Environmental and Sustainability Indicators 28 (2025) 100875

Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.sciencedirect.com/journal/environmental-and-sustainability-indicators

Spatiotemporal dynamics and multidimensional drivers of tourism development-ecological resilience coupling coordination in Jiangxi Province, China

Xingxing Wang [a,b], Sunhee Suk [c], Novelia Triana [c], Yuting Xue [a], Xiuben Ma [a], Fenghua Liu [a], Liguo Wang [a], Yiming Liu [a,*]

[a] School of Land resources and environmental, Jiangxi Agriculture University, Nanchang, 330045, China
[b] School of Business, Belarusian State University, Minsk, 220070, Belarus
[c] Graduate School of Fisheries and Environmental Sciences Nagasaki University, Nagasaki, 852-8521, Japan

ARTICLE INFO

Keywords:
Tourism development
Ecological resilience
Habitat quality
Modified coupling coordination degree model
Influencing mechanisms

ABSTRACT

Leveraging data from 2006 to 2022, this study examines Jiangxi's tourism development (TD) and ecological resilience (ER) coupling coordination (CCD) under China's ecological civilization agenda. Integrating SPA, PVAR, modified CCD, kernel density estimation, and XGBoost - SHAP, it constructs a hybrid framework to analyze spatiotemporal evolution and multi - dimensional drivers, focusing on dynamic interactions and nonlinear mechanisms.

The research reveals the following key findings: (1) Both TD and ER have increased significantly, with marked differences in growth fluctuations across cities; spatially, a pattern of strong north and weak south is observed, along with a core radiation effect. (2) The temporal progression of CCD between TD and ER has shifted from extreme incoordination to moderate coordination. Its spatial distribution is driven by Nanchang as a single core, forming a concentric circular structure with a gradient decrease around the provincial capital. (3) Factors including the proportion of the tertiary industry, municipal public investment, per capita GDP, and vegetation coverage exert significant driving force on coordinated development and exhibit synergistic interaction effects.

The added value of this study lies in revealing the evolutionary laws of the human-land relationship in Jiangxi Province, providing a policy toolkit and differentiated pathways for spatial governance of tourism-ecology systems. It also offers an interdisciplinary toolkit for balancing tourism growth and ER in eco-sensitive regions, providing policy insights for China's ecological civilization pilot zones and beyond.

1. Introduction

Tourism holds a pivotal position in both the global and national economic frameworks. It serves as a potent catalyst for stimulating consumption and propelling economic growth (Wu et al., 2023). Since the commencement of the reform and opening-up program in the late 1970s, China's tourist sector has experienced remarkable expansion. It has evolved into a strategic pillar industry that not only drives economic development but also significantly contributes to enhancing residents' well–being (Chen et al., 2020). Nevertheless, the tourism industry's heavy reliance on natural resources and a healthy ecological environment has brought to the fore an increasingly prominent contradiction between its development trajectory and ER (Liu, 2019a). Alarmingly, over-tourism has precipitated the degradation of the natural ecosystem, posing a severe threat to the long-term viability of the tourism industry (Clua, 2018; Sharif et al., 2020). In this context, China is actively engaged in exploring and implementing strategies to foster the harmonious co-development of tourism and ER (Yang et al., 2021a; Gan et al., 2023).

The dynamic development of the tourism industry and the enhancement of ER are two fundamental tenets of contemporary sustainable development. Within the paradigm of regional development, these two elements are inextricably intertwined, with their interaction mechanisms exhibiting a high degree of complexity (Zhou, 2021; Li et al., 2024a). On one hand, large-scale construction of tourism infrastructure and extensive expansion of tourism activities have

* Corresponding author.
E-mail address: imliu@jxau.edu.cn (Y. Liu).

https://doi.org/10.1016/j.indic.2025.100875
Received 2 June 2025; Received in revised form 19 August 2025; Accepted 21 August 2025
Available online 22 August 2025

significantly enhanced tourism attractiveness and economic returns. However, they have concurrently exerted substantial stress on the ecological environment. Empirical studies indicate that the fast growth of the tourism sector in recent years has led to a reduction in the self-regenerative ability of ecosystems next to prominent tourist attractions. This decline is accompanied by heightened ecological vulnerability, degradation of habitats for rare flora and fauna, and threats to biodiversity (Saha and Paul, 2021; Tang et al., 2023). As such, striking a balance between TD and ER enhancement has emerged as a formidable challenge for society. On the other hand, the tourism industry is inherently contingent upon a high-quality ecological environment (Ruan et al., 2019). A reduction in ER can exacerbate the risk of natural disasters, disrupt tourism operations, and undermine the tourism-driven economy (Zhao, 2014; Vieira et al., 2024). Therefore, when promoting TD, local authorities must prioritize the construction of ER. Comprehensive investigation of the complex interaction between the two and examination of synchronized development plans are essential. This strategy will facilitate the development of a thriving tourist sector while concurrently enhancing the stability and resilience of ecosystems, so promoting the sustainable and high-quality symbiotic growth of tourism and the natural environment. (Yang et al., 2021b; Wang et al., 2024a).

To tackle this challenge, scholars have undertaken extensive research on topics including tourism attractiveness enhancement (Li et al., 2024b), supply-demand equilibrium in tourism, ecological impact assessment of tourism activities (Gu and Liu, 2014), and formulation of ecological protection strategies (Yu et al., 2022). These studies provide valuable theoretical and practical insights for understanding the dynamics of TD and ER conservation. However, TD and ER enhancement are not isolated phenomena; unidimensional research approaches are insufficient. Although recent studies have begun to acknowledge their interaction, most remain at the level of one-way influence analysis. For example, some studies solely examine the stress exerted by TD on ER (Valasiuk et al., 2023; Ning and Wang, 2024), while others focus exclusively on ER's supportive role in tourism sustainability (Wu et al., 2024; Wu et al., 2025). A critical gap persists in systematic research on their coupling and coordination mechanisms. Overlooking ecological carrying capacity constraints can lead to overexploitation of tourism resources and disruption of ecological equilibrium. Sacrificing ecological integrity for short-term tourism gains represents unsustainable practice (Qin et al., 2021; Benner, 2020). Conversely, overemphasizing ecological protection without adequate consideration of TD can stagnate industry momentum, while simultaneously impeding the enhancement of ER through tourism-related activities and frustrating overall regional tourism economic development (Raha et al., 2024). Thus, TD must balance industry prosperity with ER enhancement and actively pursue pathways for their coupling coordination evolution.

Furthermore, current research frequently employs the entropy weight method and the coupling coordination degree model to comprehensively analyze the relationship between TD and ER (Tang, 2015). However, these methods have limitations in accurately capturing the intricate relationships among various elements and lack sufficient adaptability to real-world scenarios. Additionally, existing studies on influencing factors often focus on specific variables in isolation, neglecting the interactions among multiple factors. A multiplicity of elements, including socio-economic conditions, industrial structure, infrastructure, and the natural environment, can greatly affect the CCD of TD and ER (Zhao et al., 2025a). Existing studies mostly focus on the CCD relationship between TD and ER at the national level. For example, Zheng et al., (2023) examined the interplay between TD and the ecological environment within the framework of China's tourism ecological security, focusing on spatiotemporal heterogeneity. Liu et al. (2024) examined the issue of enhancing the resilience of China's tourism system from two perspectives: the influence of environmental factors on resilience development and the regulatory function of digital technology in this process. Nonetheless, research on the provincial-level circumstances remains rather scarce.

The study examines the interrelationship between tourist development and ER, highlighting the following marginal contributions: (1) Conduct a systematic analysis of the holistic advancement of TD and ER systems, along with their interactive dynamics; (2) Utilize a refined CCD model to evaluate the spatiotemporal evolution and regional disparities of their CCD from both macro and regional perspectives; (3) Examine the determinants of the CCD and their synergistic mechanisms. The primary aim of this research is to elucidate the fundamental principles of CCD growth between TD and ER, and to offer specific policy recommendations for attaining their sustainable integration.

2. Literature review

2.1. Research progress of TD

As the core sector of the global economy, the sustainability research of tourism has always focused on resource allocation efficiency, ecological adaptability and regional collaboration mechanisms. The existing research mainly focuses on single dimensions such as tourism resource development intensity (Liu et al., 2019b) and influencing factor identification (Zhang et al., 2023). In recent years, with the deepening of the concept of green development, the research scope has expanded to multi-dimensional frameworks such as the dynamic balance between economic growth and ecological protection (Drews et al., 2019), and the ecological adaptability of industrial structure (Kong et al., 2023). The international academic community has achieved remarkable achievements in the development of sustainable tourism assessment tools, such as the Difference Dynamic Index (DDI) and Sustainable Tourism Assessment Chart proposed by Blancas F J (2018), which provides a new path for assessing the process of sustainable tourism targets and simplifying the use of composite indicator information. Samora-Arvela et al. (2018) explores the transformation to sustainable tourism and green infrastructure planning path through the Mediterranean reliance improvement strategy through the Mediterranean tourism destination case.

2.2. Research evolution of ER

In 1973, Canadian ecologist Holling introduced the concept of ER. It denotes the capacity of an ecosystem to preserve its structure, function, and processes in the presence of disturbances. Current research on ER primarily centers around its maintenance mechanisms, covering aspects such as ecological risk assessment (Sánchez-Pinillos et al., 2024), spatiotemporal differentiation characteristics (Zhang et al., 2020), and driving factor analysis (Ma et al., 2023). In order to reveal the spatiotemporal evolution patterns of ER, research methodologies such as the entropy method, Theil index, and spatial data analysis (ESDA) are frequently implemented (Lu et al., 2022). For example, Lu et al.(2024a, b)discovered that the ER of the Yellow River Basin demonstrated a fluctuating upward trend from 2007 to 2021. Its spatial pattern evolved from "mid-stream > upstream > downstream" to "down-stream > mid-stream > upstream", vividly reflecting the interactive influence of human activities and natural conditions. In the realm of driving mechanism research, the international academic community widely adopts structural equation model and covariance-based SEM (CB-SEM) as commonly used research tools. In order to evaluate the impact of urban resilience on carbon dioxide emissions in China's Pearl River Delta urban agglomeration, Wang et al. (2024b) and others built a comprehensive framework and used the spatial Doberman model (SDM) to conduct spatial analysis to examine the spillover effect of urban resilience on carbon emissions. It is worth noting that Tong et al., (2023)'s study on the northern slope of the Tianshan Mountains revealed the synergistic impact of natural factors (temperature, precipitation) and human factors (land use intensity) on ER, which echoes the research conclusions of Halofsky et al. (2017) in North America's Rocky

Mountains.

2.3. Current status of tourism-ecosystem coupling research

The coupling theory, an essential analytical framework for examining the interrelationships among various systems (Reichman et al., 2005), has been applied to reveal the co-evolution of tourism urbanization and ER (Tong, 2024), as well as the interaction pathways between tourism efficiency and ER (Liu et al., 2025). These studies have demonstrated that TD and ER form complex interconnections through resource flow and functional complementarity (Ruiz-Ballesteros, 2011). The tourism industry may reduce ER through landscape transformation and carbon footprint expansion (Luo et al., 2023), while a strong ecosystem provides basic support for tourism sustainability (Dongjun et al., 2020). The research findings have established a robust basis for comprehensive investigation into the avenues for the synchronized enhancement of tourist development and ER, therefore promoting the sustainable advancement of the regional economy and ecological environment.

2.4. Research and innovation

In summary, the link between tourist growth and the building of ER is intricate and varied. Examining their coupling coordination mechanisms, together with affecting variables, is essential for attaining the mutually beneficial objective of sustainable tourist development and enhancement of ER. This study develops a modified CCD model for TD and ER, addressing limitations in existing research through three approaches: (1) Utilizes the SPA and PVAR model to assess the comprehensive development and interactive dynamics between TD and ER systems. (2) From the dual dimensions of Jiangxi Province as a whole and distinct urban typologies, employs the modified CCD model and kernel density analysis to examine the spatiotemporal evolution and regional disparities of their coupling coordination, emphasizing spatial-temporal trends and inter-regional variations. (3) Leverages the XGBoost-SHAP framework to identify key influencing factors of coupling coordination, exploring two-factor interaction heatmaps through variable importance decomposition and analyzing the intensity and synergistic mechanisms of each factor across different regions and developmental stages.

3. Materials

3.1. Study area

Jiangxi Province, situated in southeastern China along the southern bank of the Yangtze River's middle-lower reaches, is distinguished by its abundant tourism and ecological resources (Fig. 1). Designated as one of China's first Ecological Civilization Pilot Zones in 2016, Jiangxi has achieved notable ecological milestones, with 28 regions awarded the national Ecological Civilization Construction Demonstration Zone title. In tourism, the province experienced substantial growth in 2024, attracting 932 million visitors (a 14 % increase from 2023) and generating 1107.08 billion in revenue (a 14.5 % rise). However, this expansion has entailed environmental trade-offs, as tourism infrastructure has encroached on natural ecological landscapes. To address this, Jiangxi adheres to the "ecological priority, green development" paradigm, actively seeking to establish a sustainable model for coupling TD with ER (Liu et al., 2024b; He et al., 2020). The province aims to lead China's ecotourism sector and foster harmonious coevolution between the two domains.

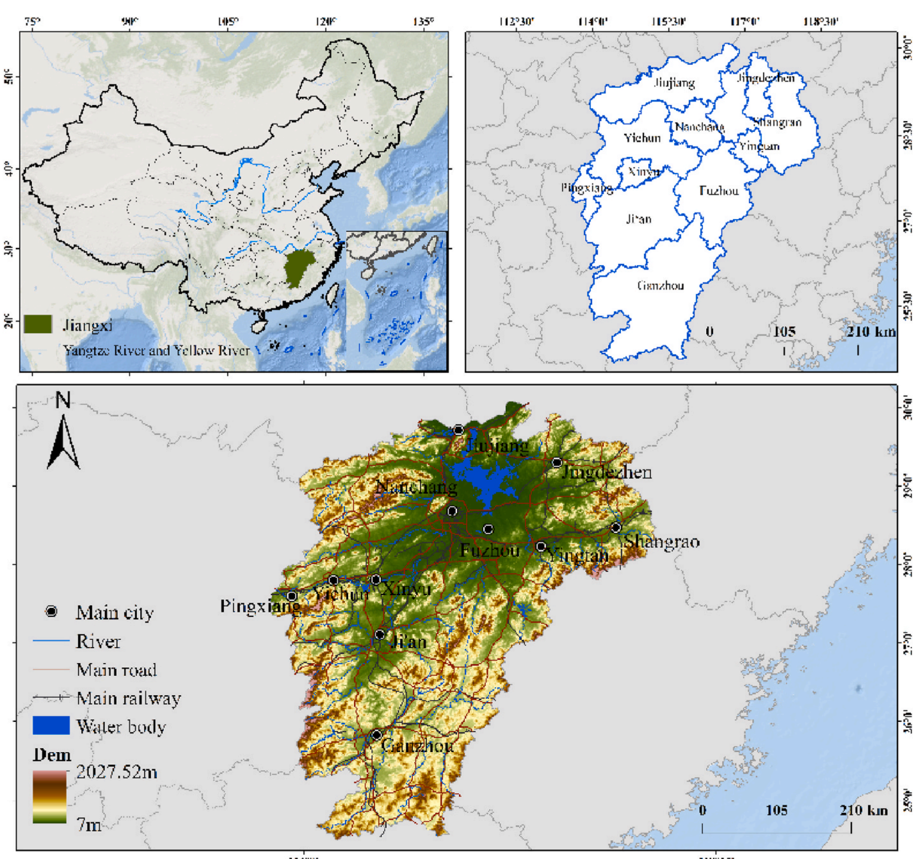

Fig. 1. Geographical location of the study area.

3.2. Data

The dataset utilized in this study is predominantly sourced from the Jiangxi Statistical Yearbook spanning 2006 to 2022, annual reports issued by the Jiangxi Provincial Department of Culture and Tourism, Statistical Communiqués on National Economic and Social Development of prefecture-level cities in Jiangxi, and municipal government work reports. To guarantee data accuracy and consistency across years and areas, preprocessing procedures, such as linear interpolation for missing values and standardization for anomalous observations, were methodically implemented.

3.2.1. Establishment of the index system

This study is guided by the actual needs of TD and ecological environment protection in Jiangxi Province, and fully refers to the policy documents of the Jiangxi Provincial Government for TD and ecological environment protection planning, and accurately anchors local development goals and constraints. At the same time, the research results of the former are widely borrowed (Weng et al., 2016; Songmao et al., 2022). An assessment index system for tourist development and ER was established based on the criteria of scientific rigour and efficacy (Table 1). The TD subsystem focuses on the four dimensions of tourism market, tourism economy, tourism services, and tourism innovation, and comprehensively portrays the scale, benefits and innovation potential of TD. The ER subsystem focuses on the four dimensions of resistance, recovery, adaptation and innovation. From multiple perspectives of ecological pressure, restoration capabilities, adaptation mechanisms, and innovation-driven, it builds an ER evaluation logic to ensure the ecological sustainability of TD.

3.2.2. Selection of driving factors

When screening factors that affect the coupling and coordination of TD and ER, this study combines previous research results, data availability and factor collinearity analysis (Zhao et al., 2025b; Lei et al., 2024), closely focuses on the four dimensions of social economy, industrial structure, infrastructure, and natural environment. Each factor collaborates to build an analytical framework covering the "human--nature" interaction, accurately capturing the multiple driving factors affecting coupling coordination (Table 2).

4. Materials

4.1. Data

A comprehensive research framework for the analysis of the CCD between TD and ER in Jiangxi Province is illustrated in Fig. 2. A visual summary of the research method process is fully elaborated in Supplementary Fig. 1. Initially, establish an assessment index system for TD and ER in Jiangxi Province, and employ the SPA technique to compute the complete development index for both systems. Secondly, implement the PVAR model to investigate the interaction response dynamics between tourist development and ER. Thirdly, the revised coupling coordination model and kernel density analysis method were used to analyze the spatiotemporal evolution trends and regional differences characteristics of the coupling and coordination of TD and ER in Jiangxi Province from 2006 to 2022. Fourth, identify the influencing factors of the CCD from various dimensions and employ the XGBoost-SHAP method to quantitatively assess the effects of driving factors on the CCD of TD and ER, subsequently conducting factor detection and interaction detection analyses. Ultimately, based on the research findings, propose policy recommendations to foster the integration and coordinated advancement of TD and ER in Jiangxi Province, thereby promoting the sustainable development of the provincial tourism sector and enhancing ecological environmental resilience.

Table 1
Evaluation index system for TD and ER.

System	Sub-system	Index	Unit	Attribute	Weight
TD	Tourism market	Number of domestic tourists	10,000 person	+	0.067
		Number of inbound tourists	10,000 person	+	0.091
	Tourism economy	Domestic tourism revenue	100 million yuan	+	0.097
		International tourism revenue	10,000 US dollars	+	0.118
		Percentage of overall tourism revenue in Gross Domestic Product (GDP)	%	+	0.064
	Tourism services	Quantity of star-rated hotels	Unit	+	0.046
		Quantity of picturesque locations rated over 4A	Unit	+	0.101
	Tourism innovation	Number of institutions with tourism-related majors	Unit	+	0.198
		Number of tourism - related patent applications	Unit	+	0.213
ER	Resistance dimension	Amount of domestic waste removed and transported	10,000 tons	+	0.011
		Up-to-standard discharge of industrial wastewater	10,000 tons	+	0.060
		Emission of sulfur dioxide from industrial exhaust gas	Tons	–	0.036
	Recovery dimension	Total water resources	100 million cubic meters	+	0.208
		Vegetation coverage ratio in developed regions	%	+	0.012
		Per capita green space in parks	m^2	+	0.019
	Adaptation dimension	Harmless treatment rate of domestic waste	%	+	0.007
		Centralized treatment rate of sewage treatment plants	%	+	0.014
	Innovation dimension	Total number of patent authorizations	Unit	+	0.268
		Total amount of scientific and technological expenditure	Unit	+	0.353

4.2. Methods

4.2.1. Set pair analysis

SPA is an analytical approach employed to deal with uncertain systems. This method treats certainty and uncertainty as an interconnected and mutually-restrictive unity. By analyzing identity, difference, and opposition, it can comprehensively and dynamically reflect the complex relationships among things. The paper used SPA to assess the scores of tourist development and ER, respectively.

Table 2
Influencing factor indicators and calculation methods.

Type	Driving Factor	Index
Socio - economic	Per capita GDP (X1) Population density (X2)	Obtained from official data such as statistical yearbooks
Industrial structure	Tertiary industry's share of GDP (X3)	Determine the proportion of the tertiary industry's output value in the total GDP using regional economic statistical data.
	Fixed-asset investment in municipal public construction (X4)	Derived from the special statistical data on fixed-asset investment released by government statistical departments
Infrastructure	Fixed-asset investment in municipal public construction (X4)	Used ArcGIS to extract road data from the national basic geographic database, and calculate the ratio of the total length of roads in the region to the area
	Road network density (X5) Railway passenger volume (X6) Per capita road area (X7)	Obtained from official data such as statistical yearbooks
Natural environment	Elevation (X8)	Obtained regional elevation values using Digital Elevation Model (DEM) data
	Vegetation coverage (X9)	Obtained remote-sensing images, calculate the NDVI (Normalized Difference Vegetation Index), and obtain the regional vegetation coverage
	Annual precipitation (X10) temperature (X11)	Obtained from official data such as statistical yearbooks
	River network density (X12)	Utilize ArcGIS to obtain water system data and compute the ratio of the total length of rivers within the region to the regional area

Assume two interrelated sets, X and Y, within the same system, which concurrently exhibit N shared properties. Then, a set pair $H = (X, Y)$ can be constructed based on these features, and this set pair is represented by the connection degree, as shown in the following formula:

$$\mu = \frac{S}{N} + \frac{F}{N}I + \frac{P}{N}J = a + bI + cJ$$

where μ is the number of connections, S is the number of features with the same characteristics among sets, F is the number of feature differences, and P is the number of opposite characteristics. I is the uncertain coefficient of the degree of difference, and the values are −1–1. J is the opposite coefficient, which is −1. a, b, and c are the connection degree components ($a = S/N$, $b = F/N$, $c = P/N$), and the condition $a + b + c = 1$ is met.

4.2.2. Panel vector autoregression model

The PVAR model is introduced to construct an evaluation model for dynamic response relationships. The PVAR model integrates the dual characteristics of time-series and panel data (Triatmanto et al., 2023). It not only effectively circumvents the endogeneity problem (Yan et al., 2024) but also, through orthogonalized impulse response functions, accurately decomposes the dynamic impact degrees of TD and ER under mutual shocks (Wang et al., 2024c). This provides a powerful empirical tool for revealing the complex dynamic correlations between the two. The model is specified as follows:

$$y_{i,t} = \alpha_0 + \sum_{j=1}^{p} A_j y_{t-j} + f_i + d_t + \varepsilon_{i,t}$$

where $y_{i,t}$ represents a vector composed of endogenous variables in the i-th province in year t, α_0 is the intercept term, j represents the lag order, p is the optimal lag order determined by the information criterion, A_j is the estimation coefficient under different lag orders, f_i and d_t represent individual fixed effects and time fixed effects, respectively, and $\varepsilon_{i,t}$ is the random perturbation term.

4.2.3. Modified CCD model

The revised CCD model is presented to investigate the spatio-temporal coupling coordination between TD and ER in Jiangxi Province (Wang et al., 2021). The alterations to the model are as follows:

$$C = \sqrt{\left[1 - \frac{\sum_{i>j,j=1}^{n} \sqrt{(U_i - U_j)^2}}{\sum_{m=1}^{n-1} m}\right] \times \left(\prod_{i=1}^{n} \frac{U_i}{max\ U_i}\right)^{\frac{1}{n-1}}}$$

$$T = \sum_{i=1}^{n} \alpha_i \times U_i \sum_{i=1}^{n} \alpha_i = 1$$

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

where $U_i \in [0, 1]$, $C \in [0, 1]$, C denotes the degree of coupling. A bigger value of C signifies a more effective interaction between the two systems, whereas a smaller value of C suggests greater discreteness of each subsystem. D is coupling coordination. A bigger D number indicates a more coordinated coupling relationship between the two entities. T is the comprehensive development index.

According to the research findings and in conjunction with the attributes of the empirical study (Meng et al., 2023), the classification table of the level of development of CCD is comprehensively elaborated in Supplementary Table 1.

4.2.4. Kernel density analysis

Kernel density estimation is a technique that utilizes kernel functions to smooth data points, therefore estimating the density distribution of data across spatial or other dimensions (Gallego et al., 2022). This work uses this approach to estimate the probability density of the coupling coordination degree, utilizing a continuous density curve to depict the spatio-temporal development of the coupling coordination degree. The expressions are as follows:

$$f(x) = \frac{1}{Nh} \sum_{i=1}^{n} K\left(\frac{CCD_i - CCD}{h}\right)$$

$$K(x) = \frac{1}{\sqrt{2\pi}} exp\left(-\frac{CCD^2}{2}\right)$$

where $f(x)$ represents the density function, h represents the broadband. CCD_i is coupling coordination degree, and CCD is coupling coordination degree the average value. $K(x)$ represents the kernel function.

4.2.5. XGBoost model

The presence of regional variability and the intricacy of the data provide significant obstacles to the creation and implementation of the analytical model for the coupling coordinating impact between TD and ER. Empirical research indicates that, in comparison to conventional tree-based ensemble learning algorithms (such as the Random Forest and Gradient Boosting Decision Tree models), the XGBoost model exhibits superior adaptability and flexibility in managing missing data values and large-scale datasets (Kanani-Sadat et al., 2024). Furthermore, it may efficiently alleviate the effects of multicollinearity among variables on model performance. Furthermore, to optimize the objective function, XGBoost employs the second-order Taylor expansion to tailor the loss function (Mushava and Murray, 2024). This technique enables optimization only through data values, eliminating the necessity for a predetermined loss function form and essentially separating loss function selection from the model optimization process. The equation for the objective function is as follows:

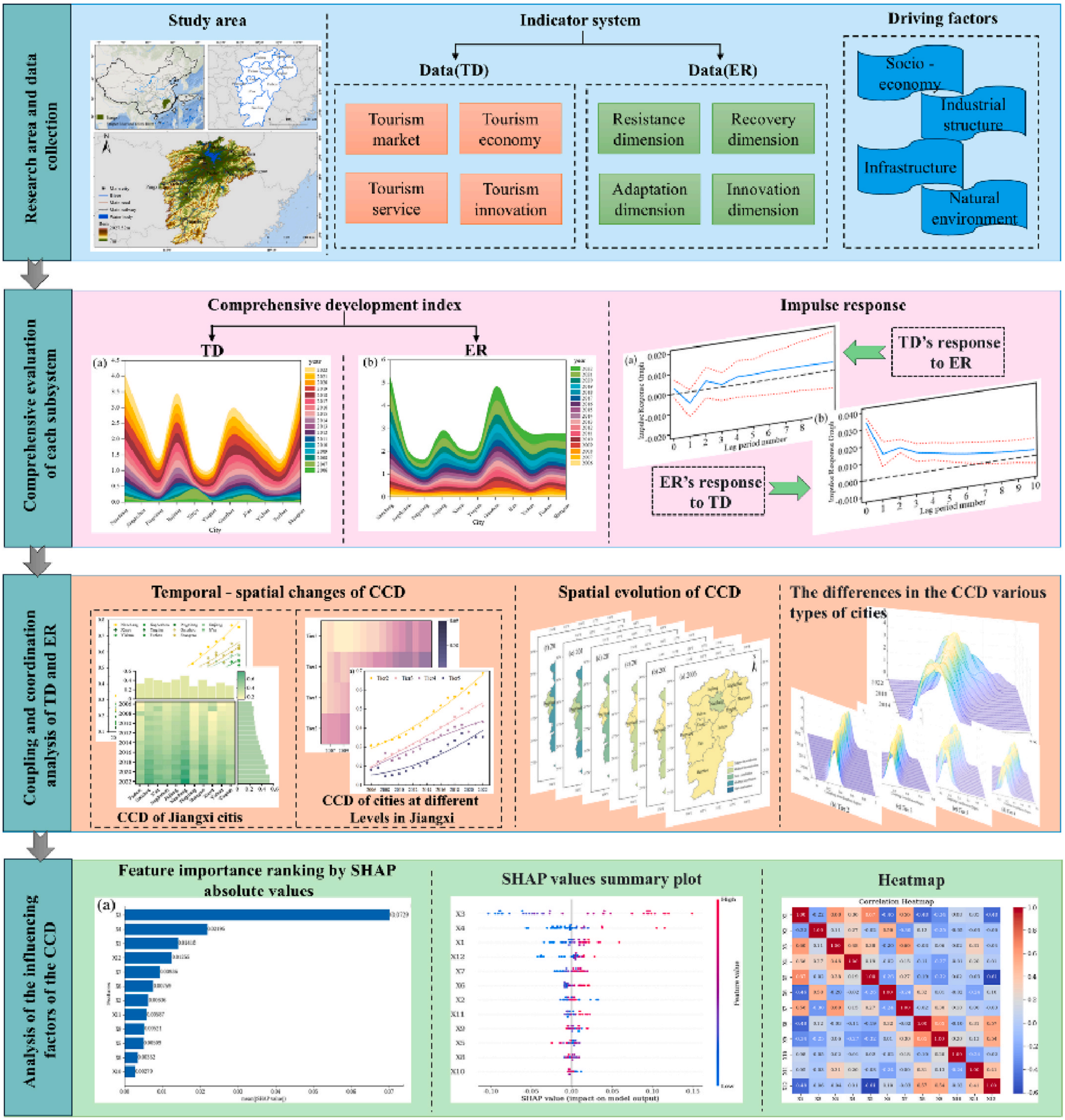

Fig. 2. Workflow of the study.

$$\widehat{y}_i = \sum_{t=1}^{n} f_t(x_i), f_t(x_i) \in R$$

where $\widehat{y}_i$ is the predicted value of the regression tree, n represents the number of trees, f_t is a function inside the function space R, x_i signifies the i-th data input, and R encompasses the entirety of potential regression tree models.

$$X_{obj} = \sum_{i=1}^{n} l(y, \widehat{y}) + \sum_{k=1}^{K} \Omega(f_k)$$

where $\sum_{i=1}^{n} l(y, \widehat{y})$ denotes the discrepancy between the model's predicted value and the actual value, and $\sum_{k=1}^{K} \Omega(f_k)$ represents the regularization component of the objective function.

$$\Omega(f_k) = \gamma T + \lambda \frac{1}{2} \sum_{j=1}^{T} \omega_j^2$$

where γ is the coefficient of the penalty function, T is the number of leaf nodes, λ is used to ensure that the score of leaf nodes does not be too large, and ω is the proportion of leaf nodes. When the regularization parameter is zero, XGBoost degenerates into the traditional lift model.

4.2.6. Shapley additive explanations model

While XGBoost is capable of ranking feature importance and revealing overall characteristics of feature variables, its ability to capture relationships between features and target variables diminishes with increasing dataset complexity. SHAP, a post-hoc explanatory method (Makumbura et al., 2024), quantifies the contribution of individual features to model predictions using Shapley values derived from cooperative game theory, therefore enhancing both global and local interpretability of complex black box models. SHAP elucidates complex models (Salih et al., 2024) and, more importantly, unlike traditional methods such as linear regression and geographical detectors, it calculates the average Shapley values of the dataset, thus enabling a global ranking of feature importance (Mitruț et al., 2024). This facilitates the identification of key elements in the coupling mechanism between TD and ER, while also uncovering potential nonlinear relationships and threshold effects.

Suppose the i-th sample be denoted as xi, the i-th characteristic of the j-th sample is x_{ij}, the predicted value of the model for this sample is y_i, and the mean value of the target variable over the samples as y_{base}. The SHAP value is computed via the below formula:

$$y_i = y_{base} + f(x_{i1}) + f(x_{i2}) + \cdots + f(x_{ik})$$

where $f(x_{i1})$ is the denotes the contribution value of the first feature in the *i*-th sample to the final predicted value y_i. When $f(x_{i1})>0$, it signifies that the characteristic enhances the anticipated value, indicating a positive influence. This indicates that the final anticipated value will decrease due to the impact of this attribute, resulting in a negative consequence.

5. Results

5.1. Analysis of comprehensive development index

From 2006 to 2022, the comprehensive development indices (CDIs) of both TD and ER systems in Jiangxi's prefecture-level cities exhibited upward trends with notable fluctuations (Fig. 3). For the TD system, Nanchang, Jiujiang, Ganzhou, and Shangrao demonstrated stronger growth momentum and more pronounced fluctuations compared to other cities, reflecting robust developmental vitality. Notably, Nanchang experienced the most pronounced growth in CDI, increasing from 0.09 to 0.51, while Xinyu showed the smallest increment, rising only from 0.09 to 0.12. In the ER system, Nanchang, Jiujiang, and Ganzhou also recorded larger CDI fluctuations and growth trajectories, underscoring their comparative advantages in ecological sustainability. Conversely, other cities maintained low CDI levels with minimal growth. Nanchang again led in index growth, advancing from 0.12 to 0.64, whereas Xinyu's growth remained stagnant (0.07–0.18). As the provincial capital, Nanchang leveraged resource aggregation and policy prioritization to invest significantly in tourism infrastructure and ecological conservation, driving rapid CDIs growth. In contrast, Xinyu-constrained by its compact urban scale, limited resource endowments, and insufficient investment in tourism-ecology initiatives-faced stagnant development momentum, resulting in marginal CDI improvements.

5.2. Analysis of interactive response relationship

Following unit root tests, optimal lag order determination, causality assessment, and validation of the PVAR model's stability, this study utilizes impulse response curves of TD and ER to unveil the long-term dynamic interactions between the two systems in Jiangxi Province (Fig. 4).

Fig. 4a illustrates that, except for the initial period, TD triggers a positive impulse response in ER. The lag-zero response is followed by a sharp negative trough in Period 1, which rebounds to a peak in Period 2 before gradually converging to stability. This pattern suggests that while short-term impacts exhibit volatility, the long-term effects tend to foster convergence. In contrast, Fig. 4b depicts an inverted "N"-shaped response of ER to TD. Initially stable ecosystem functions show positive adaptation, but tourism infrastructure expansion and increased visitor flows induce functional degradation by Period 1. A transient recovery occurs in Period 2 due to ecosystem self-regulation, yet continuous tourism growth surpasses ecological carrying capacity from Period 3 onward. Despite mitigation efforts, the ecosystem enters a phase of persistent decline, unable to fully restore equilibrium.

5.3. Analysis of CCD

5.3.1. Analysis of CCD of 11 cities in Jiangxi Province

Fig. 5a and b depicts the temporal distribution patterns of coupling coordination development between TD and ER in Jiangxi Province. The coupling coordination relationship demonstrates an upward trajectory, indicating that the interaction between TD and ER systems is undergoing positive evolution. Specifically, regarding the transitions in coupling-coordination degree classifications, all cities have experienced category shifts, which can be divided into two distinct patterns: The initial pattern is defined by a persistent improvement in the CCD. For example,

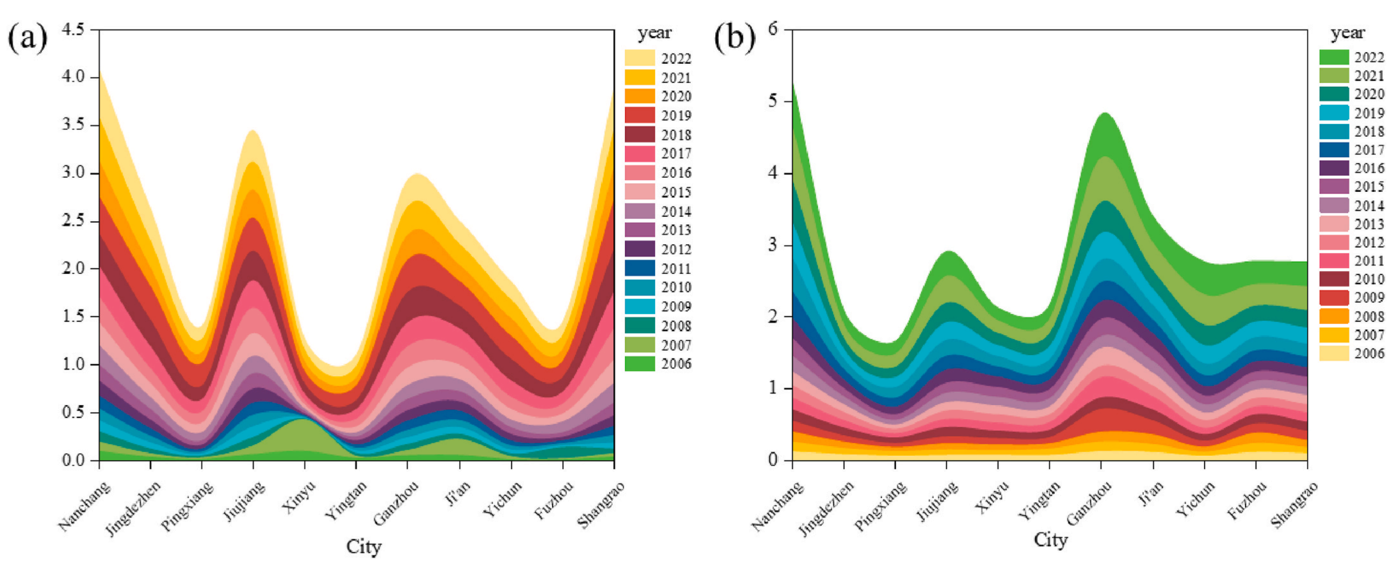

Fig. 3. The overall development index for (a) TD and (b) ER.

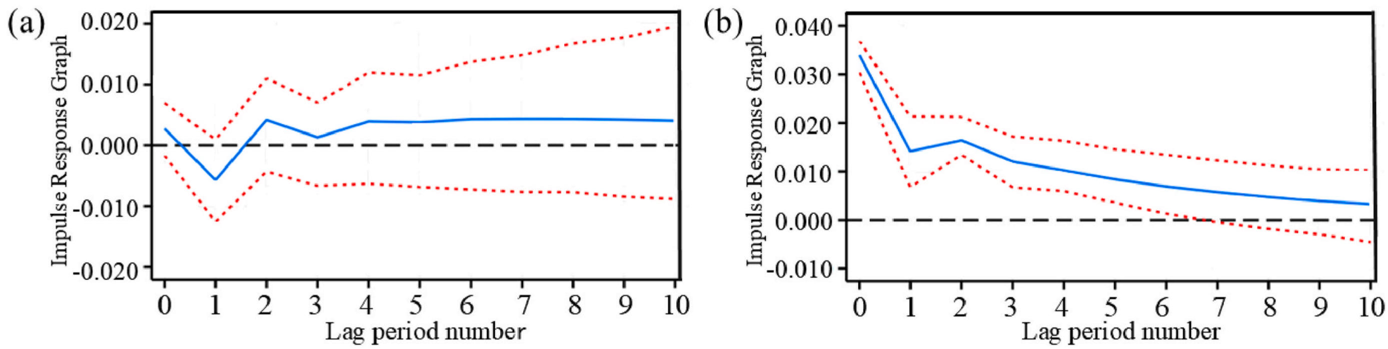

Fig. 4. The panel impulse response of (a)TD and (b)ER.

Nanchang has ascended from a near-disordered state to a highly coordinated one, while Shangrao has progressed from mild disorder to moderate coordination. The second pattern demonstrates a general rising trajectory in the CCD, although with significant oscillations, seen in cities like as Jingdezhen, Pingxiang, Jiujiang, Xinyu, Yingtan, Ganzhou, Ji'an, Yichun, and Fuzhou.

Fig. 5c illustrates the regional distribution pattern of the coupling coordination development between TD and ER in Jiangxi Province. The coupling coordination relationship exhibits distinctly manifests a "Nanchang-centric mononuclear driving" pattern, thereby highlighting substantial spatial heterogeneities. In 2006, Nanchang, despite presenting the highest coordination degree among all cities, was on the verge of dysregulation, while the remaining cities were categorized as being in a state of mild dysregulation. By 2015, the majority of Jiangxi's cities had advanced to the fundamental coordination stage, with discernible improvements in their respective coordination indices. By 2022, the inter-city disparities in coupling coordination degrees had been systematically mitigated. All cities in Jiangxi Province had successfully transitioned to the coordinated development stage.

5.3.2. Analysis of CCD of different city types in Jiangxi Province

To deeply analyze the dynamic evolution of CCD distribution across different urban types in Jiangxi Province, this study classifies its 11 prefecture-level cities into four categories based on the National Main Functional Zone Plan: optimized development cities, key development cities, restricted development cities (main agricultural product production areas), and restricted development cities (key ecological functional areas).

Fig. 6a and b demonstrate that optimized development cities, marked by advanced urban economies and industrial frameworks primarily focused on high-end services and sophisticated manufacturing, display a significant correlation between TD and ER, with an average correlation coefficient of 0.465. Restricted development cities (key ecological functional areas), tasked with core ecological service functions, adopt a cautious approach to TD. However, their superior ecological endowments grant unique advantages in ecotourism, yielding an average CCD of 0.245-hough their annual CCD growth rate remains low due to limited development intensity. Regarding average annual CCD growth rates, significant disparities exist among city types, ranked as follows: key development cities > restricted development cities (main agricultural product production areas) > optimized development cities > restricted development cities (key ecological functional areas). Key development cities demonstrate rapid tourism-ecology coordinated growth driven by strong development vitality and policy support. Restricted development cities (main agricultural product production areas) achieve steady growth through innovation-driven development on existing foundations. Optimized development cities maintain moderate growth while exploring new tourism models. Restricted development cities (key ecological functional areas), constrained by strict ecological protection mandates, exhibit relatively low growth rates.

Fig. 6c provides an in-depth examination of the dynamic progression of the CCD between TD and ER, focusing on distribution location, trend, and ductility. First, in terms of distribution location, the main peaks of the kernel density curve in Jiangxi Province and the four city types show a "right-shift" trend, indicating an overall improvement in CCD. While optimized development cities, key development cities, and both types of restricted development cities exhibit single-peak distributions, Jiangxi Province as a whole shows secondary peaks in some years. This suggests that CCD has generally increased, with mild two-level differentiation in the province's overall coupling coordination. Second, regarding distribution trends, the main peak height of Jiangxi's CCD first increased and then decreased, while the curve width gradually expanded. Before 2020, all four city types showed rising peak heights and narrowing widths; after 2020, all curves exhibited a "left-shift" with increasing width. This indicates that CCD in Jiangxi has transitioned from a relatively concentrated higher level to growing intercity disparities and a more dispersed distribution. The CCD gap among the four city types initially narrowed continuously but later widened. Third, concerning distribution ductility, the kernel density curves of Jiangxi Province, restricted development cities (main agricultural product production areas), and restricted development cities (key ecological functional areas) exhibit right-tailing phenomena, indicating continuous CCD growth in these categories. The thickening right side of Jiangxi's kernel density map signals an increase in cities reaching high CCD levels. Optimized development and key development cities show no obvious tailing, reflecting stable high CCD levels.

5.4. Analysis of influencing factors based on the XGBoost-SHAP method

5.4.1. Model performance indicators

The paper utilizes the XGBoost method to develop a non-linear regression model for an in-depth analysis of the quantitative link between the CCD of TD and ER in Jiangxi Province, along with its influencing factors. Best practices in machine learning modelling are rigorously adhered to throughout the model development process. The dataset is split into a training set and a test set at an 80:20 ratio, with cross-validation used to assess the model's generalization capability. The model optimization uses a grid search algorithm, and by adjusting key parameters such as L1/L2 regularization coefficients, taking into account accuracy improvement and overfitting control, the best parameter combination is finally determined. The model's performance is evaluated using a three-metric system including the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE), which enables a thorough assessment of both goodness of fit and predictive accuracy. For details of the experimental results, please refer to Supplementary Table 2. The model has superior predictive performance on both the training and test sets.

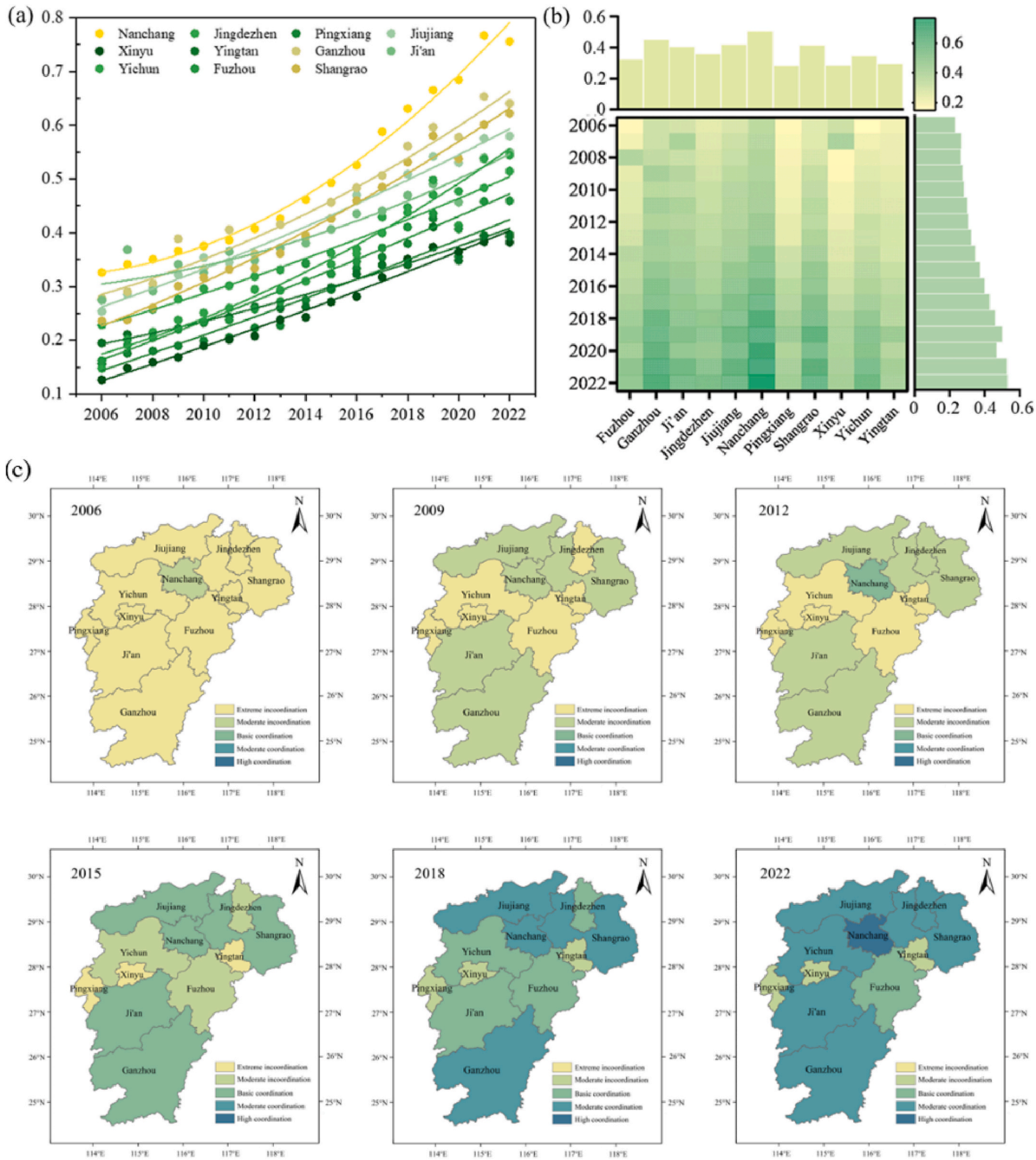

Fig. 5. (a, b) Temporal variation in the CCD between TD and ER; (**c**) spatial evolution of the CCD across regional scales.

5.4.2. Analysis of the importance of influencing factors based on the XGBoost-SHAP

This study constructs an integrated interpretive framework of XGBoost-SHAP to analyze feature importance and examine the impact directions of multidimensional factors influencing the tourism-ecological coupling system in Jiangxi Province from 2006 to 2022.

The feature importance ranking analysis (Supplementary Fig. 2a) shows that the tertiary industry's GDP share (X_3) ranks first, with an average SHAP value of 0.061. Its marginal contribution exceeds three times that of the second-ranked feature, municipal public building investment (X_4, 0.021), indicating that industrial structure optimization is the primary driver of coupling coordination growth. Per capita GDP (X_1, 0.019) and river network density (X_{12}, 0.018) rank third and fourth, forming a multidimensional driving structure of "industrial

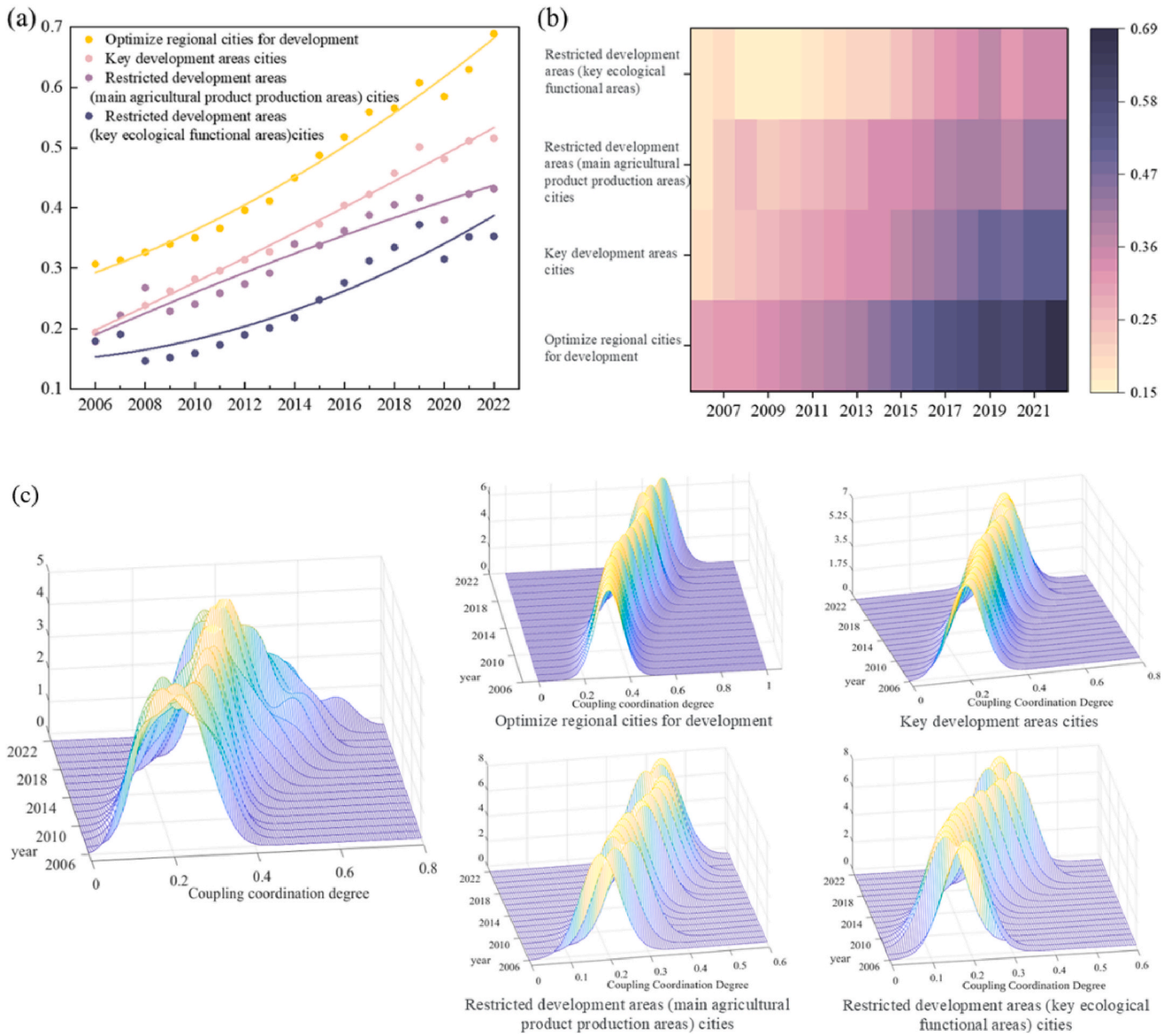

Fig. 6. (a, b) The CCD of the four types of cities; (c) its distribution dynamics.

structure–infrastructure–economic level–natural background". As indicators of the industrial structure dimension, X_3 and X_4 collectively explain 54.46 % of the variance, highlighting the strong dependence of Jiangxi's tourism-ecological synergies on industrial structure optimization.

The global impact direction analysis (Supplementary Fig. 2b) further reveals heterogeneous mechanisms among influencing factors. In the plot, red signifies the strongest influence, and blue the weakest. The SHAP values for X_3 exhibit pronounced positive skewness, indicating that the service-oriented transformation of the industrial structure exerts a beneficial driving effect with escalating marginal impacts on the CCD. Conversely, most scatter points for X_{10} cluster on the negative half-axis, showing that higher annual precipitation primarily has a detrimental effect on the CCD within this framework. Increased precipitation may disrupt the relationship between TD and ER to some extent.

5.4.3. SHAP heatmap analysis

In this study, an XGBoost-SHAP joint framework was employed to construct a visualization matrix of interaction effects (Fig. 7). Through the heatmap encoding technology, the non-linear influence mechanism of the synergistic effects of multiple factors on the tourism-ecological coupling coordination degree was analyzed. Regarding the heatmap encoding rules, a two-color gradient spectrum was adopted: the red color scale represents a positive interaction effect (SHAP interaction value > 0), indicating that the marginal effect generated by the synergistic action of the two factors is greater than the sum of the effects of the single factors; the blue color scale represents a negative interaction effect (SHAP interaction value < 0), reflecting an antagonistic relationship between the factors where one factor's increase is accompanied by the other's decrease.

The correlation coefficient between per capita GDP (X_1) and the tertiary industry's GDP share (X_3) is 0.60, while that between per capita GDP (X_1) and road density (X_5) is 0.70, both indicating strong positive correlations. This suggests that economic development facilitates industrial structure optimization and transport infrastructure improvement, thereby fostering tourism growth and strengthening the synergistic relationship between TD and ER. The correlation coefficient between road density (X_5) and river network density (X_{12}) is −0.63,

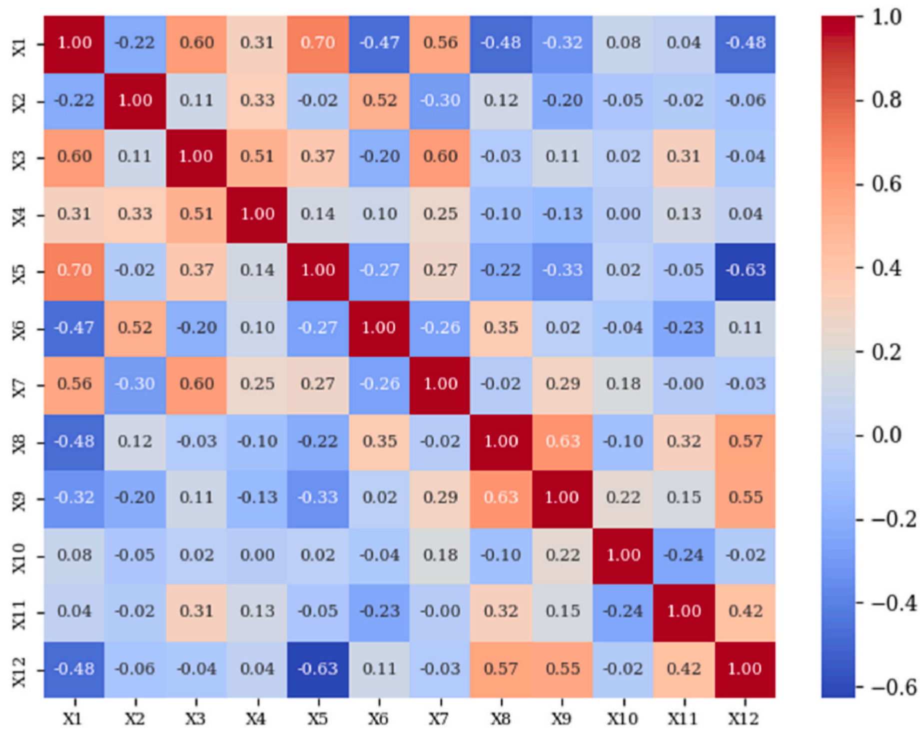

Fig. 7. SHAP-based heatmap.

reflecting a strong negative correlation. This implies a trade-off between road construction and water system distribution, impacting ER, as the two variables exert opposing effects on the CCD.

When analyzing the influencing factors of the coupling coordination degree (CCD), examining variable correlations via heatmaps allows for targeted exploration: strongly correlated variable combinations warrant further investigation into their internal linkages and joint action mechanisms, while weakly correlated variables can be treated as relatively independent during model development. This approach facilitates the identification of key drivers and provides critical insights for unraveling the formation mechanisms of CCD between TD and ER.

6. Discussion

6.1. Insights into the CCD

From the perspective of evolution of the research period, the TD and ER system in Jiangxi Province exhibit dynamic coupling characteristics. During the initial phase (2006–2012), the advancement and proliferation of tourism fostered a positive relationship with ecological conservation. Typically, the total number of tourists received in Nanchang City increased by 20.27 % annually, while the forest coverage rate in Nanchang City increased by 6.9 % during the same period. In the medium term (2013–2017), local trade-offs occurred, and the expansion of tourism land in Ganzhou City led to an increase in landscape fragmentation. However, the province has implemented the Jiangxi Province Ecological Civilization Construction Promotion Regulations, which has made positive progress in many aspects. For example, the proportion of excellent surface water quality in the province has increased by 2.7 %, and the average ratio of good days in prefecture-level cities reached 88.3 % in 2018. Later (2018–2022) the system entered the stage of restoration and reconstruction. Through institutional innovations such as the "ecological red line + green certification" mechanism, the province's PM2.5 concentration dropped to 27 μg/cubic meter in 2022, and the excellent air quality days ratio reached 92.1 %. Water environment quality remained top-tier in the central region and firmly within the "first echelon" nationwide, marking the return of TD and ER to a coordinated development trajectory.

The evolution of the spatial pattern shows double convergence characteristics. On a regional scale, the tourism revenue gap between Nanchang and Ganzhou was 14 % in 2006, and by 2022, the gap had narrowed to 7 %. The TD gap between Nanchang, the provincial capital, and marginal cities has gradually narrowed. In the dimension of urban typology, the growth rate of coupling coordination in second-tier cities (Nanchang) lags behind that of third-tier (166.55 %) and fourth-tier cities (142 %), reflecting the time-lag effect of industrial transformation and upgrading. The establishment of a "ecological bank" trading platform has notably enhanced the regional ecological environment within the ecologically sensitive zone, resulting in a 12 % increase in the proportion of days with good air quality, thereby creating a beneficial cycle of "otection-benefit"

6.2. Influence mechanism analysis for CCD

Given the complex nonlinear characteristics of human-earth system interactions, this study employs the XGBoost-SHAP interpretation framework to reveal the comprehensive influence mechanism of the four-dimensional elements-"economy-industry-facilities-nature". At the single-factor level, industrial structure optimization (e.g., a 1 % increase in the tertiary industry proportion in Nanchang City correlates with a 0.027-unit increase in coupling coordination) and socioeconomic foundations (e.g., a ¥10,000 increase in Jiujiang City's per capita GDP associates with a 0.041-unit increase) constitute the core driving forces. Conversely, natural environmental conditions (e.g., a 0.01 % increase in Nanchang City's vegetation coverage correlates with a 0.16-unit decrease in coupling coordination) and infrastructure layout exhibit constraining effects.

The interaction mechanisms manifest in a dual pattern: socioeconomic dimensions form a strong synergistic effect (the interaction effect of per capita GDP and highway density is 0.67, $p < 0.01$), driving the transmission chain of "service transformation-consumption upgrading-ecological investment". In contrast, infrastructure construction and ecological foundations display a trade-off relationship (the interaction effect of highway density and river network density is −0.61, $p < 0.01$), necessitating ecological buffer zones in traffic planning to mitigate resilience losses. For instance, Wuyuan County's "Ancient Village + Ecological Health Care" model extends tourist stay duration and enhances per-unit-area tourism revenue, positively correlating with higher ER indices-validating the feasibility of protective development pathways.

6.3. Policy implications

In light of the pronounced regional spatial heterogeneity and potential trade-off dynamics, this study formulates differentiated spatial governance policies and guidance mechanisms. The overarching objective is to facilitate the transformation of TD paradigms, enhance ER, and realize sustainable coordinated development in Jiangxi Province through structural optimization. The detail recommendations are delineated as follows.

(1) Despite the constant upward trend in the integrated development of tourism, economic, and ER systems in Jiangxi Province, significant discrepancies remain in development equilibrium at the municipal level. To mitigate these discrepancies, a dual-pronged policy-resource mechanism is proposed. Firstly, institutional reinforcement is imperative, achieved by establishing an interdepartmental collaborative policy framework through top-down strategic design. Secondly, resource allocation optimization is essential, including the establishment of dedicated funds earmarked for TD and ecological conservation. These financial resources should be strategically directed towards critical sectors, such as infrastructure network enhancement, ecosystem restoration initiatives, and the cultivation of novel cultural-tourism integration models. Through the spatial reallocation of key elements, a more balanced CCD of the two systems can be effectively promoted.

(2) The evolutionary trajectory of the CCD indicates that the tourism-ecological system in Jiangxi Province is undergoing a transition from initial-stage to medium-and high-quality coordination. However, spatial heterogeneity remains a salient characteristic. Each prefecture-level city should adopt tailored strategies contingent upon its specific developmental stage. For regions with lower coordination levels, precision-targeted enhancement plans should be devised based on local resource endowments to surmount developmental bottlenecks. Conversely, areas with higher coordination levels should prioritize the optimization of industrial layouts within the constraints of ecological carrying capacity. Leveraging their resource advantages, these regions should foster the formation of green tourism industry clusters, thereby generating spill-over effects through technological diffusion and experience sharing. Such initiatives will effectively stimulate the development of adjacent less-coordinated areas, ultimately facilitating a gradient - based elevation of the province-wide coupling coordination level.

(3) The collaborative advancement of tourist growth and ER forms the foundation of regional sustainable development. Comprehending the factors influencing the CCD is essential for the accurate development and execution of policies. It is recommended that decision-makers focus on key variables with significant explanatory power, such as advanced industrial structures and robust socioeconomic foundations. A multi-dimensional policy toolkit should be developed, encompassing measures such as regulating development intensity, implementing ecological compensation mechanisms, and deploying intelligent tourism technologies. During spatial development, adherence to the principle of "conservation-first with rational utilization" and systematic optimization of the human-environment relationship are essential for establishing a resilient ecological foundation and a robust industrial support system, thereby ensuring the long-term stability and prosperity of Jiangxi Province's socioeconomic development.

6.4. Limitation and research prospective

This study offers a robust framework for analyzing regional heterogeneity in the interplay between TD and ER, as well as the nonlinear response mechanisms of influencing factors in their coordinated development; however, several limitations persist:

Firstly, there are constraints regarding the extensiveness of the research scope. Focusing solely on panel data at the municipal scale in Jiangxi Province, this study fails to incorporate neighboring provinces with close regional economic ties and typical areas with diverse TD models (such as the Yangtze River Delta and Chengdu-Chongqing regions) as comparative samples. This oversight results in an incomplete identification of inter-regional gradient differences, spillover effects, and spatial correlation characteristics of the tourism-ecological system's coupling and coordination.

Secondly, the construction of the indicator system is restricted by data availability and methodological limitations, leading to incomplete dimensional coverage. While the study has established an evaluation framework encompassing explicit elements, it lacks scientific and effective measurement methods for implicit factors, such as cultural capital stock in TD and natural capital depreciation in ER. Additionally, it fails to adequately account for difficult-to-quantify soft constraints, including policy institutions and social perceptions. Consequently, the evaluation results exhibit certain information loss in depicting the true coupling state of the system.

Future research can be advanced in three aspects. First, expand the research scale and regional scope by incorporating urban agglomerations and other regions in the middle reaches of the Yangtze River into comparative analysis. A cross-scale spatial correlation model should be constructed to focus on testing the application potential of this research model in areas with different geographical backgrounds—such as ecologically fragile areas and tourism-saturated areas—and functionally positioned regions, thereby revealing the regional coordination mechanisms and adaptation rules of tourism-ecosystem coupling and coordination. Second, improve the index system and data sources. Integrate multiple types of data, including remote sensing monitoring data such as night light data for inversion of tourism activity intensity and social survey data such as questionnaires on residents' ecological perceptions, to develop a composite index system containing implicit elements. Special attention should be paid to integrating qualitative data and participatory data to enhance the measurement capacity of soft constraints through mixed research methods and improve the comprehensiveness of evaluation dimensions.

7. Conclusions

This study adopted a staged research methodology consisting of "theoretical modeling, empirical analysis, and mechanism analysis" to fulfill the research objectives. A rigorous review of domestic and international literature informed the construction of an evaluation index system for TD, ER, and the factors influencing their coupling coordination. The Set Pair Analysis (SPA) was used to calculate the CDIs of the two systems, while the Panel Vector Autoregression (PVAR) model was employed to analyze their dynamic interactive response mechanisms. A modified model of CCD and kernel density analysis were used to investigate the spatiotemporal evolution and static distribution characteristics of their coupling coordination. The XGBoost-SHAP model was applied to reveal the nonlinear constraint mechanisms of "society-industry-facilities-nature" variables on CCD from multiple dimensions, with corresponding policy recommendations proposed. The main conclusions are as follows.

(1) The comprehensive development index of both TD and ER systems exhibit fluctuating upward trends, with a long-term interactive relationship between the two. TD demonstrates short-term instability but a positive impulse response to ER in the long run; conversely, ER shows an inverted "N"-shaped trend in response to TD.
(2) The CCD among Jiangxi's cities is generally improving, though significant regional disparities persist; however, the gap between cities progressively diminishes over time. Temporally, the CCD in Nanchang and Shangrao has shown steady improvement, while cities like Jingdezhen, Pingxiang, and Jiujiang exhibit fluctuating growth. Spatially, a single-core development pattern centered on Nanchang is evident. The evolution of CCD is influenced by neighboring cities, with high-CCD cities exerting a catalytic effect on enhancing CCD in adjacent regions.
(3) The CCD levels of TD and ER vary across Jiangxi's four main functional city categories (as defined in the National Main Functional Zone Plan). Optimized development cities exhibit relatively high CCD, while restricted development cities (key ecological functional areas) show lower CCD. The province-wide CCD and that of the four city categories have improved overall. However, the province's CCD has transitioned from relative concentration to increasing dispersion, with intercity gaps first narrowing then widening. Meanwhile, the number of cities with high CCD has grown.
(4) Among the "social-industry-facilities-natural" factors, the tertiary industry's GDP share and municipal public construction investment are primary drivers of CCD. Industrial structure service-oriented transformation exhibits positive effects on CCD. Factor interactions show both synergistic and trade-off patterns: socioeconomic and infrastructure factors correlate strongly positively, while natural environmental factors negatively interact with socioeconomic and infrastructure factors, exerting opposite effects on CCD.

These findings enable policymakers to better understand the complex tourism-ER nexus, integrate their synergies into regional plans, and identify key CCD influencing factors. This facilitates targeted policy interventions to enhance regional sustainable development by balancing tourism growth and ER.

CRediT authorship contribution statement

Xingxing Wang: Writing – original draft, Methodology, Data curation. **Sunhee Suk:** Writing – review & editing. **Novelia Triana:** Writing – review & editing, Conceptualization. **Yuting Xue:** Visualization. **Xiuben Ma:** Visualization, Resources. **Fenghua Liu:** Visualization. **Liguo Wang:** Writing – review & editing. **Yiming Liu:** Writing – review & editing, Supervision, Conceptualization.

Ethics approval

Ethical approval is not required for this article because it does not address ethical issues.

Funding

This work was supported by the National Natural Science Foundation of China (No. 42261038), Jiangxi Provincial Social Science Fund (Research on the Integrated Development Mechanism and Spatial Effect of Rural Tourism and Regional Cultural Industries in County Areas of Jiangxi Province, No. 25GL32), Research Projects of Humanities and Social Sciences in Jiangxi Province's Universities (No. SZZX24099), Jiangxi province Early Career Youth Science and Technology Talent Training Program (No.20244BCE52049), and the Ganpo Talent Program: High-Level and Urgently Needed Overseas Talent Recruitment Project, Provincial Department of Science and Technology (No. 20242BCE50082).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 42261038), Jiangxi Provincial Social Science Fund (Research on the Integrated Development Mechanism and Spatial Effect of Rural Tourism and Regional Cultural Industries in County Areas of Jiangxi Province, No. 25GL32,Research Projects of Humanities and Social Sciences in Jiangxi Province's Universities (No. SZZX24099), Jiangxi province Early Career Youth Science and Technology Talent Training Program (No.20244BCE52049), and the Ganpo Talent Program: High-Level and Urgently Needed Overseas Talent Recruitment Project, Provincial Department of Science and Technology (No. 20242BCE50082).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100875.

Data availability

The data that being used in this research have been included in the article, further inquiries can be directed to the corresponding authors.

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