

Landscape Pattern Characteristics and Ecological Effects of the Northern Five Islands of the Miaodao Archipelago: Postprint

Authors: Chi Yuan, Shi Honghua, Wang Enkang, Guo Zhen, Feng Aiping, Ma Deming

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Abstract

Owing to spatial heterogeneity in natural characteristics, intensifying human activities, and ecosystem fragility, islands exhibit pronounced spatial differentiation in landscape patterns and increasingly complex ecological effects. Taking the North Five Islands of the Miaodao Archipelago as the study area, and based on field surveys and 3S technology, this study analyzes the spatial characteristics of island landscape patterns at the landscape, island, and patch scales, and further explores the relationships between landscape patterns and net primary productivity (NPP), plant diversity, and soil properties. The results demonstrate: (1) Landscape patterns at different scales all exhibit spatial variations. At the landscape scale, coniferous forest, broadleaf forest, and grassland constitute the three dominant vegetation landscape types with the largest areas, characterized by relatively high patch density, edge density, and mean shape index; built-up land also covers a substantial area with high patch density but the lowest mean shape index; bare land likewise occupies a considerable area with landscape metrics at intermediate levels; At the island scale, both patch density and human disturbance index increase significantly with island area, population, and GDP; At the patch scale, patch density, edge density, and mean shape index are significantly positively correlated with elevation, whereas the human disturbance index is significantly negatively correlated with both elevation and slope. Island area, terrain, and human activities serve as the fundamental factor, important limiting factor, and direct driving factor, respectively, shaping the landscape patterns of the North Five Islands. (2) The ecological effects of island landscape patterns are closely scale-dependent. At the landscape scale, various ecological effect indicators exhibit significant differences among different landscape types, while at the island scale, ecological effect indicators show limited sensitivity to landscape patterns; At the patch scale, ecological effect indicators display significant simple correlations and partial correlations with landscape

pattern indices, though the results differ between these two approaches. NPP and soil moisture are primarily influenced by landscape type and vegetation growth conditions, while diversity and soil nutrients are concurrently affected by landscape type, landscape fragmentation, and edge effects; intensified human activities lead to declines across all ecological effect indicators. Controlling construction scale, optimizing landscape layout, and improving development and utilization practices constitute important measures for maintaining island ecosystem stability.

Full Text

Landscape Pattern Characteristics and Ecological Effects on Five Northern Islands of the Miaodao Archipelago

Chi Yuan, Shi Honghua*, Wang Enkang, Guo Zhen, Feng Aiping, Ma Deming

First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China

Abstract

Landscape pattern represents the outcome of comprehensive natural and anthropogenic effects on geographical space and significantly influences ecosystem structure, function, and processes. An archipelago comprises multiple neighboring islands that exhibit substantial variations in basic geographic features such as area, shape, and terrain conditions both among and within islands. Meanwhile, human activities—including urban and rural construction, plantations, and transportation—along with the inherent vulnerability of island ecosystems, create spatial heterogeneity that diversifies landscape types and produces differential landscape patterns with complex ecological effects. This study examines five northern islands of the Miaodao Archipelago as typical islands in northern China, located north of the Shandong Peninsula at the junction of the Yellow and Bohai Seas, where landscape pattern drivers are highly complex. Based on field investigations and 3S technologies, we selected patch density (PD), edge density (ED), mean shape index (MSI), and human interference index (HII) as landscape pattern metrics. Landscape patterns were analyzed at landscape, island, and grid scales, and relationships between these patterns and ecological effect indicators—including net primary productivity (NPP), plant diversity, and soil properties—were examined. Results revealed obvious spatial heterogeneity in landscape patterns across scales. At the landscape scale, coniferous forest, broad-leaf forest, and grassland constituted the dominant vegetation landscape, occupying the largest proportion of island area with generally higher PD, ED, and MSI. Construction land also had substantial area and high PD but minimal MSI. Bare land area was smaller than the aforementioned types with intermediate landscape metrics, while other landscape types were $<100 \text{ hm}^2$. At the island scale, both PD and HII increased with island area, population, and GDP. At the

grid scale, PD, ED, and MSI showed significant positive relationships with altitude, whereas HII had significant negative relationships with altitude and slope. Different landscape pattern indices were also interrelated, with significant positive correlations among PD, ED, and MSI, and significant negative correlations between HII and PD/ED. Island area, terrain, and human activities represented fundamental, limiting, and direct driving factors of landscape patterns, respectively. Ecological effects of landscape pattern were closely related to the selected scale. At the landscape scale, all ecological effect indicators showed significant differences among landscape types. At the island scale, responses of ecological effect indicators to landscape pattern were insensitive. At the grid scale, ecological effect indicators and landscape pattern indices showed significant simple and partial correlations, yet results differed between these approaches. NPP and soil moisture content were mainly influenced by landscape types and vegetation status, while biodiversity and soil fertility were affected by landscape types as well as landscape fragmentation and edge effects. Increased human activity intensity led to decreases in all ecological effect indicators. Controlling construction scale, optimizing landscape allocation, and improving utilization methods are important measures for maintaining island ecosystem stability.

Keywords: islands; landscape pattern; spatial characteristics; scale; ecological effects; five northern islands of Miaodao Archipelago

1. Study Area Overview

The Miaodao Archipelago is located on the northern side of the Shandong Peninsula at the confluence of the Yellow and Bohai Seas, representing a concentrated distribution area of islands in northern China. The five northern islands—Da Qin Island, Xiao Qin Island, Tuo Ji Island, Nan Huangcheng Island, and Bei Huangcheng Island—constitute the main body of the northern archipelago region. These islands are relatively dispersed and exhibit typical chain-like distribution across the Bohai Strait. The area belongs to the East Asian monsoon climate zone, with an average annual temperature of 12.0°C (January: -1.6°C; July: 24.5°C), annual precipitation of 537.1 mm concentrated in summer, and abundant sunshine with 2,612 annual sunshine hours.

The terrain of the five northern islands features obvious undulation, with the highest point at 202 m elevation. Natural forest development is poor, though artificial forests dominated by black pine (*Pinus thunbergii*) and locust (*Robinia pseudoacacia*) have been extensively planted. Native herbaceous species are diverse and widely distributed. The islands' economy relies primarily on mariculture, tourism, and transportation, with significant socioeconomic development differences among islands. Marine economic development has directly driven spatial development and utilization, with residential and public facility construction, road and wharf development, and artificial forest planting creating complex and diverse landscape types across the five northern islands.

2. Data and Methods

2.1 Remote Sensing Imagery WorldView-1 panchromatic remote sensing imagery from 2014 with 0.45 m spatial resolution was used. Island outlines were extracted using ArcGIS 10.0 software to obtain basic information including island area and perimeter. Through human-computer interactive interpretation, the landscapes of the five northern islands were classified into coniferous forest, broad-leaf forest, grassland, farmland, bare land, construction land, traffic land, and other hardened ground. Coniferous and broad-leaf forests represent artificial forests dominated by black pine and locust, respectively. Grassland primarily comprises natural native herbaceous communities. Farmland mainly cultivates soybeans and corn. Bare land includes bare rock and bare soil along coasts and within islands. Construction land comprises residential and public buildings. Traffic land includes wharfs and internal roads. Other hardened ground refers to artificially paved surfaces beyond construction and traffic land, mainly kelp drying fields and squares.

Cloud-free LANDSAT 8 imagery with 30 m resolution was used to represent different seasons. ENVI 4.7 software performed image cropping and band calculation to obtain seasonal NPP data. Elevation and slope data were extracted from Aster GDEM data with 30 m vertical and horizontal resolution.

2.2 Field Survey Field reconnaissance of the five northern islands was conducted in May and September 2015 to validate surface cover types, with validation results used to correct existing data and form final landscape type vector maps. Plant community surveys were performed in July 2015, considering island area, community type, and terrain factors to establish 39 sampling plots. Geographic coordinates were measured using GPS and electronic compass. In each 10 m × 10 m plot, all tree species with DBH \geq 3 cm were recorded for species, survival status, DBH, and crown width. Two diagonal subplots surveyed all shrub species for counts, basal diameter, and height. All herbaceous species were recorded, with five 1 m × 1 m herbaceous quadrats established at plot corners and center to record species, coverage, and height. Surface soil samples were collected using multi-point mixing methods, with impurities removed in the laboratory before measuring soil moisture content, total nitrogen (semi-micro Kjeldahl method), available phosphorus (acid extraction), available potassium (ammonium acetate extraction), and organic matter (potassium dichromate oxidation with external heating).

2.3 Data Collection Meteorological data came from multi-year monitoring at Changdao County and Yantai Fushan meteorological stations. Population and GDP data for each island were obtained from Changdao County statistical records.

3. Landscape Pattern Spatial Characteristics Analysis

Based on the landscape type vector map, Fishnet tools in ArcGIS 10.0 and Patch Analyst were used to analyze landscape pattern characteristics at landscape, island, and block scales. Among numerous available landscape metrics, representative indices were selected: patch density (PD) reflecting fragmentation, edge density (ED) reflecting edge effects, mean shape index (MSI) reflecting patch shape complexity, and human interference index (HII) reflecting anthropogenic disturbance intensity. HII was calculated as:

$$HII = \frac{\sum_{i=1}^6 HCA_i \times IF_i}{TA}$$

where HCA_1-HCA_6 represent traffic land, construction land, other hardened ground, farmland, coniferous forest, and broad-leaf forest areas, respectively; IF_i is the impact coefficient of the i th artificial landscape type; and TA is total landscape area within the analysis scale.

Patch Analyst in ArcGIS 10.0 calculated landscape-scale and island-scale metrics, while Spatial Statistics tools analyzed block-scale patterns by dividing the five islands into 200 m \times 200 m grid cells.

4. Landscape Pattern Ecological Effects Analysis

Based on collected data, field surveys, and remote sensing imagery, three ecological effect indicators were calculated: NPP, plant diversity, and soil properties. Seasonal remote sensing imagery was used to calculate NPP using the CASA model:

$$NPP(x, t) = APAR(x, t) \times \varepsilon(x, t)$$

$$APAR(x, t) = PAR(x, t) \times FPAR(x, t)$$

where $NPP(x, t)$ is monthly net primary productivity at point x (g C/m²/month), $APAR(x, t)$ is absorbed photosynthetically active radiation, $\varepsilon(x, t)$ is actual light use efficiency (g C/MJ), $PAR(x, t)$ is photosynthetically active radiation (MJ/m²/month), and $FPAR(x, t)$ is the fraction of absorbed photosynthetically active radiation (%). Temperature and water stress factors were calculated following methods in reference [18].

Herbaceous plants were selected to represent island plant diversity because arboreal and shrub species are limited in the Miaodao Archipelago while herbaceous plants are well-developed and widely distributed. Field surveys recorded 57 herbaceous species. Importance values were calculated as:

$$IV_{is} = \frac{RD_{is} + RC_{is} + RH_{is}}{3}$$

where IV_{is} is importance value of species i in plot s , RD_{is} is relative density, RC_{is} is relative coverage, and RH_{is} is relative height.

Shannon-Wiener index (H'_s) and Pielou index (E_s) were calculated following standard methods [23,24]. ArcGIS 10.0 Spatial Analyst's inverse distance weighting (IDW) interpolation was used for diversity spatial interpolation based on comparison showing IDW produced relatively smaller errors and more realistic results for islands.

Soil moisture content, available potassium, and organic matter were interpolated using IDW. Soil fertility index was calculated as:

$$F_x = \sum_{i=1}^n \frac{P_{ix}}{S_i}$$

where F_x is soil fertility index at point x , P_{ix} is current value of factor i at point x , and S_i is standard value using dryland soil fertility classification reference indicators from the Green Food Origin Environment Quality Standard (NY/T391-2000).

5. Results

5.1 Landscape Scale At the landscape scale, broad-leaf forest had the largest area, followed by construction land. Bare land also had considerable extent, while traffic land and farmland were smaller. Coniferous forest, grassland, and broad-leaf forest showed relatively high landscape metrics, though patch density was relatively low. Construction land and traffic land occupied the minimum and maximum values of mean shape index, respectively. Other hardened ground had high patch density but low mean shape index. Bare land metrics were intermediate. Farmland and other hardened ground had relatively low landscape indices.

5.2 Island Scale The five islands showed obvious area differences. Overall landscape structure was similar yet distinct among islands. Farmland and other hardened ground appeared only on Tuo Ji Island and Da Qin Island, with farmland mainly distributed on Tuo Ji Island and other hardened ground (primarily kelp drying fields) concentrated on Da Qin Island. Larger islands had more diverse landscape types. Nan Huangcheng Island had intermediate area but the largest bare land extent. Xiao Qin Island, the smallest, had minimal landscape scales. Patch density ranked Tuo Ji > Da Qin > Nan Huangcheng > Bei Huangcheng > Xiao Qin. Edge density showed similar ranking except

Nan Huangcheng was notably higher. Mean shape index showed the opposite pattern. Human interference index was significantly higher on Da Qin and Tuo Ji Islands.

Table 1 shows landscape classification results for the five northern islands.

Table 2 presents landscape-scale pattern indices.

Table 3 shows island-scale landscape pattern indices.

5.3 Block Scale Landscape metrics showed more obvious heterogeneity at the block scale. Patch density and edge density varied significantly within Tuo Ji and Da Qin Islands but not on Nan Huangcheng and Bei Huangcheng Islands. Human interference index showed clear spatial differentiation, particularly typical on Tuo Ji and Da Qin Islands. Mean shape index showed opposite patterns, indicating regional concentration of human disturbance within islands. Xiao Qin Island showed limited internal spatial differentiation due to its small area.

Figure 3 [Figure 3: see original paper] illustrates spatial characteristics of landscape pattern on the five northern islands.

6. Ecological Effects of Landscape Pattern

6.1 Landscape Scale Ecological effect indicators differed significantly among landscape types. NPP was highest in broad-leaf forest, followed by grassland, traffic land, and bare land, with farmland notably lower. Shannon-Wiener index peaked in coniferous forest, while Pielou index was highest in broad-leaf forest. Soil moisture and fertility were higher in coniferous forest, broad-leaf forest, and grassland, but lower in construction land and other hardened ground.

Table 4 shows ecological effect indicators for different landscape types.

6.2 Island Scale Ecological effect indicators also differed significantly among islands. NPP was highest on Nan Huangcheng Island, followed by Tuo Ji and Bei Huangcheng Islands, with Da Qin and Xiao Qin Islands lower. Diversity indices were relatively high on Nan Huangcheng Island but lowest on Bei Huangcheng Island. Soil moisture and fertility were highest on Bei Huangcheng Island and lowest on Nan Huangcheng Island.

Regression analysis between island-scale landscape pattern indices and ecological effect indicators showed that only Pielou index significantly increased with edge density, while soil fertility significantly decreased with edge density. Other relationships were not significant, indicating ecological effect indicators were relatively insensitive to landscape patterns at the island scale. This insensitivity relates to island area differences and specific ecosystem conditions, as vegetation cover type and growth status are the primary influencing factors.

Figure 4 [Figure 4: see original paper] shows relationships between landscape pattern indices and NPP mean density at island scale.

Figure 5 [Figure 5: see original paper] shows relationships between landscape pattern indices and biodiversity at island scale.

Figure 6 [Figure 6: see original paper] shows relationships between landscape pattern indices and soil properties at island scale.

6.3 Block Scale Simple correlation analysis at block scale showed significant positive correlations between NPP mean density and PD/ED/MSI, and significant negative correlations with HII. Shannon-Wiener index was significantly negatively correlated with PD and ED, and positively correlated with MSI. Pielou index showed no significant relationships with other indices. Soil moisture was significantly positively correlated with PD, ED, and MSI, and negatively correlated with HII. Soil fertility showed no significant correlations with landscape pattern indices.

Partial correlation analysis controlling for vegetation landscape showed marked differences: correlations between NPP mean density and most landscape pattern indices weakened substantially, with only PD and ED remaining significant. Shannon-Wiener index correlations with landscape pattern indices remained significant, with negative correlations with PD and ED strengthening. Pielou index correlations remained non-significant. Soil moisture correlations with landscape pattern indices weakened, while soil nutrient correlations strengthened significantly, showing negative correlations with PD and ED and positive correlation with HII.

Table 5 presents correlation analysis results between landscape pattern indices and ecological effect indicators at grid scale.

7. Discussion

7.1 Research Approach Study Area Representativeness: The entire Miaodao Archipelago falls under Changdao County jurisdiction in Shandong Province. The archipelago shows clustered distribution with intensified human exploitation. The southern five islands serve as the political, economic, and cultural center of Changdao County, receiving considerable research attention. In contrast, the northern five islands are farther from the mainland, more dispersed, with less developed shipping and relatively lower human activity intensity, making them less studied. The varying sizes, shapes, and development levels among the northern five islands create complex driving factors for landscape pattern differences, making this study uniquely significant.

Human Interference Index Establishment: Among the eight landscape types identified, only grassland and bare land are natural landscapes; the remainder (coniferous forest, broad-leaf forest, construction land, traffic land,

other hardened ground, and farmland) are artificial landscapes causing varying disturbance degrees. To characterize human interference intensity and spatial patterns, we established HII. Determining impact coefficients (IF_i) was crucial: traffic land has the highest impact (coefficient = 1.0) due to profound geomorphological alteration during construction and persistent pollution during operation; construction land and other hardened ground have moderate impact (0.8) mainly from surface morphology changes during construction; farmland conversion of natural communities to monocultures changes community structure and reduces biodiversity (coefficient = 0.6); artificial forests help maintain ecosystem stability but may threaten native communities (coefficient = 0.4). HII considers different human activity impacts, is computationally simple, data-accessible, and universally applicable, providing important reference for rational island development.

Ecological Effect Indicator Selection: Landscape pattern evolution affects atmospheric environment, water environment, ecosystem services, and urban heat islands. For island ecosystems, pollutant emissions are relatively small with minimal atmospheric and water environmental effects. Urban construction can create surface temperature differences, but limited urban development on the northern five islands restricts heat island effects. Landscape pattern changes mainly manifest as shrinking, fragmented natural landscapes and expanding artificial landscapes, affecting island ecosystems. NPP directly reflects vegetation productivity and serves as a key factor for determining carbon sources/sinks and regulating ecological processes. Island plant diversity plays fundamental roles in material cycling, energy flow, and ecosystem stability, while increasingly affected by human disturbance. Soil provides growth substrate and nutrients while playing key roles in organic matter decomposition and element cycling. Landscape pattern changes significantly affect soil ecological processes, with soil moisture and nutrients varying significantly under different landscape types. Selecting NPP, plant diversity, and soil properties comprehensively reflects island ecosystem changes under landscape pattern influences.

7.2 Landscape Pattern Spatial Characteristics At the landscape scale, coniferous forest, broad-leaf forest, and grassland constitute the landscape matrix of the five northern islands, with large scale and wide distribution creating high patch density, edge density, and mean shape index. Broad-leaf forests often occur at slope bases with good connectivity and lower patch density. Coniferous forests on back slopes and hilltops show both continuous distribution and numerous small patches within other vegetation, creating higher patch density. Grasslands are widely distributed across the islands, adjacent to forests or scattered within construction land. Complex terrain influences vegetation growth, creating tortuous patch outlines and high edge density and mean shape index for all vegetation types. Construction land, second only to vegetation in scale, shows the minimum mean shape index due to regular patch shapes. Traffic land, primarily roads, winds through islands with high patch density but limited scale and good connectivity, creating the maximum mean shape index. Bare land,

mainly distributed around island perimeters and as bare soil patches internally, has small patch areas with regular shapes and straight boundaries, placing its metrics intermediate. Farmland and other hardened ground are only distributed on Tuo Ji and Da Qin Islands, with small area, regular shapes, and dispersed distribution, resulting in low landscape metrics.

At the island scale, landscape patterns are constrained by natural characteristics and socioeconomic conditions. Island area, population, and GDP showed significant pairwise positive correlations. As island area increases, landscape types and patch numbers increase, along with population and GDP. GDP growth directly increases artificial landscapes while reducing and altering natural landscapes. Island shape complexity (calculated as $ISI = Length/[2 \times (\pi \times Area)^{0.5}]$, where $ISI = 1$ for circular shapes) showed no clear relationship with landscape pattern indices. PD and HII increased significantly with area, population, and GDP, while other indices showed no clear patterns.

At the block scale, terrain factors constrain landscape patterns. PD, ED, and MSI showed significant positive correlations with altitude but not with slope, while HII showed significant negative correlations with both altitude and slope. Construction land with high impact coefficients tends to concentrate in low-altitude, gentle-slope areas, while high-altitude, steep-slope areas feature natural grasslands, bare land, and low-impact artificial forests. The significant positive correlation between altitude and PD/ED/MSI reflects the high values of these metrics in vegetation landscapes that dominate high-altitude areas.

7.3 Landscape Pattern Ecological Effects At the landscape scale, artificial forests (coniferous and broad-leaf) showed positive ecological effects, demonstrating successful afforestation with black pine and locust as ideal species. However, broad-leaf forests had lower diversity due to understory herbaceous dominance by single species like *Cleistogenes chinensis*, while coniferous forests had higher diversity with varied herbaceous species. Grasslands showed high diversity and soil water/fertility indicators, indicating native plant communities' richness and grasslands' water/nutrient conservation advantages. Farmland, with strong human intervention, showed low biodiversity and soil indicators due to species uniformity. Construction and traffic land had low ecological effect values, though some vegetation mixing occurred due to interpretation precision. Controlling development scale and optimizing construction layout are crucial for reducing negative impacts.

At the island scale, ecological effect indicators were relatively insensitive to landscape patterns, with only Pielou index and soil fertility showing significant relationships with edge density. This insensitivity relates to vegetation growth status differences among islands. NPP mean density correlated with vegetation landscape proportion and growth status, which varied significantly among islands. For example, Tuo Ji and Bei Huangcheng Islands showed dense, continuous vegetation, while Da Qin Island' s kelp drying fields and Nan Huangcheng Island' s livestock grazing threatened vegetation. Soil nutrients were highest on

Bei Huangcheng Island but lowest on Nan Huangcheng Island, possibly due to the latter' s frequent traffic and large bare land area.

At the block scale, simple correlations were significant but weakened in partial correlation analysis controlling for vegetation landscape, indicating NPP mean density is less sensitive to fragmentation, edge effects, and shape complexity. Shannon-Wiener index showed stronger negative correlations with PD and ED in partial correlation analysis, confirming that fragmentation and edge effects threaten biodiversity. Pielou index showed no significant correlations, suggesting landscape pattern has limited impact on species evenness. Soil moisture relationships with landscape pattern indices weakened after controlling for vegetation, indicating moisture distribution is primarily affected by landscape type distribution. Soil nutrients showed enhanced negative correlations with PD and ED in partial correlation analysis, indicating fragmentation and edge effects significantly influence soil nutrients. The shift from negative simple correlations to positive partial correlations between HII and ecological indicators suggests simple correlations better reflect actual human activity impacts, as increased human interference reduces ecological effect indicators.

Scale is a crucial factor in landscape ecology, and scale selection importantly influences landscape pattern analysis and ecological effects. Our results demonstrate scale-dependent ecological effects of landscape patterns, providing important reference for comprehensively revealing natural ecosystem changes under human disturbance on islands. Future research should further investigate island ecosystem characteristics and influencing factors at different scales.

8. Conclusions

This study examined the five northern islands of the Miaodao Archipelago, analyzing landscape pattern spatial characteristics at landscape, island, and block scales, and exploring relationships between landscape patterns and NPP, plant diversity, and soil properties. Main conclusions are:

1. Landscape patterns showed spatial heterogeneity across all three scales. At the landscape scale, coniferous forest, broad-leaf forest, and grassland dominated with large area, high PD, ED, and MSI. Construction land also had substantial area with high PD but lowest MSI. Bare land had intermediate metrics. At the island scale, PD and HII increased significantly with island area, population, and GDP, while other indices showed no clear patterns. Island shape complexity showed no significant relationships with landscape pattern indices. At the block scale, PD, ED, and MSI showed significant positive correlations with altitude, while HII showed significant negative correlations with altitude and slope.
2. Landscape pattern indices were interrelated, with PD, ED, and MSI showing significant pairwise positive correlations, and HII showing significant

negative correlations with PD and ED. Island area is the fundamental factor determining population and economic carrying capacity, representing an important limiting factor for landscape patterns. Terrain constrains human activities and vegetation distribution, while human activities are direct drivers of landscape pattern change, creating distinct spatial heterogeneity among islands and blocks.

3. Ecological effects of landscape patterns were scale-dependent. At the landscape scale, ecological effect indicators differed significantly among landscape types, with higher values in coniferous forest, broad-leaf forest, and grassland. At the island scale, ecological effect indicators were relatively insensitive to landscape patterns. At the block scale, significant simple and partial correlations existed between ecological effect indicators and landscape pattern indices, but results differed. NPP and soil moisture were mainly influenced by landscape type and vegetation growth status, while biodiversity and soil nutrients were affected by landscape type, fragmentation, and edge effects. Increased human interference intensity reduced all ecological effect indicators.

Controlling construction scale, optimizing landscape allocation, and improving development methods are important measures for maintaining island ecosystem stability.

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