

Land Use Change and Ecological Security Evaluation in Haikou City

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Abstract: With the continuous development of society and the acceleration of urbanization, profound changes have occurred in the utilization of land resources. Unreasonable land use and development pose serious threats to land ecological security, leading to a series of ecological security issues that constrain regional sustainable development. This study takes Haikou City as the research object and utilizes remote sensing (RS) and geographic information system (GIS) technologies to analyze the changes in land use in Haikou City from 2002 to 2022. Simultaneously, a land ecological security evaluation system is constructed based on the "Pressure-State-Response" (PSR) model. The weights of the indicators are determined by combining the Entropy weight method and the analytic hierarchy process (AHP). The TOPSIS (technique for order performance by similarity to ideal solution) method is then applied to evaluate the land ecological security index. The results indicate that during the period from 2002 to 2022, the cropland and impervious areas in Haikou City exhibited significant growth trends, while the areas of grassland, water, barren land, and forest decreased. Despite this, the comprehensive ecological security index of Haikou City showed an overall fluctuating upward trend, reaching its optimal state in 2022, with the land ecological security level improving from "Minor Warning" to "Relatively Safe". These research findings provide scientific evidence for adjusting land use policies and formulating relevant measures, and also serve as an important reference for promoting the sustainable utilization and ecological security protection of land resources in Haikou City.

Keywords: Land use, PSR model, AHP-Entropy, Ecological security.

1. Introduction

Land, as the cornerstone of human social development, carries multiple functions such as human production and life[1], as well as the maintenance of ecological balance. Driven by rapid economic growth and the wave of urbanization, land use patterns have undergone significant changes, undoubtedly posing new challenges to land ecological security. Haikou City, as the political, economic, and cultural hub of Hainan Province, holds significant importance in the evolution of its land use patterns and the status of land ecological security for the sustainable development of the region.

Reviewing the recent research progress in related fields both domestically and internationally, it becomes evident that the dynamics of land use change and the evaluation of land ecological security have become hot topics in academia. Foreign scholars have achieved fruitful results in areas such as the dynamic mechanisms of land use change[2], ecological impacts[3], and the theories and methods of ecological security evaluation[4]. Meanwhile, domestic researchers have focused more on the spatiotemporal characteristics of land use change[5], the analysis of influencing factors[6], and the specific impacts on land ecosystems[7]. Moreover, they are actively exploring evaluation methods and index systems for land ecological security that are tailored to the Chinese context[8-9].

However, despite the abundant research outcomes, studies specifically addressing the land use change and ecological security evaluation in Haikou City remain scarce. As the core area for the construction of Hainan Free Trade Port, the land use changes and land ecological security conditions in Haikou City have significant impacts on the sustainable development

of the entire region. Therefore, it is particularly urgent and necessary to delve deeper into the characteristics and patterns of land use change in Haikou City and reveal its impact mechanisms on land ecological security.

Based on the socio-economic statistical data and land use type data from 2002 to 2022 in Haikou City, this study closely integrates the actual situation of land use change in Haikou City. By comprehensively applying various methods such as the Analytic Hierarchy Process (AHP)-Entropy Weight Method, the Pressure-State-Response (PSR) model, and an improved Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a scientific evaluation system for land ecological security is constructed. This enables an in-depth quantitative analysis of the changing characteristics of ecological security in Haikou City. This not only helps us gain a more comprehensive and accurate understanding of the current status and trends of land ecological security in Haikou, but also provides important theoretical support and practical guidance for future ecological environment management and sustainable development in the city.

2. Study Area and Data

2.1. Study Area

Haikou City (19°31'N~20°04'N, 110°07'E~110°43'E) is located on the northern edge of the tropics and falls within a typical tropical monsoon climate zone^[10]. The region enjoys abundant sunlight and ample rainfall, providing favorable natural conditions for crop growth, making Haikou City one of the important agricultural production areas in Hainan Province[11]. Its rich natural resources provide a solid material foundation for Haikou's economic and social development as well as ecological environment protection.

Additionally, as the capital city of Hainan Province, Haikou possesses multiple ports, serving as a primary window for foreign trade in Hainan and a crucial hub for shipping in the South China Sea, playing an irreplaceable role in promoting regional trade and economic development. The geographical location of the study area is illustrated in Figure 1.

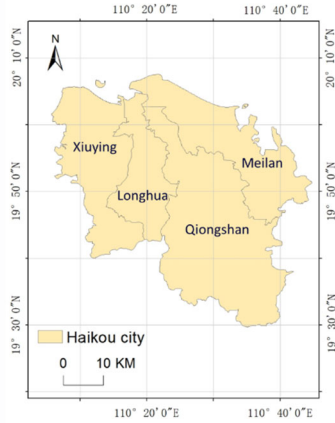


Figure 1. Location map of the study area

2.2. Data Source

The land use type data used in this study are derived from the China Land Cover Dataset (CLCD) released by Wuhan University. This dataset is generated using Landsat imagery with a resolution of 30 meters and categorizes land use types into nine categories, including Cropland, Forest, Shrub, Grassland, Water, Snow/Ice, Barren, Impervious, and Wetland. As required, the land use types were reclassified into seven categories using ArcGIS 10.8 software, namely forest, grassland, wetland, cropland, water body, impervious surface, and barren land. The statistical data required for this study are sourced from the Haikou Statistical Yearbook for the years 2002 to 2022.

3. Methodology

3.1. Evaluation model selection

In this study, the Pressure-State-Response (P-S-R) model is selected as the primary tool for evaluating land use change and ecological security in Haikou City. The P-S-R model is a conceptual framework that comprises three dimensions: Pressure, State, and Responses[12]. Each dimension encompasses a series of specific evaluation indicators, aiming to comprehensively reflect the overall status of regional ecological security. Within the framework, the Pressure dimension focuses on the environmental burden imposed by human activities and natural factors, particularly the impact of changes in land use types and structural layouts on land ecological security. The State dimension, on the other hand, reveals the current status of ecosystems, resource environments, and socio-economic development, encompassing the present condition of land resources and ecosystems as well as their evolving trends over time. Finally, the Responses dimension emphasizes the evaluation of proactive measures taken by humans to improve the ecological environment.

3.2. Selection of Indicators

During the in-depth study of land use change and ecological security in Haikou City, the selection of evaluation indicators is particularly important. These indicators not only

need to comprehensively reflect the characteristics and status of multiple factors such as nature, economy, ecology, and society in the study area, but also need to consider the interrelationships among indicators to ensure the accuracy and comprehensiveness of the evaluation. At the same time, we fully consider the availability of indicator data to ensure that reliable data support can be obtained for the selected indicators in practical operations, thus truly reflecting the status of land ecological security in Haikou City. Based on the principles of data availability, experimental scientificity, and overall indicator integrity, this study ultimately selected 19 key indicators to build a comprehensive and effective evaluation system.

3.3. Standardization of Indicators

Due to the lack of comparability among selected evaluation indicators with different dimensions and units, it is impossible to directly calculate, so it is necessary to conduct dimensionless processing for data of each indicator. In this article, the range method is adopted to standardize each indicator factor, and the range of each indicator selected above is calculated between [0,1]. Some of the ecological security evaluation indexes have positive effects, and the higher the value is, the safer the ecosystem will be, while some indexes have negative effects, and the higher the value is, the more unsafe the ecosystem will be.

The standardization calculation formula is shown below[13]:

Positive index calculation formula:

$$X'_{ij} = \frac{j - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Negative index calculation formula:

$$X'_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \quad (2)$$

Where X'_{ij} represents the j index of the i unit after standardized treatment; X_{ij} represents the original value of the j index of i units; X_{max} is the maximum value of the j index of the i cell, X_{min} is the minimum value of the j index of the i cell.

3.4. Determine the Weight of Indicators

The Analytic Hierarchy Process (AHP), introduced by American operations researcher Thomas L. Saaty in the 1970s, is an effective decision-making analysis method for assigning weights[14]. It quantifies evaluation indicators and determines the optimal solution through the construction of a hierarchical structure model, the creation of judgment matrices, and the conduct of consistency checks[15]. In this study, we established a hierarchical structure comprising the goal level, criterion level, and indicator level based on our research objectives. Using a 1-9 scaling method, we constructed judgment matrices reflecting the relative importance of indicators based on comparisons and judgments made by experts and scholars. Subsequently, through normalization, calculation of weight vectors, and consistency checks, we obtained reliable indicator weights:

W_{ahp} .

Furthermore, we introduced the entropy method as another approach for determining weights. This method, drawing from the concept of entropy in statistical physics, assesses the

impact of indicators on evaluation objectives by quantifying the degree of data dispersion[16]. By constructing a decision matrix, calculating the proportion of indicator values, entropy values, information entropy redundancy, and entropy weights, we obtained the indicator weights using the entropy method: $W_{熵}$.

Recognizing that using the entropy method or AHP alone in calculating the weights of land ecological security evaluation indicators in Haikou City might result in certain biases, this paper combines the two methods and adopts a weighted approach to recalculate the indicator weights. By comprehensively considering the advantages of both methods, we can obtain more reasonable and accurate indicator weight values. The formula for recalculating the indicator weights using the weighted approach is as follows (Equation(3)):

$$W = (W_{熵} \times 0.5 + W_{ahp} \times 0.5) \quad (3)$$

The formula represents the composite weight (W) of the n th indicator, where $W_{entropy}$ and W_{ahp} are the weights calculated by the entropy method and the Analytic Hierarchy Process (AHP), respectively.

By integrating AHP and the entropy method, we aim to achieve a more comprehensive and balanced evaluation of land ecological security in Haikou City, taking into account both expert opinions and objective data patterns. This approach allows us to make more informed and effective decisions regarding land use and ecological protection in the region.

3.5. Comprehensive Evaluation Index of Ecological Security

In this study, an improved TOPSIS model was employed to calculate the comprehensive evaluation index of ecological security, addressing the limitations of the traditional TOPSIS model[17] in handling the symmetric relationship between positive and negative ideal solutions of evaluation indicator values. The core of this method lies in the weighted processing of the distances between evaluation indicators and ideal solutions, aiming to enhance the accuracy and reliability of the evaluation results. The specific process of the improved TOPSIS evaluation method is outlined as follows[18]:

1. Establishing a Weighted Evaluation Indicator Matrix

Standardized evaluation indicator data y_{ij} are normalized to obtain a normalized matrix Z .

$$Z = \frac{y_{ij}}{\sqrt{\sum_{i=1}^m y_{ij}^2}} \quad (4)$$

In this equation, Z represents the normalized matrix of comprehensive evaluation indicators for the ecological environment, and y_{ij} denotes the standardized value of the j th indicator in the i th year ($i = 1, 2, 3 \dots m$).

2. Determining Ideal Solutions

The maximum and minimum values of the evaluation indicators z_{ij} across all years are identified from the normalized matrix Z , serving as the positive ideal solution z^+ and the negative ideal solution z^- respectively.

$$z^+ = \max z_{ij} (i = 1, 2, 3 \dots m) \quad (5)$$

$$z^- = \min z_{ij} (i = 1, 2, 3 \dots m) \quad (6)$$

3. Calculating Distances to Ideal Solutions

After determining the positive ideal solution z^+ and the negative ideal solution z^- from the normalized evaluation indicator matrix Z , the distances D_i^+ and D_i^- from each evaluation indicator to the positive and negative ideal solutions are calculated.

$$D_i^+ = \sqrt{\sum_{j=1}^n [(z_{ij} - z^+) \times w_j]^2} \quad (7)$$

$$D_i^- = \sqrt{\sum_{j=1}^n [(z_{ij} - z^-) \times w_j]^2} \quad (8)$$

In these equations, a smaller value of D_i^+ indicates that the indicator values are closer to the positive ideal solution, reflecting a better ecological environment. Conversely, a smaller value of D_i^- indicates that the indicator values are closer to the negative ideal solution, indicating a poorer ecological environment.

4. Calculating the Ecological Security Index

The closeness C_i is used to represent the state of ecological security. The formula for calculating the closeness C_i of each evaluation indicator to the ideal solutions is as follows:

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \quad (9)$$

The value of C_i ranges from 0 to 1, with a higher value indicating greater land ecological security.

Furthermore, this study also referenced relevant research [19-20] to establish a grading standard for the evaluation index (Table 1), aiming to objectively reflect the land ecological security status of Haikou City.

Table 1. The evaluation form of ecological security level

Ecological Security Index Value	Ecological Security Level
0.00-0.30	Severe Warning (VI)
0.30-0.40	Moderate Warning (V)
0.40-0.45	Minor Warning (IV)
0.45-0.50	General Safety (III)
0.50-0.60	Relatively Safe (II)
0.60-1.00	Very Safe (I)

4. Results and Analysis

4.1. Analysis of Spatial Patterns of Land Use in the Study Area

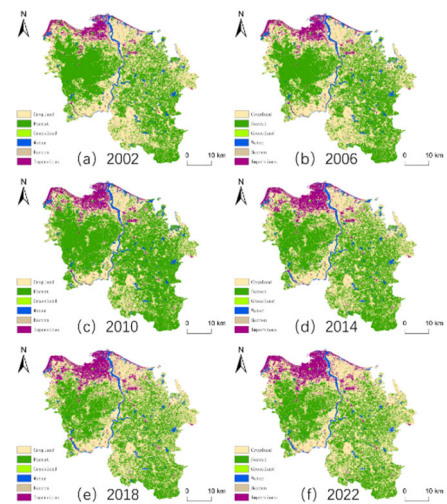


Figure 2. Land use classification of study area

Table 2. Area and proportion of various land use types in the study area

Type	Year	2002	2006	2010	2014	2018	2022
Cropland	Area(km ²)	1114.131	1093.586	819.194	1049.282	1179.515	1202.777
	Proportion(%)	44.375	43.556	32.628	41.792	46.979	47.905
Forest	Area(km ²)	1186.089	1191.974	1441.427	1185.170	1040.465	1019.423
	Proportion(%)	47.241	47.475	57.410	47.204	41.441	40.602
Grassland	Area(km ²)	4.531	3.614	2.823	2.007	1.121	0.826
	Proportion(%)	0.180	0.144	0.112	0.080	0.045	0.033
Water	Area(km ²)	80.782	82.675	86.240	84.256	78.097	65.062
	Proportion(%)	3.217	3.293	3.435	3.356	3.110	2.591
Barren	Area(km ²)	0.400	0.122	0.120	0.077	0.124	0.110
	Proportion(%)	0.016	0.005	0.005	0.003	0.005	0.004
Impervious	Area(km ²)	124.810	138.773	160.939	189.950	211.422	222.545
	Proportion(%)	4.971	5.527	6.410	7.565	8.421	8.864

The distribution maps of various land use types in Haikou City (Figure 2) reveals distinct spatial characteristics in the distribution of land use. Impervious are relatively concentrated, primarily along the northwestern coastal areas of Haikou. Cropland is distributed around the urban perimeter and adjacent to Water, suitable for crop growth. The main Water in Haikou is the Nandu River in the central region, with several lakes and reservoirs scattered throughout the city. Forest is primarily concentrated in specific regions, such as Xiuying District and Qiongsan District, where they occupy a significant proportion of the city's total Forest area. This concentrated distribution contributes to the formation of contiguous green ecological barriers, crucial for maintaining regional ecological balance and biodiversity.

Analysis of the area statistics in Haikou City (Table 2) indicates that Cropland and Forest are the primary land use types in the study area, accounting for approximately 80% of the total city area. This suggests abundant forest resources and high vegetation coverage. Additionally, Impervious surfaces occupy a relatively large area, accounting for over 4% of the total city area. The proportion of barren land is relatively small, reflecting the rapid urbanization process in Haikou, with increasing urban expansion and construction land demand. This may have led to the extensive use of barren land for urban construction and development, resulting in a reduction in its area. Overall, from 2002 to 2022, the area of Impervious surfaces in Haikou continuously increased, from 124.810 km² at the beginning of the study to 222.515 km². The areas of Grassland and Barren land continuously decreased during the entire study period, and their respective proportions were below 0.1% in 2022. The area of Cropland generally increased over the study period, with a decrease from 2002 to 2010 and a subsequent increase from 2010 to 2022. In contrast, Forest and Water areas exhibited opposite trends, initially increasing and then decreasing during the study period. Overall, the areas of Water and Forest were smaller compared to the initial stage of the study.

4.2. Analysis of the Weight of Evaluation Indicators

Combining the actual conditions of the evaluation area, the evaluation system is divided into the target level, the Rule level, and the indicator level, based on the principles of analytic hierarchy process (AHP) and following the

fundamental ideas and principles of the PSR model. Under the criterion level, pressure indicators, state indicators, and response indicators are categorized. Through consulting relevant materials and calculating the comprehensive weights, the evaluation indicators and their weights for land ecological security in Haikou City are obtained as shown in Table 3. Within the entire evaluation system, the per capita public green space area and pesticide application rate have the highest weights, with comprehensive weights of 0.1226 and 0.1034, respectively, exerting the greatest influence on the land ecological security of Haikou City. Following these are the total wastewater discharge and the comprehensive utilization of industrial solid waste, with comprehensive weights of 0.0662 and 0.0663, respectively, also having a significant impact on land ecological security. On the other hand, the total industrial output value has the lowest comprehensive weight, at only 0.0283, indicating the smallest relative impact on the land ecological security of Haikou City.

4.3. Analysis of Land Ecological Security Evaluation

Based on the PSR evaluation indicator system, the land ecological security evaluation results for Haikou City in 2002, 2006, 2010, 2014, 2018, and 2022 are presented in Table 4. The comprehensive index of land ecological security in Haikou City is determined by the pressure index, state index, and response index. From 2002 to 2022, the land ecological security index in Haikou City has seen a significant improvement. Specifically, the comprehensive index of ecological security decreased during 2002-2010, while it exhibited a trend of increase-decrease-increase during 2010-2022, with an overall increase. In 2010, the comprehensive index of land ecological security in Haikou City was the lowest, at only 0.372, while in 2022, it reached its highest value of 0.588. During the study period, the system response index fluctuated significantly, with the lowest value of 0.044 in 2006 and the highest value of 1.000 in 2022. Meanwhile, the system pressure index showed the smallest fluctuation, with a slight decrease during the study period. This indicates that due to the intense influence of human activities, the pressure on the land ecosystem in Haikou City is also continuously increasing.

Table 3. Evaluation index system of land ecological security in Haikou

Target layer	Rule layer	Index layer	Index trend	Weigh
Ecological Security Evaluation system of Haikou	Pressure layer	Average daily domestic water consumption (liters per person per day)	Negative	0.0499
		Total wastewater discharge (ten thousand tons)	Negative	0.0662
		Total exhaust gas emissions (ten thousand standard cubic meters)	Negative	0.0490
		Industrial sulfur dioxide emissions (tons)	Negative	0.0413
		Natural growth rate (per thousand)	Negative	0.0404
		Total industrial output value (ten thousand yuan)	Negative	0.0283
		Pesticide application (tons)	Negative	0.1034
	State layer	Per capita public green space area (square meters)	Positive	0.1226
		Actual paved road length at the end of the year (kilometers)	Negative	0.0481
		Cropland area (km ²)	Positive	0.0322
		Forestland proportion	Positive	0.0343
		Total urban green space area (hectares)	Positive	0.0360
		Park area (hectares)	Positive	0.0455
	Response layer	Main crop planting area (hectares)	Positive	0.0433
		Garbage removed (ten thousand tons)	Positive	0.0417
		Street sweeping area (ten thousand square meters)	Positive	0.0345
		Urban drainage pipeline length (kilometers)	Positive	0.0586
		Fiscal expenditure (ten thousand yuan)	Positive	0.0584
			Comprehensive utilization of industrial solid waste (ten thousand tons)	Positive

From the land ecological security levels in Haikou City from 2002 to 2022, it can be seen that the land ecological security levels in 2002, 2006, 2010, 2014, 2018, and 2022 were “Minor Warning (IV)”, “Severe Warning (VI)”, “Severe Warning (VI)”, “General Safety (III)”, “Minor Warning (IV)” and “Relatively Safe (II)”, respectively. During the period of 2006-2010, under the influence of natural environmental changes and human activities, the ecological function of Haikou City was relatively weak, and the land ecological pressure was considerable. Therefore, ecological reconstruction and restoration work were urgently needed, and the land ecosystem remained under severe warning for a long time. From 2010 to 2014, the land ecological security

level in Haikou City improved, and the stability of the land ecosystem gradually increased, enabling it to perform basic ecological functions. From 2018 to 2022, the land ecological structure in Haikou City became more reasonable, the ecosystem function gradually improved, and the land pressure faced decreased. With the efforts of relevant departments to carry out ecological restoration work, the system response index increased significantly, ultimately leading to a significant improvement in the comprehensive index of ecological security. The land ecosystem in Haikou City is now in a relatively safe state, greatly improving the land ecological security situation.

Table 4. The result of comprehensive evaluation on the safety of urban ecological security in Haikou

Year	System Pressure Index	System State Index	System Response Index	Comprehensive Ecological Security Index	Assessment Level
2002	0.629	0.386	0.061	0.443	Minor Warning (IV)
2006	0.547	0.348	0.044	0.380	Severe Warning (VI)
2010	0.567	0.214	0.242	0.372	Severe Warning (VI)
2014	0.349	0.675	0.341	0.461	General Safety (III)
2018	0.373	0.418	0.476	0.415	Minor Warning (IV)
2022	0.515	0.522	1.000	0.588	Relatively Safe (II)

5. Conclusion

Land use change, as a significant factor influencing urban land ecological security, has direct and indirect effects on the ecological security of Haikou City. Haikou boasts a rich variety of vegetation types, including arbor forests, shrub forests, and mangroves, which play an irreplaceable role in maintaining ecological balance, water conservation, and soil conservation. However, from 2002 to 2010, due to intensified human activities such as cropland expansion, road construction, mineral exploitation, and housing development, the land ecological security level remained in a state of mild to severe warning. These activities often came at the cost of sacrificing cropland and grassland, posing a severe threat to land ecological security.

Since 2010, relevant departments have paid greater

attention to land ecological issues. By optimizing land resource allocation and limiting human activities' occupation of cropland, the comprehensive index of land ecological security has improved slightly in the short term, achieving a certain balance and coordination of land resources. Nevertheless, the slight decline in the comprehensive index of land ecological security in 2018 indicates that the scientific nature of land-use structure still needs to be improved, and the maintenance of land ecological security remains a long-term task.

It is noteworthy that during the period from 2018 to 2022, the area of cropland increased, and the ecological security status improved from a state of mild warning to a relatively safe state. This significant change is closely related to policy regulation and the transformation of development models, reflecting positive progress in land management and

ecological protection in Haikou City.

Moreover, the development of construction land basically aligns with the set objectives of the overall planning indicator system for territorial space, contributing to achieving the basic goals of population growth targets. However, the downward trend in forest coverage still exhibits a certain gap compared to the overall planning objectives, highlighting the need to place greater emphasis on green space protection in future urban development, laying a solid foundation for sustainable development.

Amidst the accelerating urbanization process, it is particularly important to protect ecological sources, enhance the quality of ecological land use, and leverage the ecological functions of green spaces within cities. In the future, the Haikou municipal government should develop more scientific and stringent land-use planning, clarifying the direction and restrictions for various types of land use, especially strengthening the protection of ecologically fragile areas such as forests, grasslands, and water bodies. Simultaneously, efforts should be made to strengthen land law enforcement, severely cracking down on illegal occupation and destruction of land resources to ensure the effective implementation of land-use planning. For barren land and degraded forests, ecological restoration projects such as afforestation and closing mountains for afforestation should be implemented to gradually restore land ecological functions. Additionally, water body protection and governance efforts should be strengthened to restore their ecological functions and improve their self-purification capacity, ultimately enhancing the overall level of land ecological security in Haikou City.

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