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How to Recognize and Measure the Driving Forces of Tourism Ecological Security: A Case Study from Zhangjiajie Scenic Area in China

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Abstract

Rapid regional development and intensified human activities increasingly disturb ecosystems, posing substantial threats to the integrity of large-scale ecological zones. As a World Natural Heritage site and a crucial national ecological zone, the Zhangjiajie Scenic Area plays a pivotal role in China's environmental conservation efforts. To comprehensively assess tourism ecological security in the Scenic Area and strengthen the scientific basis for resource management and policymaking, this study developed a multi-dimensional ecological security evaluation system covering 2010–2024, incorporating dynamic changes in perturbation, reaction, and governance. Using entropy weight–TOPSIS and coupling coordination models, combined with obstacle degree analysis, we examined the temporal trajectory of ecological security and analyzed its underlying driving mechanisms. The study also examined factors influencing the sustainable development of the ecosystem. The results indicate the following: (1) Tourism ecological security in the Scenic Area followed a V-shaped trajectory of "rapid degradation—steady recovery—impact and rebound." It declined sharply to an unsafe level between 2010 and 2014, steadily recovered from 2015 to 2019, briefly dropped in 2020, and then rebounded, reaching a peak evaluation value of 0.519 in 2024. (2) The co-evolution of perturbation, reaction, and governance subsystems has matured: their coupling coordination degree has increased annually and has remained at the level of "intermediate coordination" since 2020. The reaction subsystem plays a central role, serving as a bridge between perturbation and governance. (3) The driving factors exhibit a phased evolutionary pattern of "elements—facilities—structure—function." Cultivated land area, total road mileage, and artificial afforestation area constitute the main long-term constraints. This research provides important insights for strengthening ecological security and sustainability in the Scenic Area while advancing regional ecosystem development. It also offers valuable guidance for ecological security management and policymaking in similar nature reserves.

Keywords: driving mechanism; comprehensive evaluation; tourism ecological security; obstacle degree model

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1. Introduction

With the ongoing development of ecological civilization in China and the implementation of the Beautiful China initiative, environmental conservation has gradually become a central component of national policy agendas [1]. Scenic areas rich in biodiversity and natural resources—such as national parks and heritage sites—are increasingly under ecological stress from large-scale tourism and rapid urban growth [2]. These areas are particularly vulnerable to environmental degradation, resource overuse, and biodiversity loss, all of which undermine the long-term sustainability of tourism regions [3,4].

As one of China's most iconic World Natural Heritage sites and a leading international ecotourism destination, the Zhangjiajie Scenic Area faces both the challenges and opportunities arising from these initiatives. On the one hand, the policy framework offers strong guidance and institutional support for ecological restoration, pollution control, and biodiversity conservation. On the other hand, Zhangjiajie faces mounting ecological pressures from rapid urban expansion, high tourist flows, and growing demands on natural resources. Therefore, protecting and managing the ecological environment of tourist destinations is essential for maintaining biodiversity and ecological balance, as well as for promoting sustainable development and fostering a harmonious society [5].

Given the above needs, scholars have closely examined the current situation of the study area, not only combining local actual conditions but also integrating international status, actively developing evaluation indicators for tourism ecological security, identifying the driving factors influencing tourism ecological security, and achieving significant results. For example, Wan et al. [6] combined global carbon neutrality emission reduction goals with tourism activities in the study area and investigated the low-carbon transition pathways of tourism in characteristic towns, using the three-dimensional impact mechanism of tourists, residents, and enterprises as a conceptual entry point. In Italy, Castellani et al. [7], through applying ecological footprint and life cycle analysis in the Italian tourism context, emphasized the dominant role of energy consumption and fossil fuel use in influencing sustainability outcomes. Similarly, Ruan et al. [8] adopted a perspective grounded in ecosystem theory to reveal key drivers across tourism, economic, and environmental dimensions. He et al. [9] constructed a multi-faceted evaluation framework using 13 indicators, capturing the dynamics of economic scale, industrial structure, service quality, and development efficiency—offering a more sophisticated perspective on tourism development quality. Cernat et al. [10] created a sustainable tourism benchmark tool—STBT—to provide benchmark indicators for evaluating sustainable tourism across different countries. In a study of the top nine urban tourist destinations in China, Wang et al. [11] established a model for assessing dynamic carrying capacity by integrating system dynamics to compare how the government influences the tourism industry in terms of resources, environmental protection, and the economy. Ai et al. [12] proposed a hybrid theoretical framework combining tourism urbanization, spatial justice, and place-based accessibility concepts to analyze the spatial evolution of facility accessibility in tourist cities. These international findings demonstrate the importance of evaluation systems that are methodologically rigorous and regionally adaptive. In the future, constructing localized and context-specific ecological security assessment frameworks will be essential for accurately capturing the dynamics of tourism–ecosystem interactions and identifying dominant drivers in different geographical settings.

Most mathematical quantification models are static in research methodology, resulting in a lack of long-term time series dynamic analysis. Morteza et al. [13] developed an evaluation model that integrates the Analytic Network Process (ANP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to identify optimal tourist destinations in coastal areas. Wang et al. [14] employed the Pressure–State–Response (PSR)

model, entropy weight–TOPSIS method, spatial variation model, standard deviation ellipse model, and gray dynamic model to analyze and describe the spatiotemporal dynamics of tourism ecological security levels along the Yangtze River Economic Belt from 1998 to 2017. A significant contribution was made by Huan [15], who innovatively created an early warning system for tourism ecological security risks by combining a Bayesian network model with the geographical detector. Building on earlier research, a more thorough assessment of tourism ecological security in the Zhangjiajie Scenic Area is conducted by incorporating static and dynamic methods.

Nevertheless, current research results still face several bottlenecks that prevent the systematic breakdown of the driving mechanisms behind tourism ecological security. These include structural bias in indicator selection—overfocusing on natural factors such as forest coverage, while tourism-specific socio-economic perturbations, like tourist density, are often ignored—and inadequate analysis of driving forces, as static cross-sectional analyses fail to capture the dynamic co-evolution of subsystems. This makes it challenging to identify the main driving factors and quantify their stage-specific mechanisms of influence. These limitations indicate a pressing need to shift from "state assessment" to the "deconstruction of driving mechanisms", which is the key approach for constructing the evaluation system in this study. Accordingly, this research focuses on assessing and managing ecological security at tourist destinations and analyzes the impact of rapid tourism growth on the ecological security of nature reserves. Using the Zhangjiajie Scenic Area as the study area and considering its regional characteristics, a research framework has been developed tailored to the area's ecological security system for tourism. This study addresses the core question: "What drives the system evolution of tourism ecological security?" The specific goals are (1) to quantitatively evaluate the temporal evolution of the tourism ecological security system in the Scenic Area and identify the main factors driving its development and (2) to analyze in detail the hierarchical structure of the forces behind tourism ecological security in the area and to uncover the driving chain and evolutionary mechanisms among the three subsystems—perturbation, reaction, and governance. The research findings provide a theoretical foundation for sustainable tourism development in the Scenic Area and practical methodological guidance for managing tourism ecological security in similar regions.

2. Materials and Methods

2.1. Study Area

The Zhangjiajie Scenic Area, located in the northwestern part of Hunan Province, China, is an ecotourism destination. It lies between 29°16′25″ and 29°24′25″ N latitude and 110°20′30″ and 110°41′15″ E longitude, covering a total area of 397.48 square kilometers (Figure 1). The district is surrounded by five mountain ranges—Zhangjiajie, Yuanjiajie, Pipajie, Yangzhijie, and Lumaojie. The terrain radiates outward from the central area. Several small valley basins are scattered around the center, while mountainous regions dominate the outskirts, creating a complex topography. In 1982, China's first national forest park was established in Zhangjiajie. In August 1988, the Zhangjiajie Scenic Area was designated as a national key scenic spot. In December 1992, Zhangjiajie was added to the World Natural Heritage List for its unique landscape of quartz sandstone peaks and forests. As a World Natural Heritage Site, a national key scenic spot and a national designated ecological zone, protecting its ecological security is of vital importance.

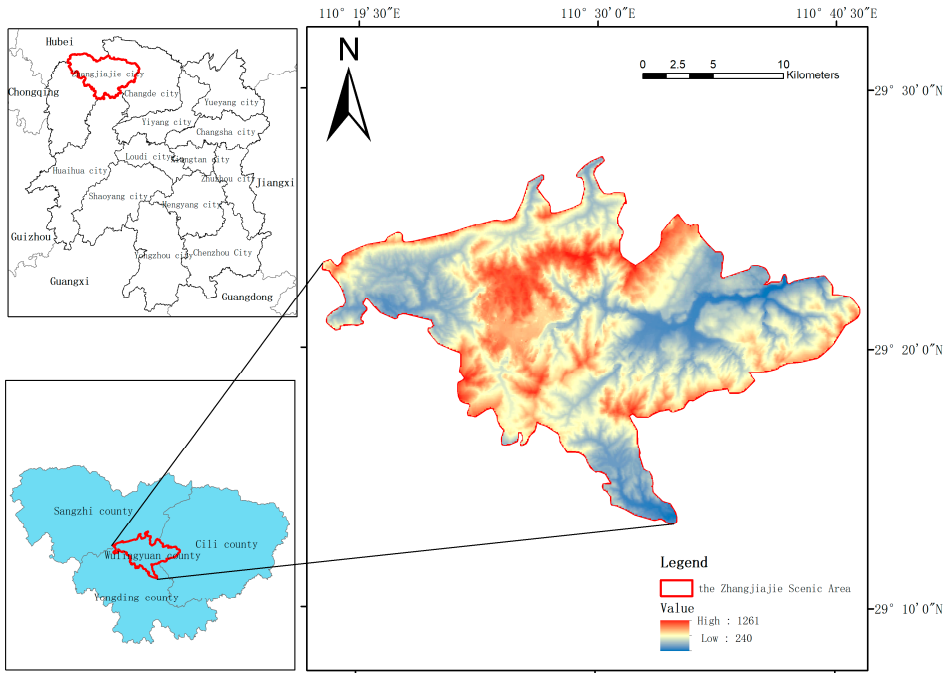

Figure 1. Study area.

2.2. Research Framework

As a nationally significant nature reserve and a UNESCO World Natural Heritage site, the Zhangjiajie Scenic Area faces various tourism-related ecological safety issues caused by human activities. Therefore, it is essential to conduct a precise and scientific assessment of the area's tourism ecological security and identify its driving factors and their impacts for its future preservation. This study establishes an evaluation model and an empirical framework to identify and measure the key factors influencing tourism ecological security. First, this study constructed a PRG model, which demonstrates that the ecosystem responds to external disturbances through transmitting stress signals to the governance level. In turn, governance measures help reduce the effects of these disturbances and improve the system's overall response. Second, through a series of deconstruction analyses, we summarized the dynamic changes in the tourism ecological security of the Scenic Area from 2010 to 2024, and explored the coupling relationship among the three subsystems. Finally, specific driving factors were identified based on the obstacle degree model, along with characteristics of different stages and their respective influence levels (Figure 2).

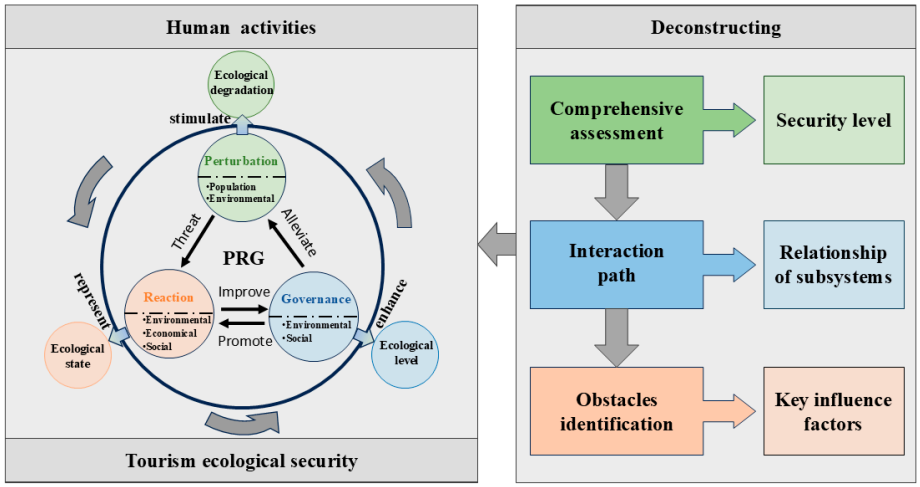

Figure 2. Research framework.

2.3. Establishment of Evaluation Index System

The level of ecological security in nature-based tourism destinations depends on the harmony between tourism development and the natural environment [16]. A high level of ecological security supports the balanced and stable growth of the destination's ecosystem and socio-economic system [17]. Changes in ecological security levels are affected by social, economic, and environmental factors, resulting in a complex and interconnected process. To fully evaluate the ecological security status of a tourism ecosystem, a comprehensive assessment index system is necessary—one that reflects the conditions of individual elements and considers the interactions among them [18].

Based on the above analysis, a PRG (perturbation–reaction–governance) evaluation index system has been developed by integrating the actual conditions of tourism development, the natural environment, and socio-economic factors in the Zhangjiajie Scenic Area. This system aims to calculate and assess the ecological security status and identify the patterns of their change over time, thus revealing the dynamic effects of tourism activities on the ecosystem and the related feedback mechanisms. In this context, "perturbation" pertains to population and environmental factors that impact the ecological security system, including the number of tourists, population size, and road mileage [19,20]. It also includes environmental degradation [21], such as loss of ecological land, increased noise levels, and natural disasters. "Reaction" describes the state of the ecological security system in response to these perturbations, specifically covering environmental and economic reactions, such as changes in forest and arable land areas [22], price levels, and the extent of urbanization [23]. "Governance" involves the measures taken to address these perturbations, including environmental and social management strategies, such as per capita disposable income, the proportion of fiscal expenditure on energy conservation and environmental protection, urban sewage and waste treatment rates [24], and the area of afforestation.

Based on the principles of problem representativeness, policy consistency, simplicity, and data availability, and drawing on the research findings of relevant scholars [25–28], this study selected a total of 19 indicators to construct the PRG (perturbation–reaction–governance) evaluation index system. The system is organized into three levels: the criterion layer, the element layer, and the indicator layer (Table 1). The criterion layer includes three dimensions: Perturbation (P), Reaction (R), and Governance (G). The element layer mainly considers population, economy, and environmental factors, which are distinct yet interconnected. These dimensions serve as key references for selecting specific indicators and collectively form the evaluation index system for tourism ecological security in the Zhangjiajie Scenic Area, as shown in Table 1.

Table 1. The evaluation index system for tourism ecological safety.

Criterion Layer	Element Layer	Index Layer	Characteristic
Perturbation	Population perturbation	X1 Tourist growth rate (%)	–
		X2 Natural population growth rate (‰)	–
		X3 Road mileage (km)	–
	Environmental perturbation	X4 Noise pollution (dB)	–
		X5 Sulfur dioxide emissions (t)	–
		X6 Inhalable particulate matter (μg/m^3)	–

Table 1. *Cont.*

Criterion Layer	Element Layer	Index Layer	Characteristic
Reaction	Environmental reaction	X7 Cultivated land area (hm^2)	−
		X8 Green coverage rate (%)	+
		X9 Forest coverage rate (%)	+
	Social reaction	X10 Urbanization rate (%)	−
		X11 Consumer Price Index (%)	−
	Economical reaction	X12 Proportion of the tertiary industry in GDP (%)	+
Governance	Environmental governance	X13 The number of days with good air quality (%)	+
		X14 Artificial afforestation area (hm^2)	+
		X15 Disposable income per capita (yuan)	+
		X16 Proportion of environmental protection in Government Expenditure (%)	+
	Social governance	X17 Tourism revenues (yuan)	+
		X18 Garbage treatment rate (%)	+
		X19 Sewage treatment rate (%)	+

2.4. Data Sources

The relevant research data and information used in this study are obtained from publicly available sources, mainly including the Environmental Status Bulletin of Hunan Province, the Statistical Bulletin on National Economic and Social Development of Zhangjiajie City, the China Forestry Statistical Yearbook, the China Urban Construction Statistical Yearbook, the Hunan Statistical Yearbook, and the China Environmental Statistical Yearbook. For this study, a variety of data were collected from 2010 to 2024. Missing values were filled using linear interpolation to ensure the dataset's accuracy, feasibility, and scientific validity.

2.5. Methods

To comprehensively investigate the temporal dynamics of tourism ecological security and reveal its core influencing pathways, this study integrates systematic evaluation tools with evaluation models. The assessment begins with a quantitative analysis of the ecological security level using a hybrid approach incorporating the entropy weight method and the TOPSIS method, ensuring objectivity in indicator weighting and precision in evaluation outcomes.

2.5.1. Comprehensive Evaluation of Tourism Ecological Security

To evaluate the tourism ecological security of the Scenic Area more accurately, objectively, and scientifically, this study adopted the entropy–TOPSIS method—a widely used multi-objective decision-making approach in systems engineering [29]. By measuring how closely each indicator approaches its ideal value, this method objectively reveals the actual strengths of the evaluated object [30]. In this study, the entropy–TOPSIS method provides a scientific and objective basis to assess the ecological security of the Zhangjiajie Scenic Area, supporting the selection of the most effective security management strategy. Compared to other methods such as the Analytic Hierarchy Process and Principal Component Analysis, the entropy method reduces bias from subjective value assignments, minimizes the influence of subjective factors, and increases the objectivity and accuracy of the evaluation results. The specific steps for the calculation are as follows:

1. Standardization of Indicators

In this study, indicator standardization is categorized into a positive indicator and a negative indicator. A higher value of the positive indicator indicates better ecological security, while a larger value of the negative indicator indicates worse ecological security.

Positive indicator:

$$Y_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \tag{1}$$

Negative indicator:

$$Y_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \tag{2}$$

In the formula, Y_{ij} represents the standardized value of the indicator; X_{ij} represents the value of the j-th indicator in the i-th year; and X_{max} and X_{min} represent the maximum and minimum values of the indicators in previous years, respectively.

2. Determination of Indicator Weights

According to Formulas (3)–(5), the specific weights of each indicator are determined using the entropy method.

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}} \tag{3}$$

$$E_j = -\frac{1}{lnm}\sum_{i=1}^{m} P_{ij} lnP_{ij} \tag{4}$$

$$W_j = \frac{1 - E_j}{\sum_{j=1}^{n} E_j} \tag{5}$$

In the formula, P_{ij} represents the proportion of the i-th indicator in the sample; E_j represents the information entropy of the j-th indicator; W_j represents the weight of the j-th indicator; m represents the number of evaluation years; and n represents the number of indicators.

3. TOPSIS

First, we establish a weighted normalization matrix and determine the positive and negative ideal solutions.

$$T = \left|T_{ij}\right|_{m \times n} = W_j \cdot Y_{ij} \tag{6}$$

$$T_i^+ = \left\{ maxT_{ij} \middle| i = 1, 2, \ldots, m \right\} \tag{7}$$

$$T_i^- = \left\{ minT_{ij} \middle| i = 1, 2, \ldots, 15 \right\} \tag{8}$$

In the formula, T represents the weighted normalized matrix; Y_{ij} represents the standardized index matrix; T_i^+ represents the positive ideal solution; and T_i^- represents the negative ideal solution.

Then, we calculate the distance from each choice to the optimal and worst solutions.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(T_{ij} - T_i^+\right)^2} \tag{9}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(T_{ij} - T_i^-\right)^2} \tag{10}$$

In the formula, D_i^+ represents the distance from the evaluation object in the i-th year to the positive ideal solution, and D_i^- represents the distance from the evaluation object to the negative ideal solution in the i-th year.

Ultimately, we calculate the comprehensive evaluation score.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} (0 \leq C_i \leq 1) \tag{11}$$

In the formula, C_i represents the comprehensive evaluation value of ecological security of the tourist area in the i-th year. The higher the value, the better the ecological security of tourism in the i-th year. Conversely, the worse it is.

2.5.2. Measurement of Interrelationships Among Subsystems

Secondly, to quantitatively evaluate the relationships among multiple subsystems within the evaluation framework—specifically, the interactions among the perturbation, reaction, and governance subsystems—and to clarify how their coordinated development influences the overall tourism ecological security system, the Coupling Coordination Degree Model is used in this study. This model offers a systematic method for analyzing regional coordinated development. Its main advantage is its ability to quantitatively measure both the level of interdependence among subsystems and their harmonious co-evolution at a specific time [31]. In this study, the Coupling Coordination Degree Model is employed to systematically analyze the coupling and coordination levels among the perturbation, reaction, and governance subsystems. Based on this analysis, the ecological security level of the Scenic Area is further assessed. The specific steps are as follows:

1. Calculate the Coupling Degree

$$C = 2 \times \left(\frac{A * B}{A + B^2}\right)^{\frac{1}{2}} \tag{12}$$

In the formula, C represents the coupling degree, and A and B, respectively, represent the comprehensive safety evaluation values of the two subsystems.

2. Calculate the Coordination Degree Development Index

$$T = \alpha \times A + \beta \times B \tag{13}$$

In the formula, α and β represent the relative importance (contribution) weights of the two systems during their development process. In most studies, it is assumed that the importance of each subsystem is consistent. Therefore, in this study, both α and β are taken as 0.5.

3. Calculate the Degree of Coupling Coordination

$$D = \sqrt{C \times T} \tag{14}$$

In the formula, D represents the coupling coordination degree, C represents the coupling degree, and T represents the coordination degree development index.

4. Classification of Coupling Coordination Degree Grades

The classification of the coupling coordination degree is based on the numerical ranges of coupling and coordination degrees, indicating the extent of interaction and harmony among subsystems within a regional system. Various scholars have proposed different classification schemes for coupling coordination levels. In this study, drawing on the work of WANG [32] and considering the specific conditions of the Scenic Area, the coupling coordination degree is categorized into 10 levels according to established classification standards, as shown in Table 2.

Table 2. Standards for the classification of coupling coordination levels.

Level	Coupling Coordinate	Degree of Coordination
1	(0–0.1]	Extreme dysregulation
2	(0.1–0.2]	Severe dysregulation
3	(0.2–0.3]	Moderate dysregulation
4	(0.3–0.4]	Mild dysregulation
5	(0.4–0.5]	On the verge of dysregulation
6	(0.5–0.6]	Barely coordination
7	(0.6–0.7]	Junior coordination
8	(0.7–0.8]	Intermediate coordination
9	(0.8–0.9]	Well coordination
10	(0.9–1.0]	High-quality coordination

2.5.3. Identification of Driving Factors and Measurement of Influence in Tourism Ecosystems

Besides identifying the specific factors that limit the improvement of tourism ecological security and evaluating the strength of their impact—thus addressing the limitations of comprehensive evaluation and coupling coordination analysis in pinpointing weaknesses—the obstacle degree model is used in this study. This model quantitatively measures the degree to which each indicator deviates from the system's development goals, thereby identifying the primary obstacle factors and their influence levels. The further an indicator's actual value is from its optimal value, the greater its negative effect on overall system performance; such an indicator is considered an obstacle factor [33,34]. The specific steps are as follows:

1. Calculate the obstacle degree of the indicator:

$$O_{ij} = \frac{W_j(1 - Y_{ij})}{\sum_{j=1}^{n} W_j(1 - Y_{ij})} \tag{15}$$

In the formula, O_{ij} represents the obstacle degree of the indicator; W_j represents the weight of the indicator; and Y_{ij} represents the standardized matrix.

2.5.4. Classification of Tourism Ecological Safety Levels

Based on previous studies [35], the equal interval method was used to categorize the tourism ecological security level of the study area into five levels according to the ecological security index: (I) Security, (II) More security, (III) Criticality security, (IV) Less security, and (V) Insecure, as shown in Table 3.

Table 3. Standards for the classification of tourism ecological safety levels.

Security Level	Security State	Tourism Ecological Security Index Value
I	Security	(0.8, 1]
II	More security	(0.6, 0.8]
III	Criticality security	(0.4, 0.6]
IV	Less security	(0.2, 0.4]
V	Insecure	[0, 0.2]

3. Results

A logically rigorous and progressively structured analytical framework was developed through the integrated use of various methods—ranging from the quantitative assessment of overall security levels to analyzing coupling and coordination relationships within

system interactions and further to identifying and diagnosing key obstacle factors. This framework aims to comprehensively reveal the dynamic evolution and the driving mechanisms of tourism ecological security in the Zhangjiajie Scenic Area. The specific results are outlined below.

3.1. Overall Evolution of Tourism Ecological Security

The TOPSIS method was used to comprehensively evaluate and analyze tourism ecological security in the Zhangjiajie Scenic Area from 2010 to 2024. During this period, the evaluation scores ranged from 0.22 to 0.52. The overall trend followed a V-shaped pattern, characterized by "rapid degradation (2010–2014)—steady recovery (2015–2019)—impact rebound (2020–2024)", as shown in Figure 3.

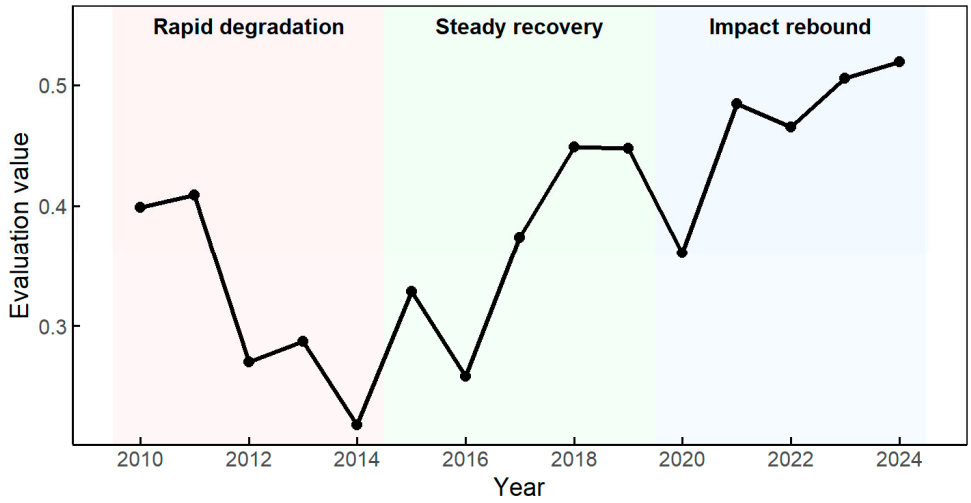

Figure 3. Evaluation value of tourism ecological safety.

Between 2010 and 2014, the tourism ecological security evaluation value in the Scenic Area declined sharply from 0.399 in 2010 to 0.218 in 2014—a decrease of 45.4%. This was the lowest in the past 15 years, indicating that the ecological security of tourism had become quite unsafe and was nearing an unsafe level. This is because the Scenic Area is in a state of continuous development. At the same time, during this period, the excessive increase in the number of tourists caused a sharp increase in ecological pressure, which in turn led to insufficient governance capabilities and overloaded ecological carrying capacity in the region.

Starting in 2015, the evaluation value increased to 0.328. Although there was a slight fluctuation in 2016, the overall trend in subsequent years showed steady growth. In 2018, the value exceeded the critical safety threshold and reached a peak of 0.447 in 2019. The continued positive development of the tourism industry has significantly boosted local economic income, along with the upgrading of the region's tertiary industry, the further improvement of related infrastructure, higher environmental investment standards, and mature pollution control practices, leading to improved tourism ecological security.

From 2020 to 2024, the evaluation value declined sharply due to external shocks affecting tourism, falling by 19.6% compared to 2018and reaching a relatively unsafe level. The global public health incident had a certain impact on the tourism industry and reduced people's enthusiasm for travel. However, a series of adjustment measures introduced in 2021 led to a quick recovery, and the evaluation continued to increase through 2024. In 2023, it surpassed the 0.5 threshold.

3.2. Evolution of the Tourism Ecological Security Subsystem

From 2010 to 2024, the evaluation value of the perturbation subsystem in Zhangjiajie Scenic Area generally declined, while the evaluation values of the system responsiveness and adaptive governance subsystems showed a fluctuating upward trend. Notably, the evaluation value of the adaptive governance subsystem increased at a faster pace. The overall trends of the three subsystems are illustrated in Figure 4. Locally Estimated Scatterplot Smoothing (LOESS) was used to generate fitted curves for each subsystem's tourism ecological security evaluation values, providing a clearer view of the system perturbation trends.

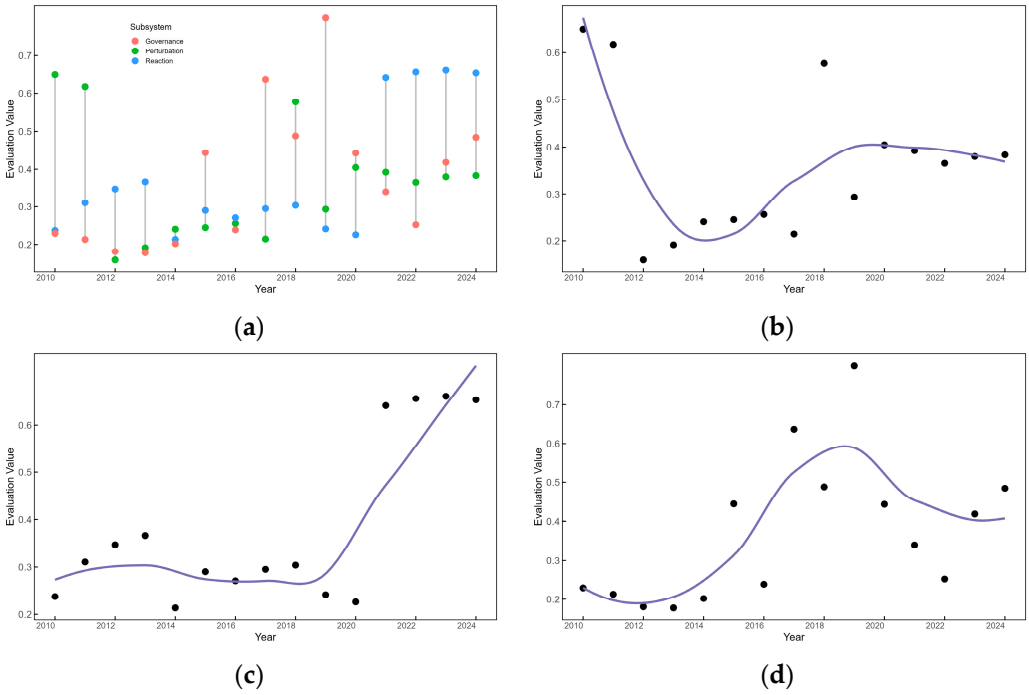

Figure 4. Evaluation value of the tourism ecological security subsystems. (**a**) Evaluation value of subsystems; (**b**) evaluation value of the perturbation subsystem; (**c**) evaluation value of the reaction subsystem; (**d**) evaluation value of the governance subsystem.

From 2010 to 2024, the overall evaluation scores of tourism ecological safety across the three dimensions—perturbation, reflection, and governance—showed a "fluctuation–transition–stabilization pattern". However, the rate of change differed considerably among them.

Regarding the perturbation dimension, the overall trend followed a three-stage "sharp decline from a high level–gradual recovery–low-level stabilization". This indicates that, in the early stage, the tourism ecological security of the Zhangjiajie Scenic Area faced significant pressure due to major perturbations from the population–environment system. In response, the Scenic Area took a series of measures to effectively alleviate the pressure. However, achieving long-term and stable control still requires implementing decisive strategic actions. The LOESS smoothing curve confirms this pattern; although periodic fluctuations continued, they had greatly diminished by the end of the period. From the perspective of the reaction dimension, the overall trend can be described as "drastic fluctuations—relative stability—rapid rise". In the early stage, the evaluation values fluctuated substantially, indicating that the system was vulnerable to external perturbations. During the mid-term, it entered a relatively stable phase with less volatility. A clear upward trend was observed in the later stages, with the highest values during the study period reaching 2022 and 2023. This trend implies a general improvement in the various reflective factors within the Scenic Area's tourism ecosystem. The LOESS curve also confirms the

pattern of "continuous rise and stabilization" after 2020, showing a steadily increasing ability of the system to respond to external perturbations.

From the perspective of adaptive governance, the trajectory follows an inverted U-shaped pattern characterized by "low-level stagnation—sharp rise—high-level correction and stabilization". From 2010 to 2014, evaluation values remained generally low with minimal fluctuations, reaching their lowest point in 2013. During this period, a series of environmental protection measures were implemented in Zhangjiajie to improve the ecological environment. In 2015, governance efforts were significantly intensified, leading to a sharp increase in the evaluation value to 0.444. Between 2017 and 2019, the evaluation value entered a rapid growth phase, reaching a historical high of 0.799 in 2019. After 2020, despite a slight decline caused by substantial external shocks, the values stayed medium-high, with noticeably reduced volatility. The LOESS curve further shows that adaptive governance has undergone a phased transformation from "steady initiation—leapfrog improvement—high-level steady state," marking the system's transition into a relatively balanced stage of development.

3.3. Evolution of Subsystem Interrelationships from the Perspective of System Reaction

To gain deeper insights into the interactions among subsystems within the tourism ecological security system and to assess more intuitively the actual feedback capacity of the tourism ecosystem in the Scenic Area in response to external perturbations and governance actions—thereby emphasizing its central role in the "perturbation–governance" chain—this study uses the Zhangjiajie Scenic Area as a case study. Focusing on the reaction system (R), a coupling coordination analysis is performed for the P-R (perturbation–reaction) and R-G (reaction–governance) systems, complemented by a comparative analysis of the P-R (perturbation–governance) system. As shown in Figure 5, the results indicate that from 2010 to 2024, the coordination levels of the three system pairs generally stayed within a coordinated state, with indices fluctuating between 0.51 and 0.82. However, the coordination levels varied significantly across different stages, showing an overall trend from low to high coordination, followed by gradual stabilization.

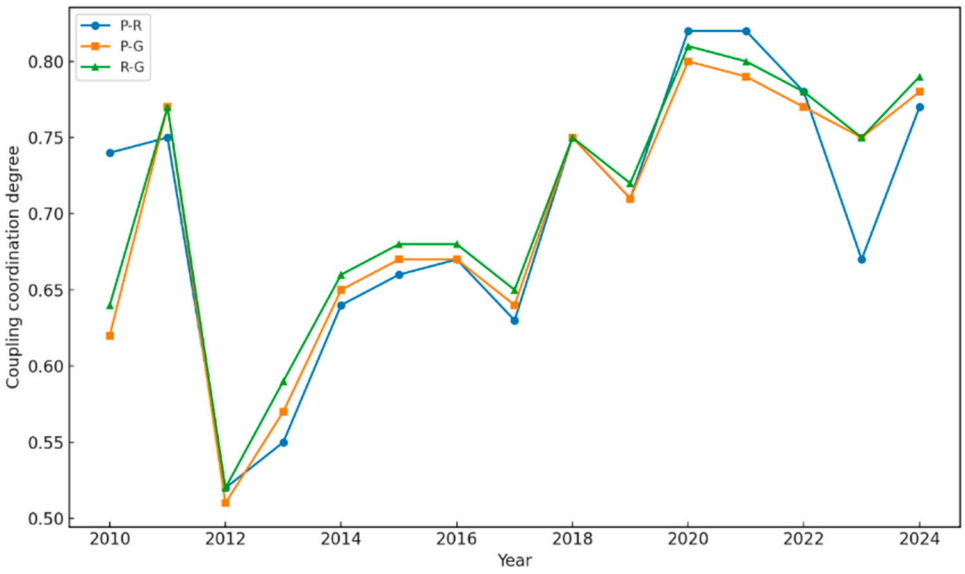

Figure 5. Coupling and coordination relationship of the tourism ecological security subsystem.

1. P–R Relationship: Sensitivity of the Tourism Ecosystem to Perturbations

From 2010 to 2012, the P–R coordination degree decreased from 0.64 to 0.52. Since 2013, it has steadily risen, reaching a favorable level of 0.82 in 2020. This indicates that the

interaction between the perturbation and reaction subsystem was initially unstable. However, as tourism growth slowed and corresponding control measures were implemented, the ecological system could provide timely and stable feedback to perturbations in the later period.

2. R–G Relationship: response efficiency of the tourism ecosystem to governance effectiveness

From 2010 to 2013, the R–G coordination degree fluctuated between 0.64 and 0.59, indicating that governance efforts had not yet been effectively translated into improved ecological conditions. After 2014, with the implementation of ecological restoration projects such as artificial afforestation and wastewater treatment, the R–G coordination degree increased rapidly, reaching 0.81 by 2020 and remaining within the "moderate–good coordination" range. This reflects a growing positive response of ecological conditions to governance measures. These findings suggest that implementing governance initiatives has significantly enhanced the reaction factors of tourism ecological security in the Scenic area.

3. P–G Relationship: coupling efficiency between perturbation and governance

The P–G coordination degree dropped to its lowest point of 0.51 in 2012 and rose above 0.75 after 2019. It shows that governance policies have effectively countered perturbations to the tourism ecological security system and reduced the associated pressures.

In summary, the reaction system is a crucial link in the "perturbation–reaction–governance" chain by transmitting and strengthening perturbation signals to the governance system, which then executes a series of counteractions to deal with the perturbations. The internal coordination among the three subsystems of the tourism ecological security system in the Zhangjiajie Scenic Area has evolved from initially weak coupling to synergistic interaction and structural integration, especially progressing to the "intermediate coordination–good coordination" stage after 2020. This developmental trajectory reflects the phased progress in ecological environment management and tourism development policies in the Scenic Area in recent years. The internal operating mechanisms of the ecosystem have been gradually refined, laying a solid foundation for the sustainable enhancement of regional tourism ecological security.

3.4. Driving Factors and Influence of the Tourism Ecosystem

To thoroughly identify the key driving factors and evolutionary mechanisms affecting the tourism ecological security in the Zhangjiajie Scenic Area, this study employs the obstacle degree model to analyze 19 indicators from 2010 to 2024. It tracks their dynamic changes, as shown in Figure 6. Unlike traditional ecological security assessments that focus solely on index aggregation and trend analysis, this study enables the ranking and quantification critical influencing factors. The results indicate that changes in the hierarchy of obstacle factors reveal phased transitions in the pressure pathways and risk structures of the tourism ecological security system over time. The main obstacle factors vary significantly across different years, with some indicators consistently showing high obstacle effects over multiple years, becoming key constraints to the system's effective operation.

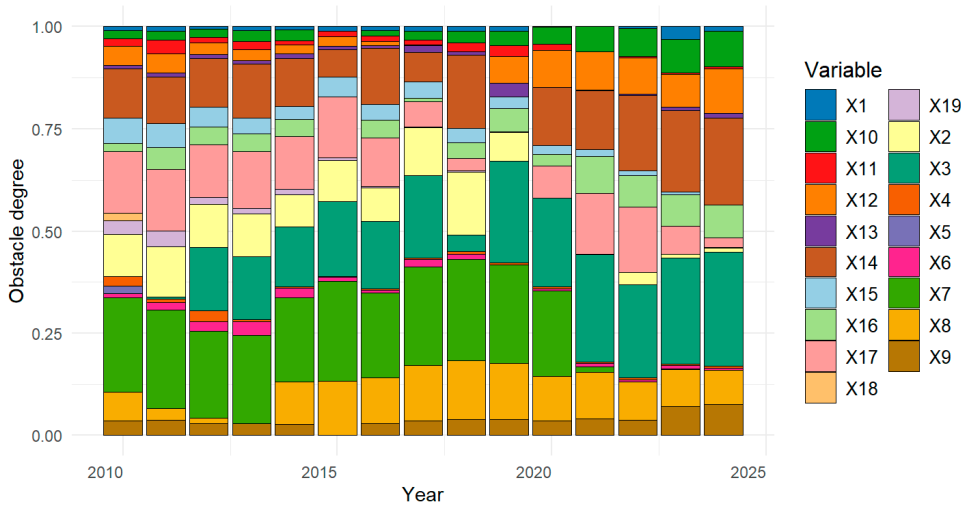

Figure 6. The obstacle degree grades of various indicators for tourism ecological security.

1. 2010–2014: Element-Driven

The cultivated land area (X7) consistently faced significant challenges in the early stages, especially between 2010 and 2018. During most of these years, the obstacle degree was above 0.20, peaking at 0.24 in 2015, and remained dominant. This shows that ongoing pressure from tourism development and urban expansion continually stresses land resources, making the imbalance between the supply and demand of cultivated land a key factor impacting ecological security.

2. 2015–2019: Facility-Driven

In the mid-term, the rapid expansion of transportation infrastructure has become a significant source of ecological pressure. The road mileage (X3) has increased significantly as an obstacle since 2012, reaching 0.25 in 2019 and climbing further to 0.26 in 2021, making it one of the most significant obstacle factors in the later stages. Although transportation development enhances tourism access and regional connectivity, its adverse effects on ecological space integrity and habitat connectivity cannot be overlooked. Future development should aim to incorporate ecological red line management and green infrastructure. Meanwhile, the natural population growth rate (X2), a key obstacle in the early stage, peaked at 0.1256 in 2011 but has steadily decreased to just 0.0087 by 2024. This indicates that, due to changes in population structure and lower birth rates, the ecological pressure from population growth is gradually diminishing, signaling an improvement in regional ecological security.

3. 2020–2024: Structure–Function-driven

In the final phase, the obstacle levels of proportion of the tertiary industry in GDP (X12) and artificial afforestation area (X14) steadily increased. The obstacle degree of X14 remained consistently above 0.18 from 2022 to 2024, reaching 0.21 in 2024. This suggests a potential overemphasis on the quantity of afforestation during ecological restoration, accompanied by insufficient attention to optimizing ecosystem structure and function. It emphasizes the need to shift ecological governance from focusing on "quantity" to prioritizing "quality".

Other environmental pollution indicators, such as noise pollution (X4) and inhalable particulate matter concentration (X6), generally show low obstruction levels, although some years experience upward fluctuations. For example, X6 reached 0.03 in 2013, indicating potential risks of temporary pollution episodes or lapses in control measures during specific periods. Indicators related to ecological environmental quality exhibit a more complex

pattern. The obstruction levels of green coverage rate (X8) and forest coverage rate (X9) are usually low but warrant attention. Notably, they peaked in 2018 and 2024, respectively. While the regional green space system is improving overall, localized degradation or insufficient maintenance persists. Performance in end-of-pipe environmental management seems relatively positive. The waste treatment rate (X18) and sewage treatment rate (X19) recorded a low level of obstacle degree in several years. Domestic waste and sewage treatment facilities have achieved relatively stable outcomes. However, caution is needed, since a low obstacle degree may reflect temporary management success rather than long-term structural improvements.

Meanwhile, total tourism revenue (X17), as a key indicator of regional economic performance, registered an obstacle degree exceeding 0.14 in several years, including 2010, 2011, and 2015. This shows that while the tourism economy drives development, it can also contribute to ecosystem instability when resource capacity is exceeded, highlighting the complex "ecology–economy" dual challenge.

The analysis of ecological security obstacles in the Zhangjiajie Scenic Area clearly shows how the main obstacle factors have changed over different stages. In the early 2010s, population pressure and land resource limits were the main obstacles; by the mid-2010s, focus shifted to the ecological effects of transportation infrastructure and reforestation projects; and at the end of the period, attention shifted to the quality of ecological restoration and the ecological strain caused by tourism. This change highlights the ongoing tension between the regional ecosystem and the socio-economic system and emphasizes the importance of shifting from isolated management actions to integrated and systematic regulation. Looking forward, efforts should aim to develop detailed monitoring and adaptive management systems for the interconnected ecological and socio-economic systems, improve early warning systems for ecological risks, and support the combined growth of ecological compensation and green tourism, all to achieve coordination between ecological protection with regional sustainable development.

4. Discussion

4.1. Main Findings

This study offers a 15-year empirical analysis of the tourism ecological security level in the Zhangjiajie Scenic Area, examining the interaction and harmony among its subsystems and identifying the main barriers. Research on tourism ecological security mainly focuses on individual provinces or multiple cities, often covering extensive areas. However, detailed studies on specific regions are still limited. This study concentrates on the Scenic Area, comprehensively assessing its tourism ecological security and the factors that impact it. The evaluation system created and the empirical results are reliable and provide valuable insights for future research on tourism ecological security in similar areas. Additionally, this study presents several significant findings.

1. Perturbation–Reaction–Governance Ternary Interaction as the Dominant Mechanism

Research findings confirm that the systemic evolution of tourism ecological security in the Scenic Area is not linearly driven by a single natural or socio-economic factor, but a nonlinear process involving the ternary coupling of "perturbation–reaction–governance". The "perturbation cluster", comprising population and environmental factors, pushes the system toward an unsafe threshold. The "reaction" subsystem, through feedback from variables such as arable land and forest cover, amplifies perturbation signals and transmits them to the governance subsystem. In response to these signals, society and government implement adaptive governance measures, forming a positive "institution–ecology" coupling that raises the overall security index to 0.519 in 2024, the highest level

recorded during the study period. This driving chain validates the PRG framework's explanation of "who drives" tourism ecological security: perturbations provide external shocks, reactions amplify and transmit the signals, and governance enables the system to surpass critical thresholds. In terms of the impact mechanism of tourism ecological security, some scholars have studied and analyzed the key factors affecting the ecological security of Tianmu Lake based on systems theory, environmental value theory, and human–land relationship theory, and they have elaborated in detail on the impact of the external environment on the ecological security of the system and the specific driving mechanism from the spatial and temporal scales [36]. Some scholars have also used the Pressure–State–Impact–Economic–Environmental–Social (PSR-EES) model to construct an evaluation index system for tourism ecological security in Huangshan City from the perspective of complex ecosystem theory and analyzed the driving mechanisms of tourism ecological security at different levels [37].

2. Stage-wise Transition of Driving Mechanisms

The obstacle degree model indicates that the key factors influencing the development of tourism ecological security varying at different stages. In the early and middle stages, the obstacle degree of cultivated land area (X7) was the main factor, indicating a land resource scarcity-driven mechanism. This shows that regional tourism development puts ongoing pressure on land resources, making cultivated land a critical constraint on the ecosystem's structural stability. The obstacle degree of road mileage (X3) increased in the middle to later stages, reflecting a shift toward a transportation expansion-driven mechanism. This means that while tourism continues to grow, it also spurred development of transportation infrastructure. However, expanding transportation facilities also created challenges for ecological systems, emphasizing the need to balance tourism growth with transportation development. At the same time, the obstacle degree of the artificial afforestation area (X14) remained important throughout the entire research timeline and became a key factor in the structure–function decoupling. This suggests that economic structural servitization has not been effectively linked with ecological restoration efforts, which could worsen ecosystem imbalances. Therefore, better coordination between these areas is necessary.

This step-by-step shift from "element–facility–structure–function" creates a three-dimensional framework—covering time, intensity, and type—to identify and evaluate the impact of driving factors. This directly helps guide the strategic change in ecological security governance in the Scenic Area.

4.2. Limitations and Prospects

This study has certain limitations. First, collecting data was difficult, mainly due to the lack of historical management data. Second, data from 2020 onward are incomplete due to exceptional circumstances such as the COVID-19 pandemic, which limits the overall comprehensiveness of the study. Continuous data collection and analysis should be conducted to ensure the accuracy and stability of the overall assessment. Additionally, there is no unified standard for the selection of tourism ecological security evaluation indicators. The establishment of the evaluation indicator system in this study may be subjective and needs further improvement. Finally, this paper does not predict future trends in ecological security status. Because ecological security has lagging and sudden characteristics, creating an early warning system based on time series analysis or multi-scenario simulations will be an essential focus for future research. In the future, the ecological security assessment system will be further refined and expanded to cover more protected areas, allowing for a quantitative evaluation of the distribution and intensity of ecological security. At the same time, by combining spatial and geographical analysis, the spatial distribution differences of tourism ecological security are studied and analyzed. This will strengthen the scientific

basis and data support for managing nature reserves, thereby contributing to developing a comprehensive natural resource governance system.

5. Conclusions

Using the Zhangjiajie Scenic Area as a case study, this research develops a PRG (perturbation–reaction–governance) evaluation index system for tourism ecological security, performs a quantitative assessment, and identifies key driving factors along with their levels of influence. It is found that the evolution of the tourism ecological security system in the Scenic Area is alternately driven by three types of forces: elements, facilities, and structure–function. These drivers work together to push the system's transformation through a process of "pressure accumulation–threshold breakthrough–institutional restoration," resulting in a V-shaped evolutionary pattern comprising "rapid degradation (2010–2014)—steady restoration (2015–2019)—impact rebound (2020–2024)".

The study explores the drives of the evolution of the tourism ecological security system: it is not due to a single natural or economic factor, but rather the dynamic and nonlinear interaction of the three PRG components—perturbation, reaction, and governance—which take turns influencing different stages. This process indicates the key role of policy intervention in reducing ecological damage. During the phased evolution of driving factors, cultivated land area (X7), proportion of the tertiary industry in GDP (X12), road mileage (X3), and artificial afforestation area (X14) emerged as the main drivers. These indicators reveal issues such as overexploitation of land resources, an unbalanced economic structure, and inadequate investment in ecological development. Consequently, they should be prioritized in future policy efforts. Furthermore, as the tourism industry continues to grow, the negative impacts of specific environmental indicators—such as air pollution, sewage, and waste management—have decreased yearly. This indicates that progress has been made in pollution control and basic environmental management in the Scenic Area, gradually strengthening its ecological foundation.

Overall, the ecological security system in the Zhangjiajie Scenic Area has steadily shifted from a high-risk state to one where risks are more controllable, with the regional ecosystem moving toward greater coordination and stability. However, underlying ecological security risks remain unresolved. Ongoing efforts are still required to increase the capacity of tourism resources, establish a long-term ecological governance mechanism, and promote mutually beneficial development between tourism and ecological conservation. Specifically, the use of arable land should be strictly regulated to prevent excessive encroachment by tourism facilities. In addition, with the continuous expansion of road networks, it is essential to actively promote green transportation to mitigate the ecological fragmentation caused by conventional roads. A long-term monitoring and evaluation mechanism for afforestation outcomes should be established, focusing not only on quantity but also on quality. More importantly, the resilience of the tourism ecosystem should be strengthened, especially in the post-pandemic era, where rapid recovery is of critical importance.

In summary, this paper systematically analyzes the tourism ecological security of the Zhangjiajie Scenic Area by proposing a new model, examines the coupled linear relationship between various subsystems, and analyzes the key factors driving tourism ecological security, providing a relatively novel perspective, reference, and guidance for other related research.

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