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Evaluating Ecological Security and Sustainability in Border Cities: A Case Study of the Transboundary Tumen River Region in China*

Qiuyun Liu Master's Student, College of Geography and Ocean Sciences, Yanbian University
Xinyu Liu Master's Student, College of Geography and Ocean Sciences, Yanbian University
Mingyu Li* Professor, College of Geography and Ocean Sciences, Yanbian University

The rapid growth of tourism highlights the critical need for evaluating ecological security to sustain urban ecosystems and align development with environmental priorities. This study examines the transboundary Tumen River region, focusing on the Yanbian Korean Autonomous Prefecture in China, by integrating the System Dynamics (SD) model with the Driving Force-Pressure-State-Impact-Response (DPSIR) framework. An ecological security evaluation index was developed to analyze spatiotemporal changes across five dimensions—driving force, pressure, state, impact, and response—from 2000 to 2020. The results revealed a "U-shaped" trend in ecological security, with scores declining between 2000 and 2010, followed by a significant improvement from 2010 to 2020. The observed recovery was primarily driven by reductions in the driving force and pressure indices, coupled with enhancements in the state, impact, and response indices. However, cities such as Yanji, Longjing, Tumen, and Hunchun exhibited lower ecological security scores due to factors such as meteorological variability, tourism-related pressures, declining resource quality, and reduced vegetation coverage. The findings of this study underscore the importance of cross-border cooperation among China, North Korea, and Russia to effectively manage shared ecosystems and address transboundary environmental challenges. Drawing on international governance models, this research offers actionable recommendations for achieving sustainable development in ecologically sensitive border regions.

Keywords Ecological Security, DPSIR Framework, System Dynamics (SD) Model, Border Cities, Cross-border Cooperation

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** Corresponding author (leemy@ybu.edu.cn)

I. Introduction

The rapid expansion of urbanization and economic development in border regions has brought significant growth opportunities, but it has also raised pressing sustainability challenges. Border cities, which often serve as hubs for international trade, cultural exchange, and regional cooperation, face unique ecological pressures due to their geographical and political complexities. Shared ecosystems, cross-border pollution, and inconsistent environmental policies between neighboring countries further exacerbate these challenges, posing significant threats to ecological security and sustainability (Li et al., 2019; Javarini & Vallim, 2022).

Ecological security refers to the ability of ecosystems to maintain their stability and resilience while supporting sustainable socio-economic development. It has emerged as a critical framework for addressing these challenges, especially in border regions where human activities intensify pressure on shared ecosystems. Effective land use policies that incorporate ecological considerations are essential for balancing economic growth with environmental sustainability in these areas (Ruan et al., 2019). This is particularly critical in transboundary regions where fragmented governance systems and conflicting policies make managing shared resources increasingly complex (Su, 2024).

The Tumen River region, encompassing parts of China, North Korea, and Russia, exemplifies the ecological challenges faced by border cities. Previous studies have extensively examined the ecological health of the Tumen River basin, with research focusing on biodiversity conservation, water quality assessments, and the impacts of urbanization on regional ecosystems (Chen et al., 2018; Zhang et al., 2020). For instance, Chen et al. (2018) analyzed the impacts of industrial pollution on the river's aquatic systems, revealing significant environmental degradation due to cross-border industrial activities. Similarly, Zhang et al. (2020) evaluated the basin's ecological security and highlighted the role of integrated governance frameworks in improving ecological outcomes. While these studies provide valuable insights, they primarily focus on specific environmental indicators, often overlooking the broader spatiotemporal dynamics of ecological security in the region. This study builds on these works by adopting a holistic approach that integrates multiple ecological, social, and economic factors, offering a comprehensive evaluation of the region's ecological security dynamics.

Yanbian Korean Autonomous Prefecture, located within the Tumen River region, serves as a vital intersection for cross-border economic cooperation and cultural exchange. Its strategic position, while fostering regional connectivity, places immense strain on local ecosystems. Shared rivers, forests, and biodiversity hotspots highlight the region's transboundary ecological interdependence. However, disparities in environmental policies and governance frameworks between the neighboring countries create challenges in managing resources sustainably. Effective ecological governance in the Tumen River region requires integrated policies that address transboundary environmental pressures while promoting local sustainability.

Governance models have proven instrumental in addressing such challenges in border regions worldwide. Successful examples include multi-stakeholder frameworks that engage governments, local communities, and international organizations. These models emphasize the importance of adaptive governance, transparent policymaking, and inclusive management strategies. For instance, the Alpine Convention in Europe demonstrates how international cooperation can balance economic development with ecological preservation in transboundary regions (Behrens et al., 2009). Similarly, collaborative initiatives between Thailand and Laos in managing shared ecological resources provide valuable lessons for balancing regional development with resource conservation (Kongbuamai et al., 2020). Drawing on these examples, cross-border regions like the Tumen River could benefit significantly from enhanced international collaboration and shared governance strategies.

This study contributes to the growing field of ecological security and sustainability research by providing a comprehensive evaluation of the Tumen River region. By integrating the System Dynamics (SD) model with the Driving Force-Pressure-State-Impact-Response (DPSIR) framework, this research examines the spatiotemporal patterns of ecological security in Yanbian Korean Autonomous Prefecture. This approach provides critical insights into the interactions between ecological, social, and economic factors that shape sustainability outcomes in border cities.

The challenges faced by the Tumen River region reflect broader global concerns in other border areas, such as the U.S.-Mexico border or the European Alps. These regions highlight the importance of transboundary cooperation in addressing ecological pressures that transcend political boundaries. This study fills a critical gap in the literature by focusing specifically on the internal dynamics of ecological security in border cities, offering a practical framework that can be adapted to other transboundary regions worldwide. By exploring the unique challenges of the Tumen River region, this research provides actionable recommendations for achieving ecological sustainability in border areas.

II. Materials and methods

1. Study area

Yanbian Korean Autonomous Prefecture, located in northeastern China,

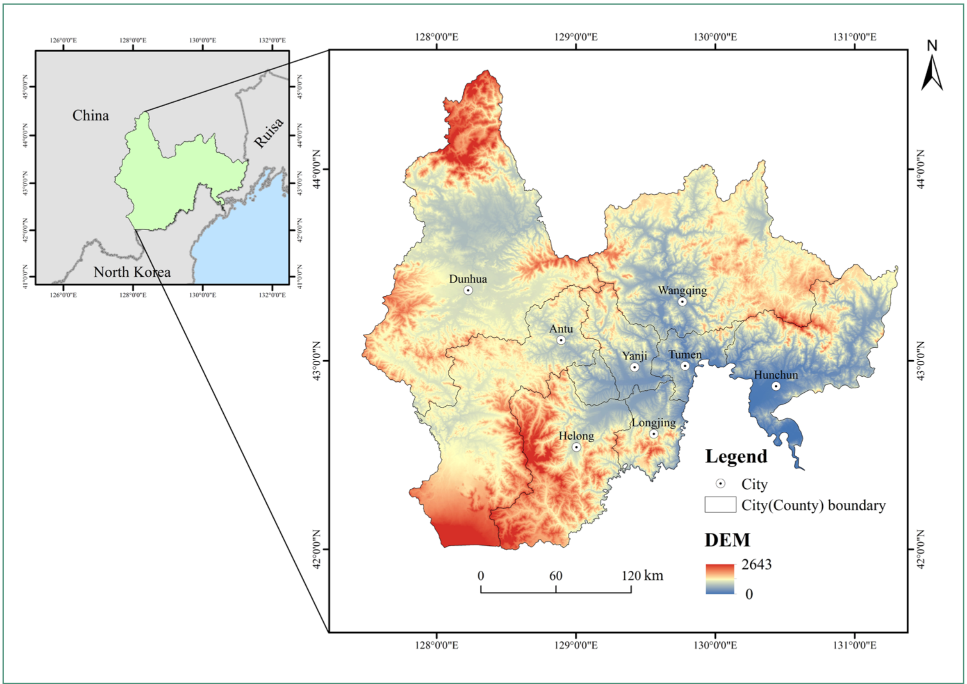

Fig. 1 Location of the Study Area.

lies at the tri-border junction of China, North Korea, and Russia. The prefecture spans 43,329.3 km² and has a border length of 768.5 km. Its geographical coordinates range from 41°9′47″ to 44°0′42″ North latitude and 127°7′43″ to 131°8′33″ East longitude (Fig. 1). Administratively, Yanbian comprises six county-level cities and two counties: Yanji City, Tumen City, Dunhua City, Longjing City, Helong City, Wangqing County, and Antu County. Among these, five jurisdictions share international borders, encompassing 22 border townships, 238 border villages, and 10 border ports (Jilin Province Statistics Bureau, 2024).

Yanbian is a region with substantial socio-economic activities, particularly in tourism, which significantly contributes to its economy. The area hosts diverse attractions, including 9 national-level, 4 provincial-level, and 65 prefectural-level destinations. In 2019, the prefecture recorded 27.51 million tourists, comprising 26.95 million domestic visitors and 565,800 international visitors, generating total tourism revenue of 55.53 billion yuan. Of this, domestic tourism contributed 53.75 billion yuan, while international tourism generated approximately 265 million USD. The tourism sector experienced a sharp decline from 2020 to 2022 due to the global pandemic. However, by 2023, the industry showed signs of recovery, with 26.46 million domestic tourists visiting the region, representing a 314% increase compared to the previous year. Domestic tourism revenue also surged to 43 billion yuan, reflecting a 409% year-on-year growth (Jilin Province Statistics Bureau, 2024).

2. Data sources

This study employs a comprehensive dataset combining remote sensing, meteorological, environmental, and socio-economic data from 2000 to 2020. Data were sourced from institutions such as the Resource and Environmental Science and Data Center, the China Earth System Science Data Center, the Jilin Province Environmental Quality Report, and the Yanbian Prefecture Statistical Yearbooks. Additional datasets, including Digital Elevation Model (DEM) data, administrative boundaries, and national borders, were incorporated to enhance spatial contextualization. To address data gaps and ensure analytical accuracy, systematic data cleaning, interpolation, and temporal alignment methods were implemented.

Table 1 summarizes the data sources, types, indicators, and resolutions used in this study. This diverse combination of datasets supports a comprehensive analysis of ecological security dynamics in the study area. Further details on variable definitions and data processing methods are provided in Sections II.2.1) and II.2.2)

Table 1 Summary of Data Sources and Resolutions

Data Type	Data Contents	Indicators Used	Data sources
Remote Sensing Data	Land use, Vegetation cover	P2, P6, I2,	Resource and Environmental Science and Data Center (http://www.resdc.cn/)
Meteorogical Data	Monthly precipitation, temperature, humidity	D4, D5, S5	China Earth System Science Data Center (http://www.geodata.cn/)
Environmental Quality Data	Eco-environmental quality, Environmental management input, Waste treatment rates	R4	Jilin Province Environmental Quality Report(http://tjj.jl.gov.cn/)
Socio-economic Data	Population, GDP, Tourism metrics (e.g., revenue, hotels, employees)	D1, D2, D3, P1, P3, P4, P5, S1, S2, S3, S4, I1, I3, R2, R3	Jilin Province Statistical Yearbook, Yanbian Korean Autonomous Prefecture Government (http://www.yanbian.gov.cn)
Other Data	National road data, DEM, Tourism infrastructure, Borders	R1	Geospatial Data Cloud Platform, Chinese Academy of Sciences (http://www.gscloud.cn/)

1) Variable Definitions and Specifications

This study integrates spatial and aspatial variables essential for analyzing ecological security dynamics and socio-economic interactions, particularly within the context of tourism impacts. These variables provide a comprehensive framework for evaluating both spatial and temporal ecological changes across the study area.

Spatial Variables: Spatially-referenced data include land use classifications, vegetation cover, and tourism resource quality, primarily derived from remote sensing data with a 30-meter spatial resolution to balance detail and computational efficiency.

Land Use Classification: Categories were standardized according to the International Geosphere-Biosphere Programme (IGBP) or equivalent systems, encompassing urban, agricultural, forest, and water bodies. This classification framework enables detailed analysis of land use shifts and their ecological implications.

Vegetation Cover: Derived from the Normalized Difference Vegetation Index (NDVI), vegetation cover serves as a proxy for ecological quality, capturing variations in vegetation density and health.

Aspatial Variables: Non-spatial indicators include population density, GDP per capita, tourism metrics (e.g., visitor counts, revenue), and environmental investment levels, allowing an in-depth examination of socio-economic drivers influencing ecological security.

Tourism Pressure Metrics: Tourism density and space indices were calculated to quantify tourism-related pressures on ecosystems, reflecting resource demands from increased visitor volumes and their impact on local infrastructure.

2) Data Processing

To ensure data consistency and support valid temporal and spatial comparisons, a structured data processing approach was applied:

① Missing Data Handling: Linear interpolation addressed missing values within time-series data, enhancing continuity across datasets, especially for tourism revenue and visitor metrics, supporting reliable trend analysis.

② Standardization and Normalization: Variables were standardized to mitigate scale differences. Positive indicators (e.g., vegetation cover) and negative indicators (e.g., tourism density) were normalized separately, ensuring unbiased contributions to the analysis.

③ Temporal Alignment: A weighted average approach reconciled datasets collected at varying intervals, maintaining temporal coherence and enabling consistent assessments of spatiotemporal trends throughout the study period.

3. Methods

This study employs an integrated approach, combining the System Dynamics (SD) model and the Driving Forces-Pressure-State-Impact-Response (DPSIR) framework, to evaluate ecological security in border cities. Socio-economic factors, including tourism, population growth, and industrial development, were considered critical influences. Fig. 2 illustrates the research framework and methodology.

1) System Dynamics (SD) Model

The System Dynamics (SD) model provides a structured framework for analyzing causal relationships among socio-economic factors, tourism pressures, and ecological outcomes. It captures the interactions within the ecological security system, utilizing empirical data and field surveys conducted in Yanbian Prefecture. Key inputs include historical records,

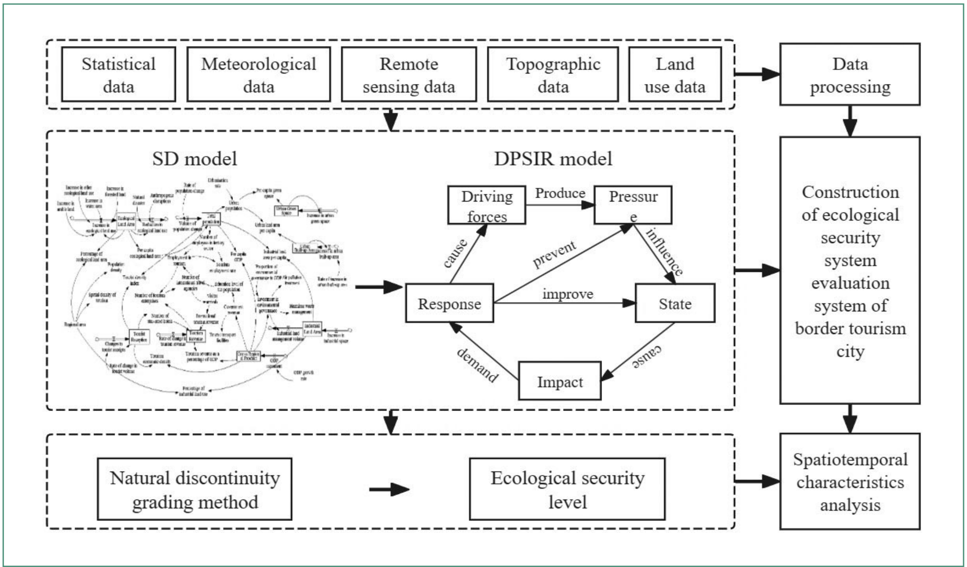

Fig. 2 Research Framework and Technological Approach

observational studies, and expert consultations, ensuring a comprehensive and robust analysis.

(1) Data Collection

Data collection efforts were organized around three key domains: environmental variables, socio-economic indicators, and tourism-related activities.

Environmental Variables: Data were obtained through site inspections of critical natural landscapes, biodiversity assessments, and monitoring of ecological parameters such as vegetation coverage and water quality.

Socio-Economic Indicators: These included population density, urbanization rates, and residents' quality of life, derived from local government reports, community surveys, and stakeholder interviews.

Tourism Data: Metrics such as visitor numbers, tourism revenue, and infrastructure development were sourced from local tourism bureaus and validated through interviews with industry professionals. Supplementary data, including satellite imagery, historical land use records, and meteorological information, were integrated to ensure data completeness.

(2) Subsystems of the SD Model

The SD model comprises three interrelated subsystems—Tourism-Socio-Economic, Tourism-Ecological Environment, and Tourism-Industry Development—each addressing specific aspects of ecological security dynamics in tourism cities.

① Tourism-Socio-Economic Subsystem

This subsystem models the relationships between population growth, urbanization, tourism consumption, and socio-economic outcomes (Fig. 3a).

Key Variables: Population growth drives urbanization and tourism demand, influencing environmental governance and residents' quality of life. Urbanization affects green space and built-up areas, reflecting the trade-offs between economic growth and environmental conservation.

Feedback Loops: A positive loop illustrates how increased tourism demand fosters urbanization, GDP growth, and employment. A negative loop shows how excessive urbanization reduces green space, adversely affecting residents' quality of life and tourism satisfaction.

② Tourism-Ecological Environment Subsystem

This subsystem examines interactions between tourism activities and ecological conditions (Fig. 3b).

Key Variables: Ecological health is shaped by positive factors such as environmental remediation and negative factors such as anthropogenic disturbances. Tourism revenue supports ecological restoration while simultaneously generating ecological pressures.

Feedback Loops: A virtuous cycle occurs when tourism revenue funds ecological remediation, improving ecological health and sustaining tourism demand. Conversely, a vicious cycle emerges when disturbances degrade natural landscapes, reducing ecological health and tourism attractiveness.

③ Tourism-Industry Development Subsystem

This subsystem illustrates the relationships among tourism resources, industry investments, and service quality (Fig. 3c).

Key Variables: Inbound tourism revenue supports infrastructure investments, while enterprises and professionals enhance service delivery. Tourist satisfaction drives demand and sustains industry growth.

Feedback Loops: A positive cycle highlights how increased revenue enhances tourism services and satisfaction. However, over-reliance on tourism revenue without sufficient ecological management poses risks to long-term sustainability.

(3) Comprehensive Integration

The three subsystems are integrated into a stock-and-flow diagram (Fig. 3d), capturing their interdependencies and overall impacts on ecological security.

Subsystem Interactions: For instance, urbanization within the socio-economic subsystem affects green space and ecological health in the ecological subsystem, while tourism revenue from the industry subsystem funds ecological remediation.

Cross-Subsystem Feedback Loops: Positive dynamics include tourism revenue supporting ecological restoration, while negative impacts stem from urbanization reducing ecological land.

(4) Alignment with the DPSIR Framework

The SD model's integration aligns with the Driving Forces-Pressure-State-Impact-Response (DPSIR) framework:

Driving Forces: Urbanization, tourism demand, and population growth.
Pressures: Expansion of built-up areas and ecological degradation.
State: Variables such as green space and ecological health.
Impacts: Changes in quality of life, tourism satisfaction, and ecological conditions.
Responses: Investments in governance and remediation.

This integrated approach facilitates a holistic understanding of the factors influencing ecological security in tourism cities, providing valuable insights for targeted policy interventions.

2) DPSIR Framework

The DPSIR framework, established by the European Environment Agency, organizes indicators into five dimensions—Driving Forces,

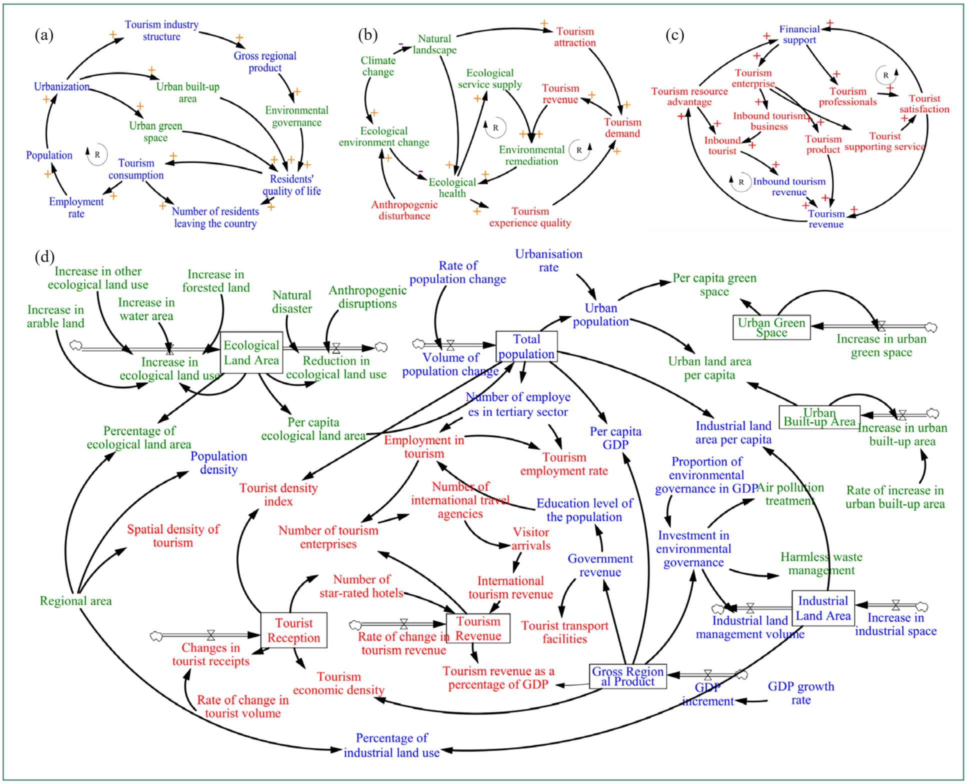

Fig. 3 (a) Causal Feedback Diagram of the Tourism-Socioeconomic Subsystem; (b) Causal Feedback Diagram of the Tourism-Ecological Subsystem; (c) Causal Feedback Diagram of the Tourism-Industry Subsystem; (d) Stock-and-Flow Diagram of the Ecological Security System for Tourism Cities

Pressure, State, Impact, and Response. This systematic classification enables a comprehensive analysis of the drivers and pressures shaping ecological states in tourism cities. Building on the System Dynamics (SD) model's stock-and-flow diagram, the DPSIR framework integrates 23 indicators across three levels—goal, criterion, and indicator layers (Table 2). These indicators were selected based on their relevance to ecological security, ensuring a balanced representation of socioeconomic, environmental, and industrial dimensions.

Indicators were identified through a rigorous review of literature on

Table 2 Weights of Ecological Security Evaluation Indicators in Yanbian Korean Autonomous Prefecture

Target layer	Criteria layer	Index layer	Subjective weight	Objective weight	Comprehensive weight
Ecological security evaluation index of Yanbian prefecture	Driving forces (0.2388)	D1-Natural rate of population growth (%)	0.029019	0.03803	0.039924498
		D2-Gross national product per capita (Yuan)	0.018678	0.07163	0.043958751
		D3-Urbanization rate (%)	0.102621	0.02957	0.066203191
		D4-Annual mean temperature (℃)	0.036022	0.04327	0.047447129
		D5-Total precipitation(mm)	0.042516	0.02775	0.041280354
	Pressure (0.2183)	P1-Population density (Person·km^{-2})	0.045713	0.02557	0.041088389
		P2-Urban built-up area(km^2)	0.043218	0.02391	0.038632686
		P3-Tourism traffic pressure	0.028521	0.03071	0.035567919
		P4-Tourism space index	0.019960	0.01637	0.021723855
		P5-Tourism density index	0.019572	0.03656	0.032148141
		P6-The proportion of industrial land area (%)	0.080906	0.02065	0.049123016
	State (0.1886)	S1-Green coverage rate of built-up area (%)	0.045610	0.02504	0.040614421
		S2-Tourism resource quality	0.017752	0.07108	0.042690502
		S3-Tourism income (Hundred million yuan)	0.017897	0.10064	0.051004610
		S4-Number of star-rated hotels	0.009028	0.09894	0.035918140
		S5-Temperature and humidity index	0.008867	0.02643	0.018397958
	Impact (0.2028)	I1-Per capita green space(m^2)	0.147837	0.04629	0.099419223
		I2-Vegetation coverage	0.131518	0.02488	0.068746779
		I3-Per capita income (Ten thousand yuan)	0.018621	0.04470	0.034672798
	Response (0.1514)	R1-Supporting capacity of tourism transportation	0.011524	0.04516	0.027416201
		R2-Number of people employed in tourism (Person)	0.011043	0.11066	0.042012301
		R3-Environmental governance as a proportion of GDP (%)	0.074296	0.03345	0.059912256
		R4-Garbage harmless disposal rate (%)	0.039263	0.00861	0.022096881

ecological security and tourism sustainability, supported by reliable data from government reports and satellite observations. Expert consultations further validated the indicators, ensuring relevance and comprehensiveness.

Preliminary statistical analyses confirmed the analytical significance and interconnections of these indicators within the framework, capturing the complex dynamics influencing ecological security in tourism cities.

(1) Indicator Weighting and Data Processing

To determine the relative importance of each indicator within the DPSIR framework, a combined weighting approach was adopted, integrating subjective expert insights and objective data-driven metrics to ensure a balanced and robust evaluation.

① Indicator Weigh ting

Subjective Weights: Subjective weights were derived using the Analytic Hierarchy Process (AHP). A panel of experts with extensive experience in environmental science and sustainable tourism conducted pairwise comparisons of indicators, assessing their relative importance based on their expertise. These evaluations provided the basis for calculating subjective weights.

Objective Weights: The Entropy Method was employed to calculate objective weights by analyzing the variability of each indicator. This data-driven approach complemented the qualitative assessments obtained from the AHP process.

Integration of Weights: The subjective and objective weights were integrated using the Lagrangian multiplier method, minimizing information entropy to achieve an unbiased weighting scheme. This integration harmonized expert insights with empirical data, enhancing the transparency and robustness of the evaluation framework.

② Selection of Experts for AHP

The AHP panel consisted of professionals and researchers from leading academic institutions and organizations specializing in environmental management, ecological modeling, and tourism development. These experts were selected based on their academic credentials and professional expertise, ensuring a multidimensional perspective on indicator prioritization.

③ Transparency of the Process

To ensure reproducibility, the revised manuscript provides a detailed outline of the weighting process, which includes conducting pairwise comparisons in the Analytic Hierarchy Process (AHP) to derive subjective weights, calculating indicator variability using the Entropy Method to obtain objective weights, and integrating both subjective and objective weights to compute comprehensive weights. This step-by-step description ensures clarity and facilitates the replication of the methodology.

(2) Data Standardization

To facilitate comparability across datasets, missing values in time-series data were interpolated, and all data were normalized using the Range Method. Positive and negative indicators were standardized as follows:

$$\text{Positive indicators: } P_{ij} = \frac{(X_{ij} - X_{jmin})}{(X_{jmax} - X_{jmin})} \tag{1}$$

$$\text{Negative indicators: } P_{ij} = \frac{(X_{jmax} - X_{ij})}{(X_{jmax} - X_{jmin})} \tag{2}$$

Where X_{ij} represents the raw value of the j-th indicator in year i, P_{ij} is the standardized value, and X_{jmin} and X_{jmax} are the minimum and maximum values, respectively.

(3) Model Validation and Scenario Analysis

The SD model was validated through regression testing, achieving a 95% accuracy rate in predicting historical ecological data from 2000–2020.

Scenario simulations further assessed the impacts of various policy interventions, including tourism restrictions, environmental investments, and cross-border cooperation, providing actionable insights for decision-making.

(4) Ecological Security Index (ESI) Calculation

Using the DPSIR framework's dimensions—Driving Forces, Pressure, State, Impact, and Response—annual ecological security scores were computed on a scale from 0 to 1. These scores were used to classify ecological security levels in Yanbian Prefecture's tourism cities into five categories: Low, Low-Medium, Medium, Medium-High, and High (Sui et al., 2024).

III. Results

1. Spatial and Temporal Variation of Ecological Security Indices

The ecological security indices for Yanbian Prefecture—including the Driving Forces Index, Pressure Index, State Index, Impact Index, and Response Index—were analyzed for 2000, 2010, and 2020. These indices were classified into five levels (Low, Low-Medium, Medium, Medium-High, and High), and their spatiotemporal variations were visualized through heat maps to identify key trends.

1) Driving Forces Index

The Driving Forces Index reflects environmental and socioeconomic pressures, such as population growth and economic activity, that influence ecological systems. Fig. 4 illustrates the spatiotemporal variation of this index across Yanbian Prefecture from 2000 to 2020.

2000: The highest values were concentrated in Antu County in the western region, driven by high precipitation and socioeconomic pressures, while Yanji City in the central area recorded the lowest values, indicating lower environmental and demographic pressures.

2010: Wangqing County in the northeast showed the highest index, reflecting shifts in population and environmental factors, while Hunchun City in the southeast recorded the lowest, indicating relative stability in socioeconomic and environmental conditions.

2020: Helong City in the southern region exhibited the highest index due to economic activity and tourism growth, whereas Dunhua City in the north recorded the lowest values, attributed to declining population and precipitation levels.

The trends in the Driving Forces Index highlight the dynamic interplay between natural and anthropogenic pressures. Regions like Antu and Dunhua experienced significant changes influenced by variations in precipitation and population dynamics, making them vulnerable to both environmental and socioeconomic challenges. Conversely, regions like Hunchun and Helong showed more stability, reflecting consistent

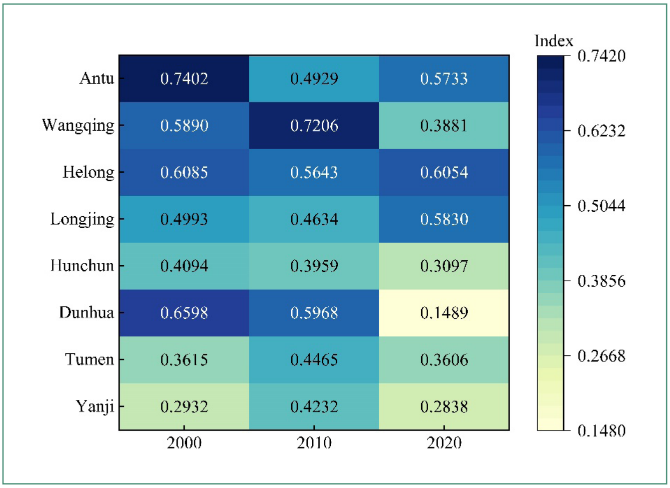

Fig. 4 Heat map of the Driving Forces Index (2000–2020)

management or environmental conditions.

The overall decline in the index in northern cities, such as Dunhua, suggests reduced pressures due to population decline and improved environmental management. However, this trend raises concerns about economic sustainability in these areas. Policymakers should adopt tailored strategies to address regional challenges, promoting sustainable development while managing environmental pressures effectively.

2) Pressure Index

The Pressure Index captures tourism-related stresses, including infrastructure demands and resource utilization, across Yanbian Prefecture from 2000 to 2020. Heat maps of its spatiotemporal variation (Fig. 5) highlight key trends in the southeastern regions, particularly Longjing and Helong, which consistently exhibited high Pressure Index values due to substantial tourist inflows and infrastructure limitations. In contrast, central regions such as Yanji maintained lower values, indicating more resilient infrastructure.

Key temporal trends show that by 2010, Helong City surpassed Longjing in Pressure Index values, reflecting an increase in tourism pressures. By 2020, Helong maintained its high index, while Yanji continued to show resilience with the lowest values, suggesting effective management of tourism impacts. Meanwhile, Antu County displayed the most significant growth in pressure, with its transportation and tourism density indices surging nearly 90-fold between 2000 and 2020, driven by rapid tourism infrastructure expansion.

The trends reveal uneven tourism development across the prefecture. Helong and Antu counties experienced mounting pressures, emphasizing the need for sustainable tourism strategies to manage resource and infrastructure demands. In contrast, areas like Wangqing County

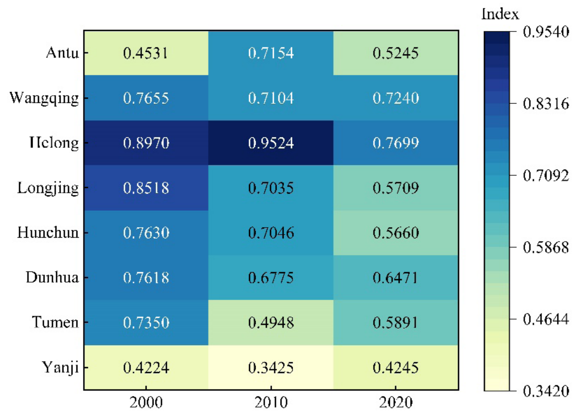

Fig. 5 Heat map of the Pressure Index (2000–2020)

demonstrated stability, suggesting effective management or slower tourism growth. Addressing these disparities through balanced tourism development and resource conservation strategies will be crucial for ensuring the sustainable growth of tourism across Yanbian Prefecture.

3) State Index

The State Index reflects the condition of tourism resources and ecological systems in Yanbian Prefecture. Heat maps in Fig. 6 highlight significant regional disparities from 2000 to 2020, emphasizing the varying pace of tourism development across the prefecture.

From 2000 to 2010, the central and western regions demonstrated higher State Index values, with Yanji City standing out due to its advanced tourism infrastructure and economic prominence. Antu County also showed notable improvement, driven by the development of attractions such as the 4A-rated Antu Changbai Mountain Gorge Pumice Forest Scenic Area. In contrast, Helong City consistently recorded lower values, reflecting a lag in tourism resource development.

By 2020, Dunhua City emerged as the highest-ranking area, surpassing

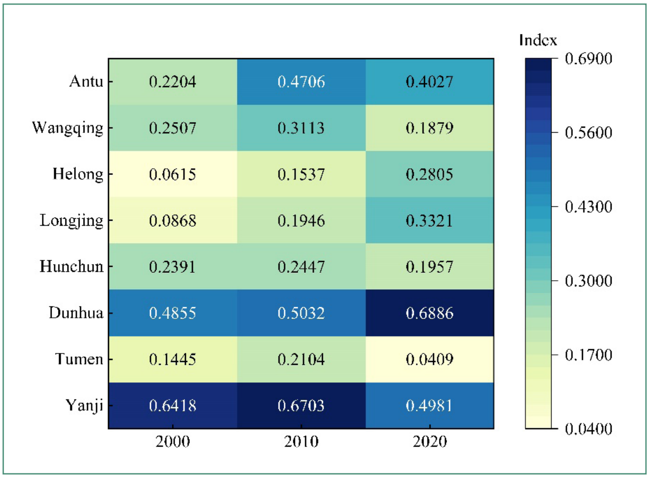

Fig. 6 Heat map of the State Index (2000–2020)

Yanji City, due to investments in star-rated tourist attractions such as the 5A-rated Liuding Mountain Cultural Tourism Area and the 4A-rated Yanming Lake Hot Spring Resort. Tumen City, on the other hand, exhibited the lowest State Index, indicating slower tourism development compared to other regions.

The trends in the State Index underscore disparities in tourism resource development. Counties like Antu and Dunhua, which invested strategically in high-quality attractions, saw significant growth in tourism-driven development, serving as models for enhancing regional competitiveness. Conversely, areas such as Tumen and Helong lagged, highlighting the need for balanced investment and equitable resource allocation across the prefecture.

In summary, the evolution of the State Index reveals uneven tourism development in Yanbian Prefecture. While the central and western regions experienced significant progress, southeastern areas struggled to keep pace. To promote sustainable and equitable growth, targeted investments in underdeveloped areas and the strategic promotion of local resources are essential.

4) Impact Index

The Impact Index measures environmental and human-induced pressures across Yanbian Prefecture from 2000 to 2020. Heat maps in Fig. 7 show significant spatial variations, with shifts in high-impact areas over time.

In 2000 and 2010, northwestern regions, particularly Dunhua City, recorded the highest Impact Index, reflecting pressures from urbanization, industrial activity, and population density. By 2020, the highest values shifted to southwestern and southeastern areas, with Antu County experiencing increased pressures from tourism, infrastructure development, and land-use changes near Changbai Mountain. In contrast, Yanji City consistently recorded the lowest values, suggesting effective environmental management or reduced population pressures.

Targeted regional strategies, such as urban greening in Wangqing County, which increased per capita green space from 1.69 m² in 2000 to 8.26 m² in 2010, and Longjing City's vegetation coverage expansion from 85.49% to 88.31% between 2010 and 2020, significantly reduced environmental stress. These improvements highlight the success of policies prioritizing afforestation, habitat protection, and urban sustainability.

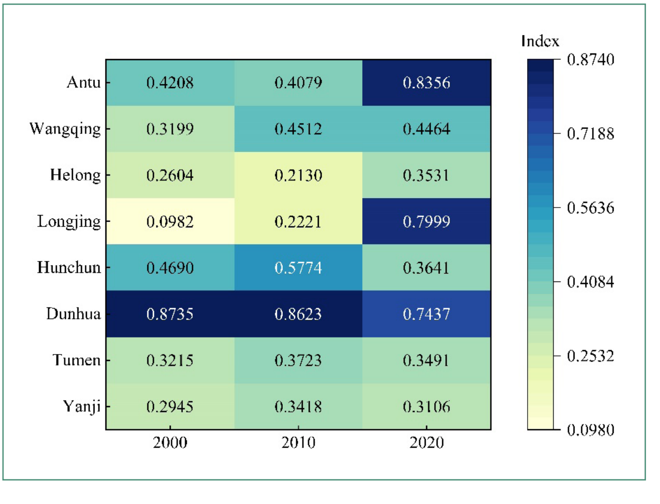

Fig. 7 Heat map of the Impact Index (2000–2020)

The Impact Index trends reveal uneven distribution of environmental pressures. Regions like Dunhua and Antu faced heightened impacts due to tourism and urbanization, while Wangqing and Longjing benefited from proactive ecological management. Addressing these disparities will require continued investment in green space expansion, sustainable tourism practices, and conservation policies to ensure balanced development and reduced ecological stress across the prefecture.

5) Response Index

The Response Index reflects the capacity of regions in Yanbian Prefecture to address environmental challenges through infrastructure development, policy implementation, and management efforts. Fig. 8 visualizes key spatiotemporal changes in the Response Index from 2000 to 2020 (Fig. 8).

From 2000 to 2010, Helong City demonstrated the most significant improvement, driven by investments in tourism infrastructure and increased allocation of GDP to environmental management, which rose from 4.34% to 7.51%. Conversely, Hunchun City recorded consistently low Response Index values, indicating persistent challenges in environmental governance and sustainability practices.

Between 2010 and 2020, Wangqing County emerged as the leader in the Response Index, reflecting enhanced ecological management and increased investments in environmental protection. Meanwhile, Longjing City showed notable growth in tourism employment but experienced a sharp decline in the proportion of GDP dedicated to environmental management, from 7.9% to 1.11%, highlighting an imbalance between economic expansion and ecological sustainability.

Overall, the Response Index trends reveal disparities in regional capacities to manage environmental pressures. Regions such as Helong and Wangqing benefited from targeted investments, while others, such

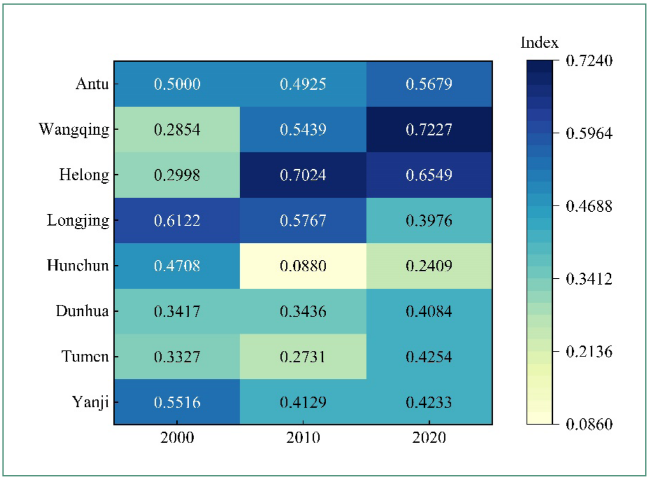

Fig. 8 Heat map of the Response Index (2000–2020)

as Hunchun, struggled with limited resources and policy focus. Longjing's rapid tourism growth and declining environmental investments further underscore the importance of balancing economic and ecological priorities.

To achieve sustainable growth across Yanbian Prefecture, it is essential to strengthen environmental governance in underperforming regions and ensure balanced investment in infrastructure and ecological management. Prioritizing sustainable practices will enable the prefecture to effectively mitigate the environmental impacts of tourism and urbanization.

2. Evaluation and Analysis of Ecological Security Subsystems in Border Cities

Fig. 9, integrated with the DPSIR model, illustrates the temporal evolution of ecological safety across Yanbian Prefecture's cities from 2000 to 2020. This analysis identifies the key factors influencing ecological safety during this period and offers insights into the dynamics of each subsystem.

1) Driving Forces Index

The Driving Forces Index remained relatively stable from 2000 to 2010,

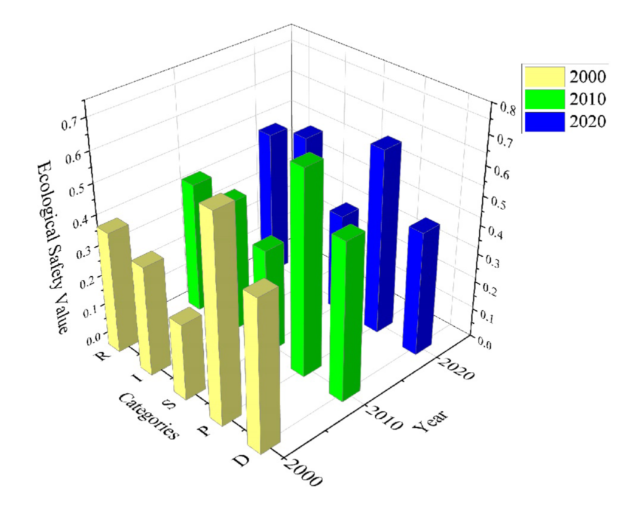

Fig. 9 Ecological security values for each subsystem (2000–2020)

reflecting consistent trends in population growth, economic activity, and resource utilization. However, from 2010 to 2020, the index declined significantly from 0.5130 to 0.4066.

Key contributors to this decline include reductions in natural population growth, urban migration, and declining birth rates, which collectively reduced the availability of human capital to support tourism development. Additionally, rising annual temperatures, likely driven by climate change, negatively affected ecosystems and tourism landscapes. Decreased precipitation further strained the region's ecological balance, exacerbating challenges for tourism reliant on natural resources. These factors collectively weakened the foundational drivers supporting ecological and tourism stability.

2) Pressure Index

The Pressure Index exhibited a general downward trend from 2000 to 2020, despite rising tourism pressures such as increased transportation demands and tourism density. This decline can largely be attributed to urban expansion, which redistributed human activity and reduced pressures on ecologically sensitive areas.

Infrastructure enhancements, particularly in tourism transportation, played a critical role in managing tourist inflows and mitigating localized environmental stress. Similarly, urban development shifted human activities away from vulnerable ecosystems, reducing direct ecological impacts. These trends highlight the importance of strategic infrastructure development and urban planning in balancing tourism growth with ecological conservation.

3) State Index

The State Index, representing the condition of tourism and ecological systems, improved significantly between 2000 and 2010. This improvement was driven by investments in new and upgraded tourist attractions, which concentrated visitor activity in well-managed areas, thereby preserving natural ecosystems and mitigating environmental impacts.

From 2010 to 2020, the State Index stabilized, reflecting sustained earlier improvements. However, further enhancements are needed to continue advancing ecological health. The development of high-quality attractions and improved management practices in high-traffic areas proved essential in maintaining this stability, underscoring the need for continued investment in sustainable tourism practices.

4) Impact Index

The Impact Index increased significantly from 0.3822 in 2000 to 0.5253 in 2020, indicating heightened environmental and social pressures stemming from tourism expansion. This increase reflects greater impacts on local infrastructure, ecosystems, and community dynamics.

Urban greening initiatives significantly contributed to this trend by expanding per capita green space, which improved air quality, enhanced biodiversity, and mitigated urban heat island effects. While these efforts offset some negative impacts, the rising index underscores the need to balance tourism growth with ecological sustainability, emphasizing the importance of proactive strategies to mitigate long-term pressures.

5) Response Index

The Response Index remained stable from 2000 to 2010 but showed notable improvements from 2010 to 2020, highlighting an enhanced capacity to address environmental challenges. Key improvements included the expansion of the tourism workforce, which strengthened the ability to manage increasing tourist numbers while minimizing environmental impacts. Enhanced waste treatment rates further demonstrated increased investments in managing tourism-related environmental consequences.

These advancements underline a growing commitment to sustainability, supported by infrastructure upgrades that met the rising demands of the tourism sector while protecting ecological integrity. However, regional variations suggest the need for consistent investment across all areas to ensure equitable progress.

6) Overall Trends and Implications

Between 2000 and 2020, the Driving Forces and Pressure Indices declined, reflecting reduced environmental pressures and improved management of stressors like population growth and resource utilization. Conversely, the State, Impact, and Response Indices improved, demonstrating significant progress in balancing tourism development with ecological preservation.

Despite these advancements, challenges persist. Declining population growth, reduced precipitation, and long-term environmental vulnerabilities pose risks to ecological stability. Continued investment in green infrastructure and the promotion of sustainable tourism practices will be essential to addressing these challenges. Policymakers must prioritize strategies that balance tourism growth with environmental conservation to ensure long-term sustainability.

In conclusion, the DPSIR analysis highlights the intricate interplay of environmental pressures, ecosystem conditions, and human responses. While tourism development has positively contributed to the region, addressing underlying driving forces and pressures remains critical for ecological stability. Strategic planning, targeted infrastructure investments, and sustainable tourism promotion will be indispensable in safeguarding ecological integrity while fostering sustainable growth.

3. Temporal and Spatial Evolution of Ecological Security Patterns in Border Cities

Fig. 10 and 11, combined with the DPSIR model, illustrate the temporal and spatial variations in the Ecological Safety Index across Yanbian Prefecture from 2000 to 2020. The analysis identifies four distinct ecological safety patterns—"Low-High-High," "High-Low-Low," "High-Low-High," and "Low-High-Low"—representing diverse ecological trajectories and regional disparities.

1) "Low-High-High" Pattern: Antu County and Helong City

Antu County and Helong City exhibit a "Low-High-High" pattern, demonstrating consistent improvement in ecological safety over the 20-year period. Initially low in ecological safety in 2000, these cities experienced steady progress, reaching their highest levels by 2020.

This improvement can be attributed to strengthened environmental management practices, including sustainable resource utilization and conservation initiatives. For example, Antu County prioritized sustainable tourism in the Changbai Mountain region, successfully balancing tourism development with environmental protection. Key drivers included investments in tourism infrastructure, green space expansion, and enhanced waste management systems. Additionally, economic diversification that reduced reliance on environmentally intensive industries further supported this upward trend. As depicted in Fig. 10, these developments highlight the potential of eco-tourism in enhancing ecological stability.

2) “High-Low-Low” Pattern: Tumen, Dunhua, and Hunchun Cities

Tumen, Dunhua, and Hunchun follow a “High-Low-Low” pattern, characterized by an initially high level of ecological safety in 2000, followed by consistent decline in subsequent decades. This trend reflects the growing pressures that compromised ecological integrity, including rapid urbanization and insufficient environmental planning. For instance, Tumen’s unchecked urban expansion increased ecological stress due to inadequate environmental safeguards. Additional contributing factors included poor waste management, deforestation, and resource overexploitation. Industrial activities and unregulated tourism also exacerbated environmental pressures in Dunhua and Hunchun. As shown in Fig. 10, this downward trend underscores the need for revised urban planning strategies and stricter environmental regulations to mitigate ongoing ecological degradation.

3) “High-Low-High” and “Low-High-Low” Patterns

Cities exhibiting the “High-Low-High” and “Low-High-Low” patterns demonstrate fluctuating ecological safety, reflecting variability in the effectiveness of environmental management. The “High-Low-High” pattern involves an initial decline in ecological safety from 2000 to 2010, followed by recovery by 2020, likely driven by efforts such as reforestation, pollution control measures, and habitat restoration. Adaptive policies addressing

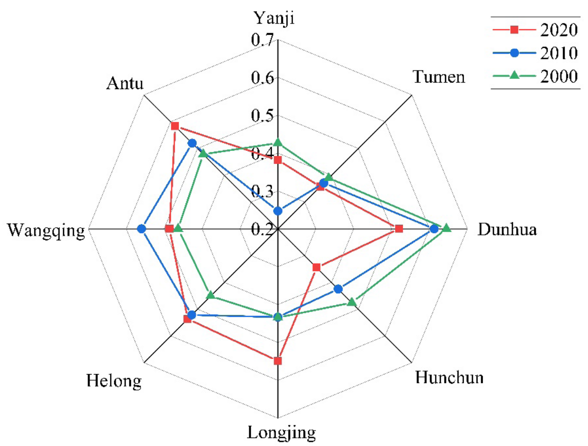

Fig. 10 Changes in Ecological Security Index in Yanbian Prefecture

earlier environmental challenges likely contributed to this recovery, as depicted in Fig. 10. Conversely, the "Low-High-Low" pattern indicates improvements in ecological safety from 2000 to 2010, followed by a decline by 2020, potentially due to renewed pressures stemming from resource exploitation and unsustainable urbanization. These patterns highlight the challenges faced by cities in maintaining long-term ecological stability under fluctuating environmental and socioeconomic conditions.

4) Regional Insights and Spatial Analysis

The spatial analysis of ecological safety across Yanbian Prefecture reveals a notable divide between the western and eastern regions (Fig. 11). Over the 2000–2020 period, the western region consistently recorded higher ecological safety levels than the eastern region. For instance, Dunhua exhibited the highest ecological safety index in 2000, while Tumen recorded the lowest. By 2020, this pattern persisted, with the western region maintaining its ecological advantage. Antu County, in particular, demonstrated significant progress, while Hunchun continued to face

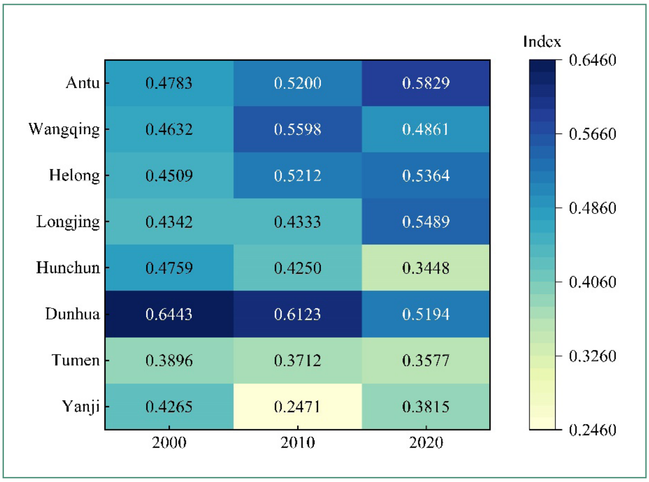

Fig. 11 Heat map of the of Ecological Security Index in Border Cities (2000–2020)

heightened environmental pressures.

These patterns underscore the dual role of tourism as both an economic driver and a potential ecological burden. For example, Antu leveraged sustainable tourism to improve ecological safety, while cities such as Tumen and Dunhua suffered environmental degradation due to overdevelopment. This contrast highlights the necessity of sustainable tourism practices that prioritize ecological preservation alongside economic benefits. Cities experiencing declines or fluctuations in ecological safety often face infrastructure limitations or weak policy enforcement. Effective resource management, such as green space expansion and comprehensive waste management, correlates with more stable ecological conditions (Fig. 11).

5) Strategic Recommendations for Sustainable Development

To enhance ecological stability across Yanbian Prefecture, strategic interventions include strengthening environmental regulations, promoting sustainable tourism, and encouraging regional collaboration. Reinforcing enforcement mechanisms is critical, particularly in “High-Low-Low” cities, to mitigate ongoing ecological degradation and ensure compliance with environmental standards. Implementing eco-friendly practices in ecologically sensitive areas can balance economic growth with environmental preservation, reducing the negative impacts of tourism while supporting long-term ecological integrity. Additionally, fostering regional collaboration among cities to share best practices in urban planning, waste management, and tourism development can harmonize ecological outcomes and promote sustainable growth across the prefecture.

IV. Discussion

The findings and analyses presented in this study are discussed in terms of their novelty, key findings, policy implications, and limitations, offering a holistic perspective on ecological security in border cities.

1. Novelty and Contribution to the Field

This study addresses a critical gap in the literature by providing a comprehensive temporal and spatial analysis of factors shaping ecological security in border cities. Unlike macro-level studies such as Zhang et al. (2023), which explore broader spatial regions, this research delves into the specific socioeconomic and environmental dynamics of tourism-dependent border cities. By identifying distinct ecological safety trajectories—such as the “Low-High-High” pattern in Antu County and Helong City, which saw their ecological safety scores rise from 0.423 (2000) to 0.687 (2020), it introduces a practical framework for assessing regional disparities and deriving actionable insights for localized policies (Fig. 10).

A key contribution of this study is the consideration of tourism types and the diversity of attractions, which significantly impact ecological security.

For instance, Antu County's investments in eco-tourism saw a surge in tourism revenue by 90%, coupled with an improvement in vegetation coverage from 73.42% (2000) to 85.62% (2020). Conversely, urban tourism hubs like Yanji, which experienced higher visitor density, faced ecological pressures that hindered their ability to achieve similar gains.

The integration of the System Dynamics (SD) model with the DPSIR framework enhances traditional ecological assessments by explicitly linking socio-economic drivers—such as tourism and urbanization—with ecosystem dynamics. For example, the Driving Forces Index, which dropped from 0.513 (2010) to 0.406 (2020), highlights how reduced population growth and urban migration mitigated pressures on natural resources. This dynamic methodology captures feedback mechanisms unique to border tourism cities, enabling policymakers to anticipate long-term impacts of interventions on ecological security.

2. Key Findings and Comparison with Existing Studies

The findings align with global research that connects tourism-induced environmental degradation, urbanization, and resource management (Zou et al., 2021). However, this research diverges from broader analyses, such as Zhang et al. (2023), by isolating the ecological challenges unique to border cities. For instance, Tumen City, which experienced a decline in ecological safety from 0.611 (2000) to 0.477 (2020), faces challenges from unchecked urban expansion and resource overexploitation. This decline contrasts with the upward trajectory in Antu County, underscoring the importance of tailored local strategies.

In cities like Dunhua, proactive environmental policies-such as afforestation efforts, which increased green coverage from 78.49% (2000) to 82.71% (2020)-demonstrate the benefits of sustainable resource management. These cases validate the efficacy of eco-tourism models to balance economic growth with environmental preservation.

3. Implications for Policy and Regional Development

This study offers actionable recommendations for policymakers to promote sustainable development in border regions. Unlike macro-level policy proposals such as those in Zhang et al. (2023), this localized approach enables targeted interventions to address specific disparities. For example:

Eco-tourism hubs like Antu: Continued investments in conservation and infrastructure could sustain ecological advantages. Between 2010 and 2020, GDP allocation to environmental management increased by 3.5 percentage points, correlating with notable gains in ecological indices.

Urban centers like Yanji: Targeted infrastructure upgrades, particularly in waste management, are essential to address pressures from visitor density, which rose by 12% annually between 2000 and 2020.

Sustainable tourism management, including eco-friendly accommodations, is critical in high-pressure areas such as the "Yanji-Longjing-Tumen" corridor, where the Pressure Index remained above 0.6 throughout the study period. Regional collaboration across borders is essential to address shared ecological challenges, particularly in transboundary areas where environmental pressures are compounded by governance disparities (Ren et al., 2023).

4. Research Limitations and Future Directions

While this study provides valuable insights, certain limitations should be addressed in future research. For example, reliance on ecological indices—such as the Response Index, which improved from 0.461 (2000) to 0.578

(2020)—provides a broad overview but does not fully capture nuances like biodiversity loss. Incorporating additional indicators, such as soil quality and water availability, could refine the analysis.

Advancements in GIS technology could facilitate finer spatial analyses, revealing subtle ecological patterns. For example, county-level variations in vegetation coverage highlighted through NDVI data (Antu: 85.62% in 2020 vs. Yanji: 68.24% in 2020) could be extended to micro-level studies for targeted interventions.

Future research should also expand its scope to include cross-border trade impacts and transboundary pollution, as cities like Hunchun and Longjing recorded rising environmental pressures despite modest improvements in green space. This underscores the need for coordinated strategies in shared ecosystem management.

V. Conclusion

This study examines the ecological security dynamics of border cities along the Tumen River in Northeast China, focusing on socio-economic pressures such as tourism and urban development. By integrating the SD model with the DPSIR framework, the research provides a detailed spatiotemporal analysis of ecological security indices—driving forces, pressure, state, impact, and response—from 2000 to 2020. These findings contribute to strategies for ecological protection and sustainable development in Yanbian Prefecture.

During the 20-year period, ecological security in Yanbian Prefecture followed a “U-shaped” trajectory, characterized by a decline from 2000 to 2010 and subsequent improvement from 2010 to 2020. This trend reflects reductions in driving forces and pressure indices, alongside increases in state, impact, and response indices, resulting in overall enhancement. Key contributing factors included meteorological conditions, tourism traffic pressure, vegetation coverage, and GDP allocation to environmental management. However, cities like Yanji, Longjing, Tumen, and Hunchun exhibited relatively lower scores, requiring targeted policy interventions.

The integration of localized findings with broader transboundary frameworks underscores the potential for scalable approaches to ecological security. This work provides a critical reference for policymakers and researchers striving to harmonize development with environmental preservation in sensitive border regions.

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