address the neglect of topographic factors in the Invest model, this study aims to amalgamate the Terrain Diversity Index with the Invest model. We have selected islands, being relatively autonomous ecological systems [33,34], as our subjects of study. The intention is to develop a more holistic methodology for integrated habitat quality assessment, thereby furnishing novel perspectives and empirical cases for a more scientifically rigorous and sensible evaluation of regional habitat quality. Islands serve as ideal sites for biogeographical and biodiversity research [35–37] and hold high conservation and research value. However, with rapid urbanization, islands face numerous ecological challenges. Existing research on habitat quality spans from micro to macro urban and natural habitats [33,38–45], but no studies have reported habitat quality evaluations in island urban areas. Therefore, this study aims to conduct habitat quality assessment research in island urban areas, laying a scientific foundation for evaluating complex island habitats and providing references and practical applications for island habitat restoration and ecological planning.

Spanning a continental coastline of approximately 18,400 km, China hosts numerous provinces, among which Fujian stands out for its extensive coastal line. Positioned off the shore of this province, Haitan Island emerges as the largest of its kind in Fujian. Owing to its significant resource conditions and unique geographical location, the Pingtan Comprehensive Experimental Zone was established on Haitan Island, experiencing rapid development in recent years. However, urbanization issues on the island have also surfaced, necessitating urgent research on habitat quality evaluation and protection. Consequently, this study focuses on Haitan Island and employs the Invest model, terrain diversity index, Moran's I, LISA, and other methods to comprehensively assess habitat quality and spatial distribution characteristics of the island, see Figure 1. It investigates the scientific and feasible aspects of combining the terrain diversity index with the Invest model for habitat quality evaluation, provides a theoretical foundation for Haitan Island's habitat protection and ecological planning research, and reference for studies on other islands or mainland habitats.

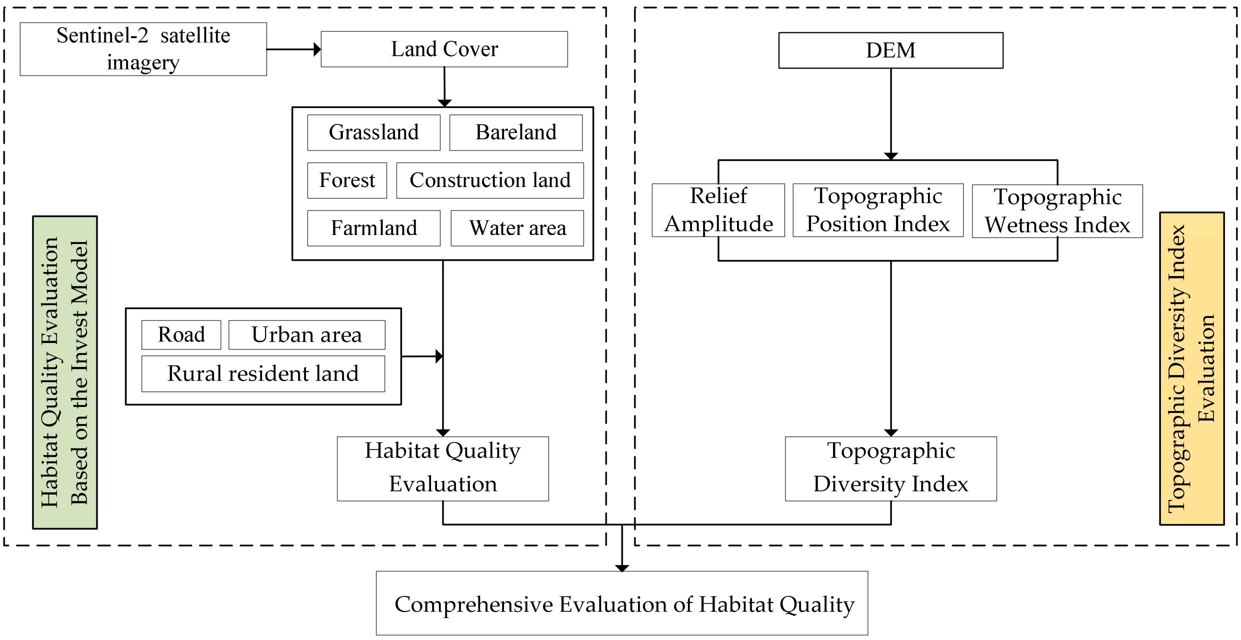

Figure 1. Research flowchart.

2. Materials and Methods

2.1. Materials

2.1.1. Study Area

Haitan Island (E 119°47′, N 25°31′) is situated in the southeastern part of China and covers approximately 280.45 km^2, making it the largest island in Pingtan County, Fujian Province. The terrain primarily consists of low hills, with elevations ranging from 100–300 m, and the highest peak, Junshan, located in the north with an elevation of 434.6 m. The region experiences a subtropical maritime monsoon climate, characterized by distinct seasons and abundant sunshine. Furthermore, the annual evaporation significantly exceeds precipitation, resulting in a scarcity of water resources. The soil types primarily include red soil, sandy soil, and saline soil, creating relatively harsh habitat conditions for species and sparse natural vegetation with a simple community structure. Presently, approximately 327 wild plant species from 234 genera and 83 families inhabit the island, including plant species unique to the region and not found in mainland China. Owing to its strategic location, Haitan Island has become a crucial passage for migratory birds between East Asia and Australia, including endangered species such as the Black-faced Spoonbill listed in the IUCN Red List. Since the establishment of the "Pingtan Comprehensive Experimental Zone" in 2009, Haitan Island has entered a period of rapid development. However, the economic growth and urban expansion have inevitably led to habitat disturbances, causing habitat reduction, fragmentation, and quality degradation. Consequently, conducting a habitat assessment and protection for Haitan Island has become an urgent necessity.

2.1.2. Data Sources

In this study, Sentinel-2 satellite imagery (https://scihub.copernicus.eu) accessed on 22 July 2020, with 0% cloud cover and a resolution of 10 m, was employed as the land cover base data (downloaded from the US Geological Survey). DEM data were acquired from ALOS with a 12.5 m accuracy (https://www.earthdata.nasa.gov/) (accessed on 13 December 2010). Road network and residential point data were sourced from vector data in the National Geographic Information Resources Catalogue Service System (https://www.webmap.cn/main.do?method=index) (accessed on 1 January 2017).

2.1.3. Data Processing

The sen2cor software 2.8 was utilized to perform atmospheric correction on the satellite images, converting the L1C data to L2A data. Envi software was used for resampling, and the study area land-use types were classified into six categories: forestland, water area, farmland, grassland, construction land, and bare land, using supervised classification (random forest algorithm) and visual interpretation. Finally, the study area was clipped, and a land cover map with a resolution of 10 × 10 m and a projection coordinate of WGS 1984 UTM Zone 50 N was obtained (see Figure 2).

2.2. Methods

2.2.1. Comprehensive Evaluation Methods for Habitat Quality

1. The Invest Habitat Quality Model

In this study, the habitat quality module of the Invest model was employed to analyze the habitat quality of Haitan Island. This module assesses the quantitative degree of various threats to habitats based on land cover maps, impact distance, and spatial weight of threats, and displays the spatial distribution characteristics of habitat quality [46].

Given that Haitan Island is the main island of Pingtan County, characterized by a dense population and rapid urbanization, this study identified urban land, rural residential land, primary and secondary roads, and farmland as threats due to their greater human disturbance. Relevant parameters were established based on the Invest model user guide and related literature [24,47,48] (see Tables 1 and 2).

Table 1. Attributes of threat data.

Threat Factor	Maximum Distance (km)	Weight	Spatial Decay Type
Urban land	3	1.0	Exponential
Rural resident land	2.5	0.8	Exponential
Farmland	1.2	0.5	Linear
Primary road	1.8	0.7	Linear
Secondary road	1.2	0.6	Linear

Table 2. Landscape types and sensitivity of landscape types to each threat.

Landscape Type	Landscape Type	Landscape Type	Landscape Type	Landscape Type	Landscape Type	Primary Road	Secondary Road
1	Farmland	0.6	0.6	0.5	0.1	0.2	0.2
2	Forestland	1	1	0.9	0.4	0.3	0.4
3	Grassland	0.7	0.7	0.7	0.3	0.4	0.3
4	Water area	0.9	0.9	0.8	0.3	0.5	0.2
5	Construction land	0	0	0	0	0	0
6	Bare land	0.3	0.6	0.5	0.1	0.3	0.3

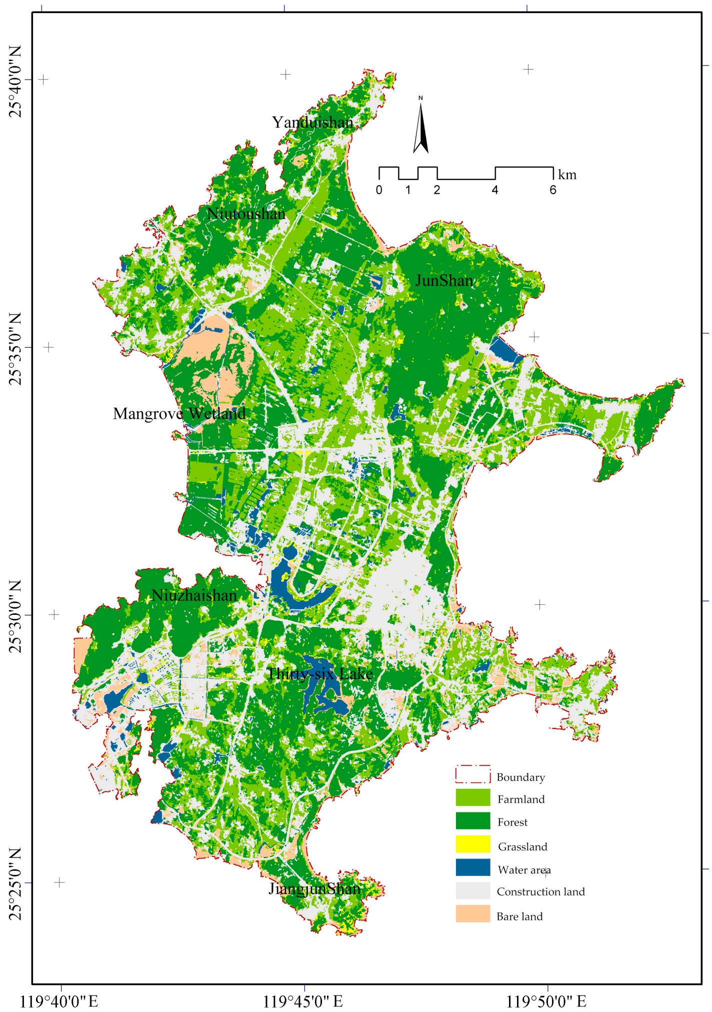

Figure 2. Land cover classification map of the study area.

2. Topographic Diversity Index

Topography is an essential geographic parameter in habitats and a critical component of biological habitat composition, significantly impacting the distribution, reproduction, and habitat of species [47,49]. Numerous studies have shown that topographic features such as altitude, slope, and aspect significantly affect species' distribution patterns in local climatic environments by influencing the distribution of regional water and heat, material transfer, and conversion. In mid-elevation and valley regions, moderately complex topography has been widely demonstrated to have higher species richness. Topographic indices, including the topographic position index, topographic wetness index, and relief amplitude, can accurately reflect the spatial heterogeneity characteristics of slope, fractal type, soil moisture saturation, and surface relief degree. Consequently, these indices have been widely used to describe the impact of topography on the distribution pattern of regional biodiversity. Based on the complex impact mechanism of topography on habitats and with reference to relevant literature [50], this study utilized multiple indicators, such as slope position index (SPI), relief amplitude (RA), and topographic wetness index (TWI), to evaluate the topographic diversity characteristics of surface elevation changes. These indicators were integrated into a comprehensive index, the topographic diversity index (TDI), to reflect the habitat conditions of the study area from the perspective of topographic factors. As SPI, RA, and TWI calculate topographic features from different aspects and have different units, this study conducted range normalization for each index, obtaining the corresponding normalized indices: SPI$'$, RA$'$, and TWI$'$. Based on relevant research and the environmental characteristics of the study area, this study set the SPI, with specific values detailed in Table 3. The calculation formulas for RA, TWI, TDI, and topographic position index (TPI) used in the SPI calculation are as follows:

$$TPI = Z_0 - \frac{1}{n_R}\sum\nolimits_{i \in R} Z_i \tag{1}$$

$$RA = Dem_{max} - Dem_{min} \tag{2}$$

$$TWI = \ln(Area/\tan slop) \tag{3}$$

$$TDI = \frac{SPI' + RA' + TWI'}{3} \tag{4}$$

where the *TPI* in Equation (1) is the terrain position index, which identifies terrain morphology types based on the difference between the elevation of the central point raster in the convolution window and the average elevation of the window [51]. Here, Z_0 represents the elevation value of the central point raster, R represents the window radius, n represents the number of raster cells in the convolution window, and Z_i represents the elevation value of a raster cell in the window. The *RA* in Equation (2) is the relief amplitude index, with higher values indicating greater terrain diversity [52]. Demmax and Demmin represent the maximum and minimum elevation values, respectively, within the predefined convolution window. The *TWI* in Equation (3) is the topographic wetness index, where higher values indicate increased soil moisture content in the area, which supports habitat quality [53]. Here, Area represents the catchment area, and slope represents the slope value. Finally, the *TDI* in Equation (4) is the topographic diversity index, which integrates the *SPI*, *RA* index, and *TDI*. The SPI', RA', and TWI' represent the normalized values of their respective indices.

Table 3. Table of setting and assignment of terrain slope position index parameters.

Index	Definition	Slop Position	Habitat Suitability
SPI	TPI > 1 SD	Ridge	1
	0.5 SD < TPI ≤ 1 SD	Upper slope	2
	−0.5 SD < TPI < 0.5 SD, Slope > 5°	Middle slope	3
	−0.5 SD ≤ TPI ≤ 0.5 SD, Slope ≤ 5°	Flat slope	4
	−SD ≤ TPI < −0.5 SD	Lower slope	5
	TPI < −SD	Valley bottom	6

SD = standard deviation, (>) = above mean. The assignment was based on expert consultation, taking into account the characteristics of the topography and geomorphology of the island area under study and related research results [48].

The calculation results of *RA* and *TPI* in this study are affected by the size of the analysis window. Therefore, the mean change point method was employed to determine the optimal window size [48], and Python programming was utilized to calculate the optimal window size for the average *RA* and *TPI* at $n*n$ (n = 2, 3, 4, ... , 32) to be 5 and 12, respectively, corresponding to rectangular windows of 50 m and 120 m.

3. Integrated Evaluation of Habitat Quality Based on the Invest Model and Topographic Diversity Index

The standardized range method was employed to normalize the TDI and habitat quality index, using habitat quality as the base and TDI as an indicator of the impact of topographic factors on the habitat. The product of the two formed the integrated evaluation of habitat quality.

2.2.2. Spatial Distribution Evaluation

Spatial autocorrelation analysis can quantify the correlation between attribute values and their spatial locations within the study area, including global and local autocorrelation [54]. This study utilized the global Moran's I to explore the spatial autocorrelation of habitat quality in the study area. Moran's I index ranges from −1 to 1, where a value less than 0 indicates a dispersed distribution of the attribute (i.e., habitat quality evaluation value), a value greater than 0 indicates an aggregated trend in space, and a value of 0 signifies no significant spatial correlation between attribute units in the study area. The study employed the Local Indicators of Spatial Association (LISA) index for hot and cold spot analysis to investigate the spatial clustering characteristics of the attribute values. LISA index analysis can identify spatial aggregation patterns within the study area and determine which areas have significant high or low value aggregation.

3. Results

3.1. Integrated Evaluation of Land Use and Habitat Quality

The study area encompassed a total area of 280.45 km^2, with land-use types classified into construction land, forestland, grassland, farmland, water area, and bare land using supervised classification. Forest covered an area of 104.08 km^2, accounting for 36.9% of the total area, followed by construction land and farmland, which accounted for 27.5% and 25.4% of the total area, respectively. Bare land, water area, and grassland occupied areas, accounting for 5.6%, 3.1%, and 1.4% of the total area, respectively. Forestland, grassland, water area, and farmland constituted the blue-green space of Haitan Island, where these ecologically sustainable lands had high species diversity and ecosystem service functions, serving as the primary habitat for various species and accounting for 66.8% of the island's total area.

3.1.1. Habitat Quality Evaluation Based on the Invest Model

In this study, the Invest model's habitat quality module was utilized to analyze the habitat quality of Haitan Island. Using the natural break and referencing previous studies [32], the habitat quality index was divided into five levels: Level I (0.82–1), Level II (0.64–0.81), Level III (0.45–0.63), Level IV (0.19–0.44), and Level V (0–0.18). As depicted in Figure 3 and Table 4, the area of Level I, representing the best habitat quality, was 35.22 km^2, accounting for 12.5% of the total area; the area of Level II representing relatively good habitat quality, was 37.26 km^2, accounting for 13.2%; the area of Level III, representing moderate habitat quality, was 94.43 km^2, accounting for 33.5%; the area of Level IV, representing relatively poor habitat quality, was 36.55 km^2, accounting for 13.1%; and the area Level V, representing the worst habitat quality, was 76.99 km^2, accounting for 27.7%. The results indicated that the Level I areas with the best habitat quality were mainly located around the outskirts of Haitan Island, with the largest patch situated in Junsan near the beach to the north, and others distributed in a strip from the south to the north on the west side of the island, with the land-use type being forest. The Level II areas with relatively good habitat quality were mainly distributed outside the Level I areas, serving as natural barriers. The important freshwater lake "Thirty-six Lake" was evaluated as a Level II area, while other Level II areas were sporadically distributed in the island's interior, such as park green spaces and scenic green spaces, with the land-use type mainly being forest, water area, and grassland. The Level III areas with moderate habitat quality had the largest area and were mainly distributed in the island's interior, with the primary land-use type being farmland, followed by forestland, water area, and grassland. The Level IV areas with relatively poor habitat quality were located in the center of the island and distributed around the city, with the primary land-use type being forestland, farmland, bare land, grassland, and water area. The Level V areas with the worst habitat quality were mainly distributed along the construction land throughout the island, including construction land, forest, and bare land.

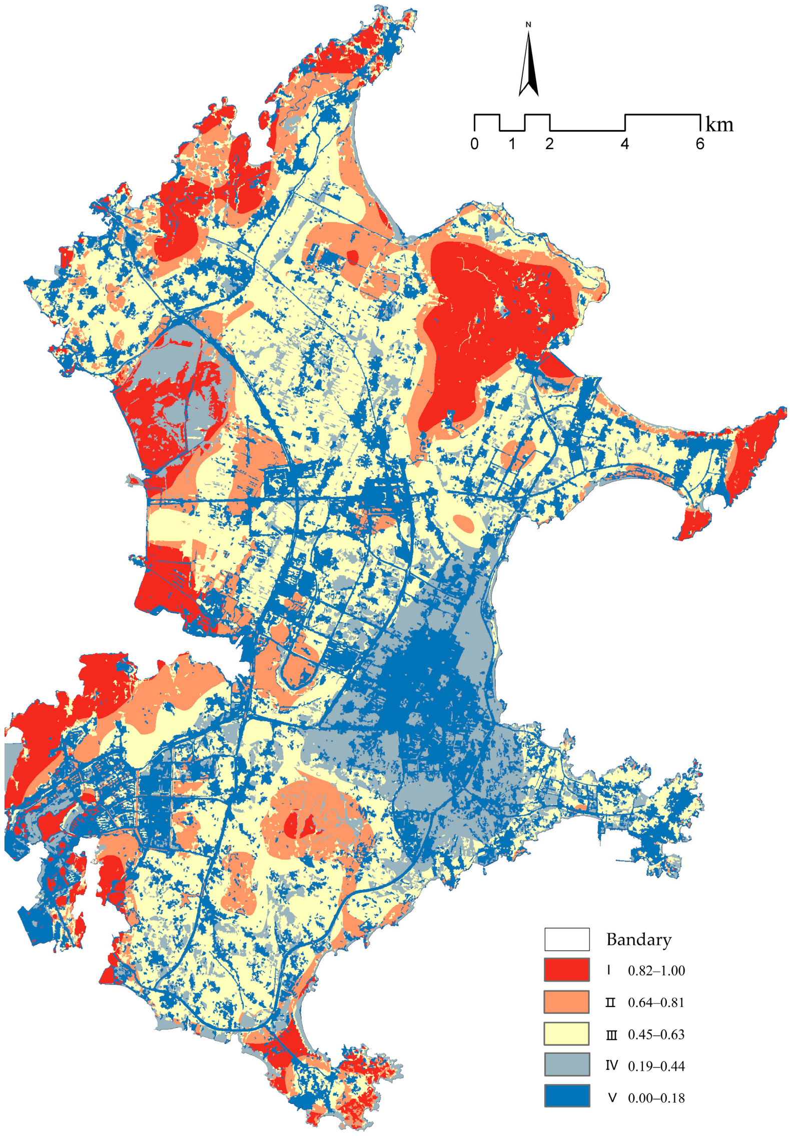

Figure 3. Evaluation zones of Invest habitat quality index.

Table 4. Based on the Invest habitat quality evaluation zoning and land-use characteristics statistics.

Habitat Grade	Farmland (km^2)/ Percentage (%)	Forest (km^2)/ Percentage (%)	Grass (km^2)/ Percentage (%)	Water Area (km^2)/ Percentage (%)	Construction Land (km^2)/ Percentage (%)	Bare Land (km^2)/ Percentage (%)	Total (km^2)
I	0/0	33.22/31.91	0/0	2/22.65	0/0	0/0	35.22
II	0/0	29.37/28.22	2.51/62.53	5.37/60.82	0/0	0/0	37.26
III	66.24/92.53	25.93/24.91	1.11/27.54	1.15/13.02	0/0	0/0	94.43
IV	5.35/7.47	15.22/14.62	0.41/10.17	0.31/3.51	0/0	15.26/99.28	36.55
V	0/0	0.33/0.34	0/0	0/0	76.55/100	0.11/0.72	76.99
Total	71.59/100	104.08/100	4.03/100	8.83/100	76.55/100	15.37/100	280.45

3.1.2. Integrated Evaluation of Habitat Quality Based on Topographic Diversity Index

Figure 4 displays the distribution patterns of TDI, RA, TPI, and TWI. Overall, TDI demonstrated a consistent distribution pattern with RA and TPI, while TWI exhibited a contrasting pattern. The high SPI values were concentrated in the slope and valley bottoms of island mountains, such as Junshan, Longtoushan, Yanduishan, and Niuzhaishan. Areas with high SPI values were distributed on flat land, including water areas and farmland, which were relatively concave and flat. These areas provided ideal habitats for species, offering favorable conditions for wind protection and water retention. The areas' RA values were concentrated in mountainous terrain and undulating areas, particularly on slopes, valleys, and mountainous terrain tops. These areas have diverse habitat conditions and can support various species' habitats. The distribution of TWI was considerably different from that of other topographic indices, with relatively low values on slopes and high values in comparatively flat areas such as water bodies and valleys (wide areas), especially in tidal flats, lakes, and ponds. These areas have high surrounding terrain and large catchment areas, with high soil moisture content, which is beneficial for species reproduction.

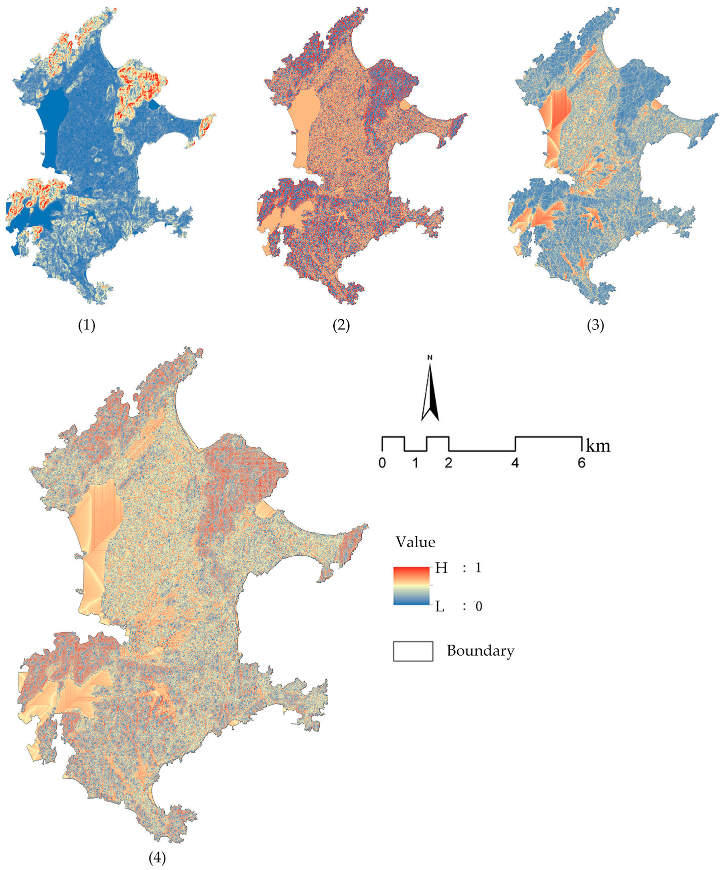

Figure 4. Flowchart of topographic diversity index evaluation: (**1**) relief amplitude; (**2**) Topographic Position Index; (**3**) Topographic Wetness Index; (**4**) Topographic Diversity Index.

The TDI highlights areas of varied topography, with study results indicating that high-value areas are primarily located near Junshan, Longtoushan, Niuzhaishan, and Sanliujiao Lake. These areas currently represent significant ecological land on the island, boasting excellent ecological quality and high vegetation coverage on the mountains, particularly Sanliujiao Lake, the island's largest natural freshwater lake. This lake provides essential habitats and ecological resources for surrounding ecosystems. Conversely, low-value TDI areas are distributed across flat ridge or mountaintop regions and scattered around farmland. Notably, terrain ridgelines and elevated regions have a higher concentration, making them unfavorable for species inhabitation and reproduction on the windy and dry island, as these areas offer little protection from wind and water collection.

3.1.3. Comprehensive Evaluation of Habitat Quality

Figure 5 and Table 5 present the results of the comprehensive evaluation of habitat quality and landscape feature statistics based on the Invest model and the integrated habitat quality index. The habitat quality index was divided into five levels using natural breakpoints, ranging from the best to the worst: Excellent habitat ($0.47 < \text{Value} \leq 1$), Good habitat ($0.31 < \text{Value} \leq 0.47$), Moderate habitat ($0.19 < \text{Value} \leq 0.31$), Fair habitat ($0.07 < \text{Value} \leq 0.19$), and Poor habitat ($0 \leq \text{Value} \leq 0.07$). The Excellent habitat covered only 15.25 km^2 and was mainly distributed in the wetland and tidal flats in the western part of the island. It provides a stopover for bird breeding and migration, particularly in the largest natural freshwater lake on the island. Other Excellent habitats were scattered in northern Junshan, Longtoushan, southwestern Niuzhaishan, SanliuJiao Lake, and the southernmost Jiangjunshan. The Good habitat covered an area of 30.26 km^2 and was mainly distributed around the first-level habitats and the suburbs of the island's southern area. The Moderate habitat covered an area of 63.09 km^2 and was distributed across the island, particularly in the flat areas of the northern region, with few distributions in the main urban area of the eastern bay. The Fair habitat covered an area of 71.29 km^2 and was distributed similarly to the Fair habitat. The Poor habitat covered the largest area of 100.56 km^2, which was distributed oppositely to the Excellent habitat. The important mountains and lakes were less distributed in this habitat, whereas other areas had few distributions, particularly concentrated in the main urban area of the eastern bay.

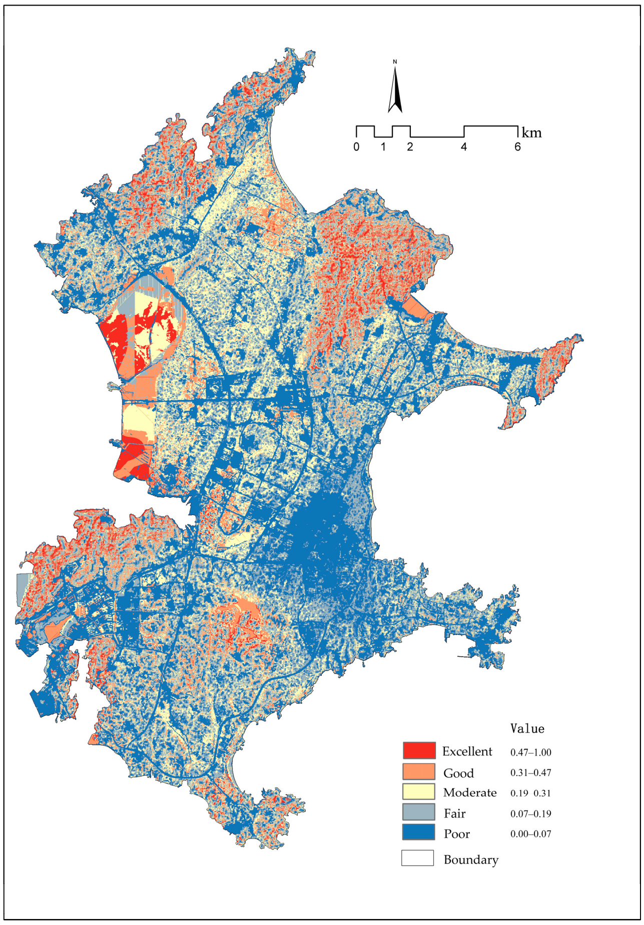

Figure 5. Comprehensive habitat quality assessment zoning.

Table 5. Statistical table of comprehensive habitat quality assessment and landscape characteristics.

Habitat Grade	Farmland (km^2)/ Percentage (%)	Forest (km^2)/ Percentage (%)	Grass (km^2)/ Percentage (%)	Water Area (km^2)/ Percentage (%)	Construction Land (km^2)/ Percentage (%)	Bare Land (km^2)/ Percentage (%)	Total (km^2)
Excellent	0.03/0.04	14.12/13.56	0.29/7.20	0.81/9.17	0/0	0/0	15.25
Good	7.38/10.31	17.60/16.91	0.89/22.08	4.37/49.49	0/0	0.02/0.13	30.26
Moderate	31.34/43.78	24.20/23.25	1.20/29.78	2.20/24.92	0/0	4.15/27.00	63.09
Fair	25.78/36.01	34.22/32.88	1.23/30.52	1.08/12.23	0/0	8.98/58.43	71.29
Poor	7.06/9.86	13.94/13.39	0.42/10.42	0.37/4.19	76.55/100	2.22/14.44	100.56
Total	71.59/100	104.08/100	4.03/100	8.83/100	76.55/100	15.37/100	280.45

Table 5 shows the statistical characteristics of the landscape features of each level in the comprehensive evaluation of habitat quality. In the Excellent habitat, forest landscape types accounted for 92.59% of the area, followed by water bodies, grassland, and farmland, without any construction or bare land landscape types. In the most abundant Good habitat, forest landscape types accounted for 58.16% of the area, followed by farmland, water bodies, and grasslands, with almost no barren land landscape types (accounting for only 0.07% of the area) and no construction land landscape types. The most common landscape type in the Moderate habitats was farmland (48.00%), followed by forestland (36.16%) and bare land (12.6%), with few other landscape types, and again, no construction land landscape types were found. The dominant landscape type in the Fair habitats was forestland (48.00%), followed by farmland (36.16%), with relatively fewer bare land, grassland, and water body landscape types, and no construction land landscape types. The main landscape type in the relatively poor habitats was construction land (76.12%), followed by forest (13.86%), with farmland, bare land, grassland, and water bodies having the smallest area coverage.

3.2. Spatial Statistical Analysis of Integrated Habitat Quality Index

The spatial statistical analysis function in the Geoda platform and the Queen adjacency spatial weight were used to analyze the spatial clustering of the integrated habitat quality index in the study area. The results indicated that with $p < 0.01$, the global Moran's I value was 0.378, signifying a general positive spatial correlation of the integrated habitat quality index on Haitan Island. In other words, areas with higher integrated indices neighbored other areas with higher indices, while areas with lower integrated indices neighbored other areas with lower indices.

The spatial clustering distribution of the integrated habitat quality index in the study area was represented using the LISA index (Figure 6). The results revealed that 67.4% of the study area exhibited insignificant spatial clustering, while 32.6% demonstrated significant spatial clustering. Among them, the hot spot areas (H-H), representing the high-value aggregation area of the integrated habitat quality index, covered 11.7% of the total area. These areas were primarily distributed in Junshan, the western coast, Niuzhaishan, SanliuJiao Lake, and other locations. These regions represented important ecological green spaces in the Haitan island, with Junshan Scenic Spot and Sanliujiao lake Nature Reserve being crucial ecological protection areas within the study area. The cold spot areas (L-L), representing the low-value aggregation area of the integrated habitat quality index, covered 14.6% of the total area and were mainly distributed in the southeast of the study area, predominantly in the main urban area of the Haitan island. These areas were dominated by urban construction land, exhibited poor habitat quality, and focused on human production activities and economic development. The H-L and L-H represented areas with high-value and low-value indices adjacent to low-value and high-value indices, respectively. These two types of areas were less common and scattered in their distribution.

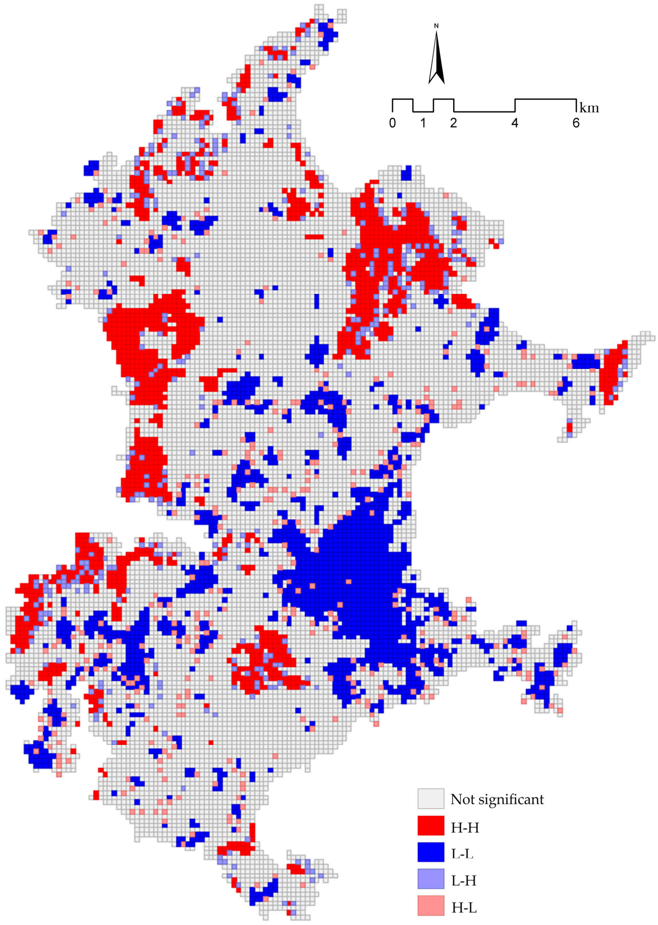

Figure 6. Haitan Island habitat quality comprehensive evaluation hot and cold spot distribution.

4. Discussion

4.1. Habitat Quality Evaluation of Hai Tan Island Based on Invest Model

The evaluation of habitat quality on Haitan Island based on the Invest model is scientifically rigorous, albeit with some limitations. The model's analysis of land cover types, habitat sources, and threats to habitat quality is sound. For instance, the Junshan region generally exhibits good habitat quality due to its forest composition and distance from the city center and main roads, providing favorable habitat conditions and distancing from threats. However, the Invest model's evaluation of habitat quality is biased concerning land cover types, such as the absence of farmland and grassland in level I and level II areas. Similar results have been observed in related studies, such as those by Qiu et al. and Wang et al., which investigated habitat quality in the Chang–Zhu–Tan agglomeration using the Invest model [55]. They found that the best-quality habitats lacked farmland and grassland, which were primarily located in areas of medium or poor habitat quality. Although grasslands and farmland are critical components of urban habitats, they are underrepresented in areas of high-quality habitats due to specific spatial and topographical characteristics. Qin and Gao's research on building ecological networks on Haitan Island also selected network hubs with farmland and grassland cover types. Ecological network hubs [56,57], representing the best and most crucial ecological patches in the region, were selected based on multiple factors, including MSPA, area, and connectivity, which are scientifically valid.

Other researchers have employed the Invest model to study various habitats, such as forests [38], rivers and lakes [39], wetlands [41], oceans [42], nature reserves [43], and urban areas [44]. Their research has focused on habitat quality, dynamic changes, driving factors, and other aspects, including urban or wetland habitats. Research on habitat quality evaluation in Haitan Island revealed that the spatial distribution of habitat quality exhibits heterogeneity, with better quality habitats primarily distributed around the island and poorer quality habitats mainly located in the city center and the eastern part of the island. This indicates that habitat quality is impacted by human activities. Coastal areas of the island have poor living conditions due to strong winds and other climatic factors, which have reduced human interference and ensured support for species, highlighting the unique geographic features of the island. The study on habitat quality on Haitan Island also demonstrates the impact of human activities on habitat quality and shows that the degree of influence depends on the source and distance of the activity. Nevertheless, the coastline is an important tourism resource, and the island's ecosystems are relatively rare and fragile. Therefore, any development of tourism facilities or projects along the coast should be approached with caution, with appropriate ecological evaluation and protection planning to ensure reasonable development and construction of coastal resources.

4.2. Terrain Diversity Index and Analysis of Island Habitat Quality

The Invest model considers the support provided by different land-cover types for species habitats and the disturbance and threats posed by human activities to habitat quality when assessing regional habitat quality. Nevertheless, the model overlooks the influence of terrain factors on habitat quality. Although prior studies have examined the impact of terrain on habitat quality using the Invest model, they have not addressed how to incorporate terrain into the evaluation [30,31]. In this study, we evaluate the suitability of various habitats on Haitan Island based on a terrain diversity index. Our findings indicate that areas with high terrain diversity, such as those featuring large undulations and valleys, typically exhibit superior habitat quality. The mountainous regions surrounding Haitan Island, including Junshan, Longtoushan, and Niuzhaishan, are high-value areas for terrain diversity and possess an enhanced habitat quality.

This study employs the terrain diversity index to quantify the contributions of various terrain features, including different degrees of slopes, valleys, depressions, and undulations, to habitat quality. In a manner akin to Zou et al.'s study on habitat research of quarry mountains and slopes [58], the terrain slope index was found to be significantly related to vegetation diversity. Furthermore, John W. et al. discovered that terrain diversity and vegetation coverage are crucial contributors to species habitats in their study on the multi-philic tendencies of species using remote sensing images [59]. This study builds upon previous research and employs the terrain diversity index as an influencing factor for habitat quality, aiming to further explore a more comprehensive, refined, and scientific evaluation of habitat quality.

4.3. Comprehensive Evaluation of Island Habitat Quality Incorporating Terrain Factors

This study conducts a comprehensive evaluation of habitat quality on Haitan Island based on the Invest model and TDI. The spatial distribution of habitat quality corresponds well with the actual situation. The Excellent habitat areas are mainly distributed in the ecological conservation zones of the study area, such as the Sanliujiao Lake Nature Reserve and Junshan Scenic Area, which are strictly protected areas. Comparing the comprehensive evaluation results of this study with other scholars' research on Haitan Island's ecology, the spatial distribution of areas with high ecological quality is similar, such as the important ecological patches in Pingtan studied by Gaoling et al. [57], the ecological environment quality assessment of Pingtan Island by Zheng Zhencan et al. [60], and the spatial distribution of important ecological source areas selected by Qin Zibo et al. [56]. All these studies agree that Junshan, Sanliujiao Lake, Niuzhaishan, and Longtoushan in Haitan Island have relatively good habitats.

The comprehensive habitat quality evaluation results incorporating the TDI (Figure 5) are generally consistent with the spatial distribution of the habitat quality assessment results based on the Invest model (Figure 3). However, the comprehensive evaluation results demonstrate a higher evaluation accuracy and highlight the role of terrain in habitat quality. Compared to the one-sided Invest model evaluation, the habitat quality assessment incorporating terrain diversity not only reflects the main components of habitat coverage and the impact of threats on quality, but also reveals the influence of terrain on habitat quality. For example, better habitat quality is found in valleys, downslope areas, depressions, and areas with significant undulations, indicating that the comprehensive evaluation is affected by terrain.

In a comparative analysis of quantitative distributions, the level 1 habitat ranking in the comprehensive evaluation improved by 56.7% compared to the evaluation results generated by the traditional Invest model. Class 2 and 3 evaluation results have also improved, while the areas with poorer habitat quality Classes 4 and 5 have significantly increased. The quantitative comparison indicates a higher evaluation accuracy, particularly for identifying areas with higher habitat quality. There are differences in cover composition between the two evaluation results. Compared to the traditional Invest model evaluation results, the comprehensive evaluation results include all important habitat cover types in Class 1 habitats, such as farmland, forestland, grassland, and water area, while the traditional Invest model only includes forests and water bodies. It is well-known that farmland and grassland are also important habitats, and under certain spatial characteristics, they should possess high-quality habitat conditions. For the poorest habitat quality in Class 5, the comprehensive evaluation results include all types, while the traditional Invest model evaluation only includes forests and construction land. Clearly, in addition to forests, areas with poor habitat quality in human production and living areas also include grasslands, water bodies, and farmland, with their habitat quality being undoubtedly poor. The other three habitat quality classifications also exhibit differences. The comparison of cover-type composition between the two methods suggests that the comprehensive evaluation results are more reasonable, in line with reality, and possess scientific and rational qualities.

The TDI has been widely applied in ecological environment assessment and vegetation distribution studies, allowing for a more comprehensive consideration of the impact of terrain on ecosystems [61]. However, the relationship between the index and habitats is not a simple linear one, but is influenced by various factors [38,62]. For instance, the impact of the TDI on vegetation distribution might differ under different vegetation types and climate conditions [63]. This research focuses more on the unique and relatively independent habitat quality of islands, using a spatial autocorrelation model to describe their spatial distribution characteristics. The application of the TDI allows for a more comprehensive consideration of the impact of terrain on ecosystems, providing more targeted measures for the protection and improvement of the ecological environment in the area.

5. Conclusions

Islands, due to their unique geographical characteristics, embody valuable and vulnerable habitats, underscoring the crucial importance of habitat evaluation and protection research in such regions. The focus of this study is Haitan Island, for which we have conducted an integrative evaluation of habitat quality utilizing the Invest habitat quality model, terrain diversity index, global Moran's I, and LISA index. Although the conventional Invest model ably reflects regional habitat quality via land-use types, our integrated assessment—combined with the terrain diversity index—captures the influence of vegetation cover types on habitats, as well as accentuating the role of terrain on habitat effects. These results present a more reasonable, scientifically robust, and accurate evaluation, demonstrating a 56.7% improvement over the conventional Invest model. Additionally, the composition of vegetation-cover types across all levels of habitat quality is more scientifically and reasonably structured. Spatial autocorrelation analysis revealed spatial heterogeneity in the distribution of the comprehensive habitat quality index across the study area, with hot and cold spots clustering in each region. Currently in a significant phase of development, China's Haitan Island possesses important geographical advantages and characteristic island features. Therefore, our evaluation of Haitan Island provides valuable reference material for the Pingtan Comprehensive Experimental Zone and augments the theoretical underpinning for sustainable urban development.

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