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How to Coordinate Regional Economic and Ecological Resilience: Evidence from the Yangtze River Economic Belt

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Abstract

This study focuses on the coordination between regional economic and ecological resilience in developing countries, constructing an integrated research framework of "resilience assessment—coupling coordination measurement——influencing factor ranking——policy simulation." Using the Yangtze River Economic Belt as a typical case, this research conducts a multidimensional quantitative evaluation of economic and ecological resilience within the region. The findings reveal a common contradiction: regions with weak economic foundations generally exhibit economic resilience lagging behind ecological resilience. By employing a coupling coordination model, this study quantitatively characterizes the synergy between economic and ecological systems and identifies key driving factors for regional coordination through grey relational analysis. Furthermore, system dynamics-based policy simulation results indicate that precise and targeted economic policies significantly enhance regional coupling coordination in the long term, providing theoretical evidence to address the "pollution first, treatment later" dilemma. These findings offer a novel theoretical perspective and practical pathway for developing countries to establish green and sustainable regional development models.

Keywords: Regional Resilience; Economic Resilience; Ecological Resilience; Coupling Coordination; Policy Simulation.

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DOI: https://doi.org/10.25120/jre.5.1.2025.4216

1. Introduction

Global climate change, ecological degradation, and resource depletion have become central challenges restricting human sustainable development, particularly in developing countries characterized by limited resources and governance capacities. In recent years, accelerated industrialization and rapid urbanization have exacerbated environmental problems, such as excessive resource extraction and intensified ecological pollution. Fast economic growth frequently depends heavily on the over-exploitation and high-intensity consumption of natural resources, leading to severe environmental issues, including ecosystem service degradation, land desertification, and water scarcity. At the same time, many developing countries suffer from insufficient environmental governance capacity and inadequate technological innovation, leaving their ecosystems vulnerable to external shocks and unable to effectively recover or sustainably provide ecological services. Thus, finding strategies that simultaneously promote economic prosperity while ensuring ecosystem adaptability, resilience, and regenerative capacity has become an urgent concern shared by scholars and policymakers worldwide.

Regional resilience theory provides a novel analytical lens for addressing these complex issues. This theory emphasizes not only the capacity of regional economic systems to maintain continuity and rapidly recover from external disturbances, such as natural disasters and economic fluctuations (i.e., economic resilience), but also highlights the ability of ecosystems to sustain their functions and services under environmental disturbances (i.e., ecological resilience). However, the relationship between economic and ecological systems is complex, characterized by both interdependence and inherent tensions. On one hand, rapid economic growth increases resource consumption and pollution emissions, placing significant pressure on ecosystems. On the other hand, ecological degradation undermines the foundations of economic growth, limiting long-term development potential. Balancing economic advancement with ecological conservation, and coordinating interactions between these two systems, therefore, represent significant challenges and pressing practical problems that countries urgently need to resolve in their pursuit of sustainable regional development.

Taking the Yangtze River Economic Belt (YREB) as a representative case, this study establishes an integrated research framework comprising resilience evaluation, coupling coordination degree measurement, driving-factor identification, and policy simulation, aiming to reveal the intrinsic mechanisms of coordination between regional economic and ecological resilience and to identify optimal policy pathways for achieving their harmonious development. Although the YREB, as a critical economic region in China (as shown in Fig 1), has distinctive geographical conditions and resource endowments, the challenges it faces are globally representative, offering valuable theoretical insights and policy lessons for other developing countries. By conducting a comprehensive quantitative assessment of the economic and ecological dimensions and applying the coupling coordination degree model along with grey relational analysis to accurately identify key driving factors, this paper provides novel theoretical perspectives and practical strategies for addressing common dilemmas, such as the prevalent “pollute-first, treat-later” scenario and mismatches between economic growth and ecological restoration efforts in developing countries, thereby contributing to the global discourse on regional sustainable development.

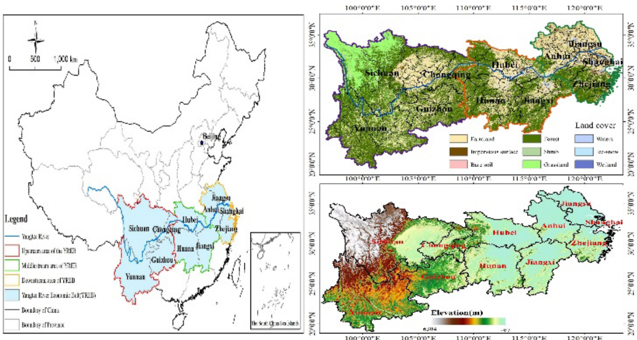

Figure 1- Geographic Location of the Yangtze River Economic Belt in China

2. Literature Review and Research Framework

2.1 Regional resilience theory and its applications

The concept of "resilience" originally comes from physics, initially describing the ability of an object to return to its original shape after experiencing external forces (Pawar et al., 2021). With continuous scholarly exploration, resilience has gradually expanded into the fields of society, economy, and ecology, becoming a key measure of a complex system's capacity to adapt, recover, and develop in response to external disturbances. In urban studies, resilience typically emphasizes a city's capacity to respond to and recover from crises such as natural disasters and social conflicts (Liu et al., 2022). In recent years, as regional development issues have become increasingly complex, scholars have expanded resilience theory to the regional scale and introduced the conceptual framework of "regional resilience."

Regional resilience is defined as the comprehensive capability of a region to effectively manage diverse uncertainties and disruptions arising from ecological conditions, resource supply, economic fluctuations, and social transformations during its developmental process (Desouza & Flanery, 2013). Regional resilience goes beyond merely emphasizing the recovery ability of individual cities or localities after shocks; rather, it highlights the interconnectedness and coordination among different regions. Martin (2012) argues that compared to urban resilience, regional resilience places greater importance on collaborative actions between regional actors, where multiple regions jointly mitigate the negative impacts of external shocks through coordinated efforts. Regional resilience primarily comprises two core dimensions: ecological resilience and economic resilience. Ecological resilience emphasizes the adaptability and recovery capacity of ecosystems under stress or disturbances (Mu et al., 2022), while economic resilience reflects an economic system's capability to withstand risks and recover from external shocks (Lu et al., 2022). Peng et al. (2023) further highlight that ecological resilience plays an essential role in supporting economic activities and maintaining ecosystem stability.

In terms of resilience measurement methods, current research typically integrates qualitative and quantitative approaches. Qualitative methods, including expert interviews and questionnaire surveys, help analyze the dynamics and interactions among system variables. Quantitative methods, by contrast, utilize numerical tools such as resilience indices, temporal function evaluations, and model simulations to achieve precise measurement (Moosavi & Hosseini, 2021; Quinlan et al., 2016). Among these approaches, resilience indices are widely applied to evaluate the resilience of ecological and economic subsystems (Han et al., 2023), providing robust theoretical foundations and practical frameworks for measuring regional resilience.

2.2 Multi-system coordination and coupling analysis research

Complex systems consist of multiple interacting components and subsystems, making internal coordination an essential research focus. In physics, the concept of "coupling coordination degree" is employed to measure the degree of interactive coordination among subsystems within complex systems. In recent years, the social sciences have adopted this concept to evaluate interactions and coordination between social, economic, and ecological systems. Xu et al. (2019) point out that economic, ecological, and social systems in regions such as the Yangtze River Economic Belt (YREB) exhibit high interactivity. Consequently, revealing the co-evolutionary characteristics among these systems through coupling coordination analyses has become a critical research direction in the field. The coupling coordination degree model, as an important quantitative analytical tool, effectively identifies potential bottlenecks encountered in regional development processes.

Recently, scholars have continuously expanded and improved upon coupling coordination models. For instance, Xiao et al. (2021) propose an innovative grey multivariable coupling model to evaluate the coordination between science and technology systems and economic systems at various developmental stages. Xu and Chen (2023) developed a more refined classification method, categorizing the coupling coordination states into ten types ranging from "extreme uncoordination" to "high-quality coordinated development," thus providing a more precise analytical framework for dynamically monitoring complex systems. Furthermore, Sun et al. (2024) introduced a novel coupling coordination assessment method for analyzing the relationship between socio-economic development and ecological environment quality, emphasizing its critical role in the sustainable development of mining towns.

Additionally, coupling coordination models have been progressively applied to more complex multi-dimensional system analyses. Cheng et al. (2023) established a coupling coordination model for food, water, and energy systems, revealing nonlinear interactions among these critical resources and their significant impacts on sustainable development goals. Zhu et al. (2023) further demonstrate that the coordination between economic development and ecosystems directly influences regional sustainability, making the improvement of coupling coordination between these two systems a crucial policy focus. These cross-system coordination analyses not only reveal the complexity of interactions among economic, ecological, and social systems but also provide robust scientific evidence for policy design aimed at achieving regional sustainable development.

2.3 Application of Policy Simulation in Complex Systems

Policy interventions, as critical external tools for influencing complex systems, significantly impact the dynamic evolution of these systems. Thus, how to effectively promote system coordination through policy implementation has become an essential research topic. System dynamics (SD), a powerful simulation modeling tool, plays a pivotal role in addressing this issue. With deepening research into complex systems, system dynamics has evolved into a fundamental approach for simulating the coupling and coordinated dynamic behaviors among multiple interacting systems. By establishing causal feedback relationships among system variables, the SD approach effectively reveals the dynamic evolution paths of complex systems under various policy scenarios.

For instance, Jiang et al. (2020) developed a system dynamics simulation method to analyze conflicting objectives in multipurpose reservoir scheduling, thoroughly uncovering the feedback mechanisms among different functional modules. Their study not only provides theoretical support for water resource management but also highlights the unique advantages of system dynamics in resolving multi-objective conflicts. Furthermore, system dynamics has been widely employed to explore the dynamic interactions among economic, ecological, and resource systems (Jia et al., 2021).

Moreover, the integration of system dynamics with coupling coordination models has offered a novel analytical perspective for policy optimization in complex systems. Xing et al. (2019) combined system dynamics with coupling coordination models to design and simulate four typical scenarios: a current scenario, an economic scenario, a resource scenario, and an environmental scenario. Their results indicated that the environmental scenario showed optimal coordination in the short term, whereas the resource scenario exhibited superior coordination effectiveness in the long term. Additionally, Cui et al. (2019) proposed a comprehensive analytical method integrating system dynamics with coupling coordination modeling. Their findings suggest that moderate economic growth combined with intensive water resource conservation significantly enhances system coordination. System dynamics is also extensively applied in multi-scenario forecasting analyses, simulating the long-term impacts of policy interventions under various hypothetical situations, underscoring its critical role in the design of policies for complex systems.

2.4 Research Framework

Although current research on regional resilience and complex system coordination has established a solid theoretical foundation, the existing literature still exhibits three notable shortcomings. First, prior studies have predominantly concentrated on urban resilience, leading to comparatively limited research on more comprehensive and macro-level regional resilience. Second, the mechanisms underlying interactions between regional ecological and economic resilience lack in-depth and systematic theoretical exploration. Third, existing simulation studies often suffer from a lack of systematic and theoretically grounded variable selection, making it difficult to adequately capture the interactive and feedback relationships among variables within complex systems.

To address these gaps and shortcomings, this study proposes an integrated and systematic research framework designed to thoroughly elucidate the complex interactive mechanisms between regional ecological and economic resilience, as illustrated in the Fig. A1 (Appendix) Specifically, the framework begins with a multidimensional resilience assessment, establishing a robust theoretical foundation for subsequent analyses. Next, the coupling coordination degree model is employed to quantitatively characterize the coordination levels between regional ecological and economic systems. Furthermore, grey relational analysis is utilized to accurately identify key influencing factors and deeply analyze their interactions. Finally, a system dynamics model is integrated to simulate system evolution under different policy scenarios, proposing optimized decision-making strategies. This integrated framework encompasses resilience assessment, coupling coordination measurement, influencing factor analysis, and policy simulation, providing a systematic analytical tool for regional sustainable development and offering solid practical guidance and theoretical support for policymakers and relevant researchers.

3 Research Methods

3.1 Construction of the Regional Resilience Evaluation Index System

This study focuses on the eleven provinces and municipalities within the Yangtze River Economic Belt (YREB). Data were primarily sourced from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook, and statistical yearbooks of respective provinces. All economic indicators were uniformly adjusted to 2010 constant prices to ensure data consistency and comparability.

To comprehensively assess ecological and economic resilience across the YREB, this research develops a multidimensional regional resilience evaluation indicator system. The ecological resilience indicator system encompasses three primary dimensions: ecological support capacity, ecological pressure perception, and ecological recovery capacity (Dakos & Kéfi, 2022; Nathwani et al., 2019; Zhang et al., 2020). These dimensions collectively reflect the ecosystem's performance in terms of resource carrying capacity, ecological stressors, and ecological recovery potential when responding to external disturbances. Specifically, the ecological resilience system comprises 19 sub-indicators (X1 to X19), detailed in Table 1.

The economic resilience evaluation index system includes three key dimensions: economic risk resistance, economic recovery momentum, and economic renewal capacity (Kou et al., 2024; Rao et al., 2023). These dimensions reflect the adaptive capability, vitality, and innovative potential of regional economic systems, respectively. This system is further subdivided into 17 detailed sub-indicators (Y1 to Y17), presented in Table 2. Utilizing these two indicator systems, this study aims to achieve a comprehensive and multi-level evaluation of regional ecological and economic resilience.

Regarding data processing, to ensure scientific validity and comparability of the evaluation results, economic indicators were standardized as follows: GDP data were adjusted to the base year of 2010 to eliminate inflationary effects; foreign trade and foreign direct investment (FDI) data were corrected using GDP deflators to remove biases caused by economic scale expansion; urban residents' disposable income per capita and social consumption expenditures were adjusted by the consumer price index (CPI) to ensure annual data comparability.

In determining indicator weights, this study employs the entropy weight method. Initially, the original data are standardized, followed by the calculation of each indicator's proportion. Subsequently, information entropy is utilized to measure the uncertainty of each indicator, and redundancy calculations yield the relative information content of each indicator. Finally, these weights are applied to calculate the comprehensive resilience indices. This methodological approach enhances the scientific rigor and rationality of weight determination, significantly improving the reliability and practical value of the evaluation system.

Table 1- Ecological Resilience Evaluation Indicators

Subsystem	**Code**	**Indicators**	**Unit**	**Indicator Attribute**
Ecological support capability system	X1	Per Capita Water Resources	m3/person	Positive
	X2	Forest Coverage Rate	%	Positive
	X3	Green Coverage Rate	%	Positive
	X4	Per Capita Green Area	m2	Positive
	X5	Public Transport Density	Standard Buses/10,000 People	Positive
	X6	Rural Renewable Energy Utilization Intensity	m2/person	Positive
	X7	Urban Sewage Pipeline Density	km/10,000 People	Positive
Ecological stress perception system	X8	Wastewater Emission Intensity	Tons/100 Million Yuan	Negative
	X9	SO2 Emission Intensity	Tons/100 Million Yuan	Negative
	X10	Carbon Emission Intensity	10,000 Tons/100 Million Yuan	Negative
	X11	Electricity Consumption Intensity	100 Million kwh/100 Million Yuan	Negative
	X12	Population Density	People/km²	Negative
	X13	Population Growth Rate	%	Positive
Ecological restoration capability system	X14	Industrial Solid Waste Treatment Rate	%	Positive
	X15	Harmless Waste Treatment Capacity	10,000 Tons/Day	Positive
	X16	Total Sewage Treatment Capacity	10,000 Tons/Day	Positive
	X17	Urban Sewage Treatment Rate	%	Positive
	X18	Urban Environmental Infrastructure Investment Intensity	%	Positive
	X19	Industrial Pollution Control Investment Intensity	%	Positive

Table 2- Economic Resilience Evaluation Indicators

Sub-system	Code	Indicators	Unit	Indicator Attribute
Economic risk resilience system	Y1	Per Capita Disposable Income in Urban Areas	Yuan /Person	Positive
	Y2	Urbanization Rate	%	Positive
	Y3	Foreign Trade Dependence	%	Negative
	Y4	Unemployment Insurance Coverage Rate	%	Positive
	Y5	Medical Insurance Coverage Rate	%	Positive
Economic momentum recovery system	Y6	Per Capita GDP	10,000 Yuan/Person	Positive
	Y7	Per Capita Freight Turnover	10,000 Ton-Kilometers/Person	Positive
	Y8	Fiscal Self-sufficiency Rate	%	Positive
	Y9	Per Capita Social Consumption Expenditure	Yuan/Person	Positive
	Y10	Traffic Line Density	km/km2	Positive
	Y11	Market Economic Activity	%	Positive
Economic development renewal system	Y12	Education Expenditure Level in Fiscal Budget	%	Positive
	Y13	Science Expenditure Level in Fiscal Budget	%	Positive
	Y14	Industrial Upgrade Index	/	Positive
	Y15	Openness to the Outside World	%	Positive
	Y16	Higher Education Development Level	Students/0.1 Million People	Positive
	Y17	Green Technology Innovation Level	Patents/10,000 People	Positive

3.2 Coupling Coordination Degree Measurement Model

To quantitatively analyze the cooperative or conflicting relationship between regional ecological resilience and economic resilience, this study designs a coupling coordination degree model. First, coupling degree (C) is computed using formula (1) to measure the interaction intensity between ecological and economic systems, where n = 2. The study adopts the modified approach proposed by Wang et al. (2021), effectively overcoming the limitations inherent in traditional equal-weight assumptions. Second, a comprehensive evaluation index (T) is calculated according to formula (2), reflecting the overall developmental level of ecological and economic systems and providing the foundation for coupling coordination measurement. Subsequently, coupling coordination degree (D) is obtained by integrating coupling degree and comprehensive evaluation index based on formula (3), comprehensively assessing the coordinated development status between ecological and economic systems.

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

$$T=\sum_{i=1}^{n}\alpha_i\times R_i\ ,\ \sum_{i=1}^{n}\alpha_i=1 \tag{2}$$

$$D=\sqrt{C\times T} \tag{3}$$

Following the research of He et al. (2017), coupling coordination degree (D) is classified into 4 major categories further subdivided into 12 subcategories, detailed in Table 3. This model quantitatively evaluates the coordination between ecological and economic systems, thereby providing clear theoretical guidance and practical directions for policy-making aimed at regional sustainable development.

Table 3- Classification of Coupling Coordination Degree

Coupling Coordination Degree Value	Major Type	Ecological and Economic Resilience Comparison Relationship	Subtype
$0.8<D\leq1$	Advanced Coordination	$R_{ecology}-R_{economy}>0.1$	Advanced Coordination - Economic Resilience Lagging
		$R_{economy}-R_{ecology}>0.1$	Advanced Coordination - Ecological Resilience Lagging
		$0\leq\lvert R_{economy}-R_{ecology}\rvert\leq0.1$	Advanced Coordination
$0.5<D\leq0.8$	Basic Coordination	$R_{ecology}-R_{economy}>0.1$	Basic Coordination - Economic Resilience Lagging

		$R_{economy}-R_{ecology}>0.1$	Basic Coordination - Ecological Resilience Lagging
		$0\leq\lvert R_{economy}-R_{ecology}\rvert\leq0.1$	Basic Coordination
$0.3<D\leq0.5$	Basic Non-coordination	$R_{ecology}-R_{economy}>0.1$	Basic Non-coordination - Economic Resilience Lagging
		$R_{economy}-R_{ecology}>0.1$	Basic Non-coordination - Ecological Resilience Lagging
		$0\leq\lvert R_{economy}-R_{ecology}\rvert\leq0.1$	Basic Non-coordination
$0<D\leq0.3$	Severe Non-coordination	$R_{ecology}-R_{economy}>0.1$	Severe Non-coordination - Economic Resilience Lagging
		$R_{economy}-R_{ecology}>0.1$	Severe Non-coordination - Ecological Resilience Lagging
		$0\leq\lvert R_{economy}-R_{ecology}\rvert\leq0.1$	Severe Non-coordination

3.3 Model for Analyzing Influencing Factors of Regional Resilience Coordination

To further identify key influencing factors affecting the coupling coordination between regional ecological and economic resilience, this study constructs a grey relational analysis (GRA) model following Long et al. (2022), detailed in formulas (4)–(7). The analysis encompasses five specific steps: first, constructing a panel data matrix that systematically represents the distribution of each indicator and observation year, reflecting multidimensional data structures; second, initializing the panel data to ensure consistency and comparability, removing outliers, and addressing missing values to enhance data quality; third, calculating grey relational coefficients by comparing differences between initialized data and reference matrices, thereby quantitatively assessing correlations between subsystem indicators and reference indices; fourth, calculating the overall relational degree (γi) to further evaluate the strength of the relationship between each indicator and the reference index; fifth, identifying the key factors significantly influencing coupling coordination between ecological and economic resilience based on the overall relational degree. This analytical method systematically and accurately identifies core influencing factors, providing robust theoretical support for regional resilience coordination research and precise directional guidance for subsequent policy interventions.

$$\gamma_i(x,t)=\frac{\Delta(\min)+\rho\Delta(\max)}{\left|y_i(x,t)d_i-y_1(x,t)d_1\right|+\rho\Delta(\max)} \quad (4)$$

$$\gamma_i=\frac{1}{XT}\sum_{x=1}^{X}\sum_{t=1}^{T}\gamma_i(x,t) \quad (5)$$

$$\gamma_{i,t}=\frac{1}{X}\sum_{x=1}^{X}\gamma_i(x,t) \quad (6)$$

$$\gamma_{i,x}=\frac{1}{T}\sum_{t=1}^{T}\gamma_i(x,t) \quad (7)$$

3.4 Policy Simulation Model for Regional Resilience Coordination

To effectively simulate policies aimed at coordinating regional ecological and economic resilience, this study develops a system dynamics-based simulation model. The model seeks to deeply analyze the long-term effects and effectiveness of policy interventions within complex systems. The model construction involves two key stages: initially, a causal feedback analysis is conducted to identify and clarify the interaction mechanisms and feedback relationships among variables within ecological and economic resilience systems. The causal feedback diagram (see Fig. A2 in Appendix 2) explicitly illustrates the dynamic evolution and influence pathways of each variable on the coupling coordination degree.

Subsequently, based on the causal feedback analysis, a system dynamics simulation model is constructed using Vensim software, explicitly defining and representing dynamic relationships among variables within ecological and economic resilience systems. A stock-flow diagram (see Fig. A3 in Appendix 3) visually demonstrates dynamic changes and interactions among variables under various policy scenarios. This model enables the simulation of dynamic behaviors of ecological and economic systems under different policy interventions, effectively predicting the long-term effects and trends of policy measures on regional resilience coordination. Ultimately, the model provides policymakers with robust theoretical support, assisting them in optimizing policy pathways for regional resilience coordination.

4 Results and Discussion

4.1 Analysis of Regional Resilience Evaluation Results

This study systematically assessed ecological and economic resilience within the Yangtze River Economic Belt (YREB). As shown in Fig. 5, several key patterns were revealed. These patterns not only facilitate an understanding of regional disparities within the YREB but also provide valuable references for regional resilience studies in other developing countries.

First, substantial differences exist in economic and ecological resilience across regions, reflecting significant imbalances. Economically advanced downstream areas (e.g., Jiangsu, Shanghai) demonstrated relatively higher levels of resilience in both economic and ecological dimensions, while economically disadvantaged upstream and middle regions (e.g., Sichuan, Guizhou, Hubei) showed lower resilience in both aspects. This phenomenon highlights a common issue among developing countries: regions with weaker economies often exhibit vulnerability not only economically but also ecologically, further constraining their overall capacity for sustainable development.

Second, ecological resilience generally outpaced economic resilience. With the exception of Shanghai, most provinces exhibited higher ecological resilience compared to economic resilience. This trend indicates that although economically less-developed areas often possess relatively strong ecological recovery capabilities, these ecological advantages rarely translate automatically into economic growth. The primary reason is the absence of effective mechanisms and channels to convert ecological assets into economic benefits. Specifically, insufficient infrastructure has restricted the development of eco-tourism and green industries; underdeveloped market mechanisms have hindered the economic valuation of ecological products; and slow industrial transformation has limited the industrialization of ecological resources. As a result, ecological resilience does not directly translate into tangible economic advantages.

Finally, the growth rate of economic resilience significantly lagged behind that of ecological resilience, underscoring considerable regional heterogeneity within developing countries. In economically disadvantaged regions, economic resilience improvements typically trail behind gains in ecological resilience, making economic development the central task in these areas. Unlike developed countries, these regions primarily face the challenge of enhancing economic resilience rather than ecological resilience. Consequently, despite improvements in ecological resilience, the pace of economic resilience growth remains considerably slower. Thus, economically lagging regions in developing countries must place greater emphasis on building economic resilience, particularly by strengthening economic fundamentals alongside accelerated growth, to effectively cope with external shocks and secure sustainable development.

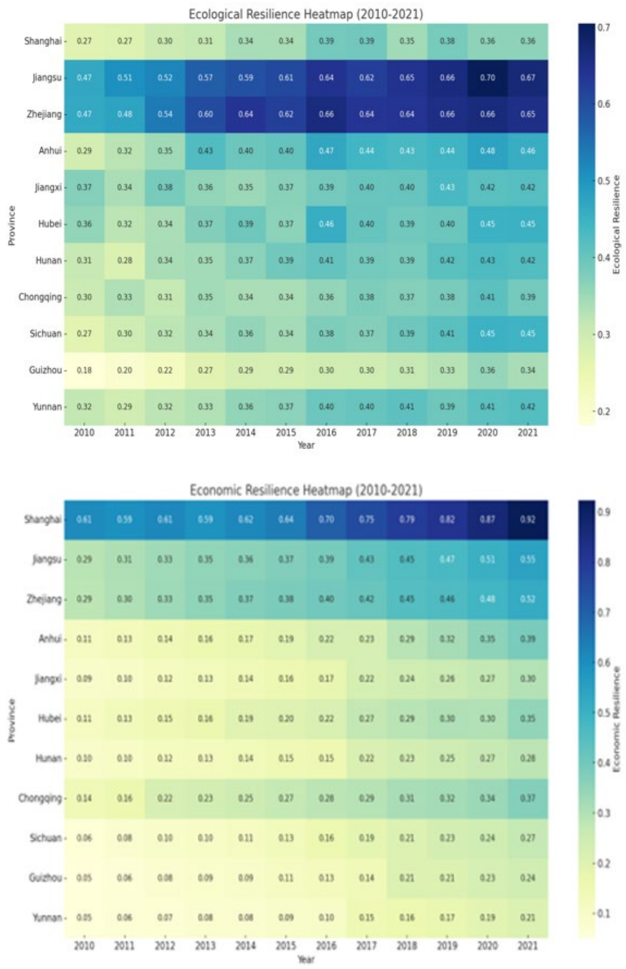

Figure 2- Evaluation results of regional ecological and economic resilience.

4.2 Discussion on the Coordination Relationship Between Economic and Ecological Resilience

This study calculated the annual coupling coordination degree across provinces within the YREB (see Fig. 6), extracting three broadly applicable patterns that illustrate regional differences and provide theoretical insights for coordination between economic and ecological resilience in developing countries.

First, clear distinctions emerged among upstream, middle, and downstream regions within the YREB. Economically advanced downstream regions (Shanghai, Jiangsu, Zhejiang) exhibited high levels of coordination between economic and ecological resilience, reflecting effective interplay between the two systems. Conversely, middle (Jiangxi, Hubei, Hunan) and particularly upstream regions (Chongqing, Sichuan, Guizhou, Yunnan) initially displayed relatively low coordination, with economic resilience notably lagging behind ecological resilience. This regional disparity underscores a common issue facing economically underdeveloped areas in many developing countries: despite relatively robust ecological resilience, limited economic resilience restricts productive interactions between ecological assets and economic development. Consequently, ecological resources remain inadequately leveraged for economic benefit, presenting a prevalent challenge.

Second, the overall coupling coordination degree within the YREB has gradually improved, with notable advancements in provinces such as Sichuan and Hubei, transitioning from "basically uncoordinated" to "basically coordinated" states. This improvement primarily resulted from strengthened economic resilience driven by industrial transformation and green development policies, particularly evident in Hubei after 2017, fostering positive interactions between ecological and economic resources. However, certain provinces, like Jiangxi, remain in a state of "basic uncoordination," reflecting inherent challenges due to weaker economic foundations. The inefficient economic utilization of ecological resources in these regions arises specifically from inadequate financial investments, limited technological applications, and insufficient integration within industrial value chains.

Third, insufficient economic resilience is identified as the primary factor contributing to low coordination levels. Despite favorable ecological conditions, the upstream provinces' weak economic fundamentals limit their ability to recover and adapt, thereby constraining their coordination with ecological systems. In contrast, downstream regions with stronger economic resilience better align with the carrying capacity of ecological systems, resulting in higher coupling coordination degrees. This observation underscores that enhancing economic resilience is essential for fostering coordinated development between regional economic and ecological systems.

In conclusion, challenges associated with regional resilience coordination are not unique to the YREB but are widespread among developing countries. Future policy interventions should prioritize enhancing economic resilience in economically disadvantaged regions, particularly through targeted investments in infrastructure development, market mechanism improvements, and industrial transformation and upgrading. These efforts will stimulate productive interactions between economic and ecological systems, thereby achieving sustainable regional development.

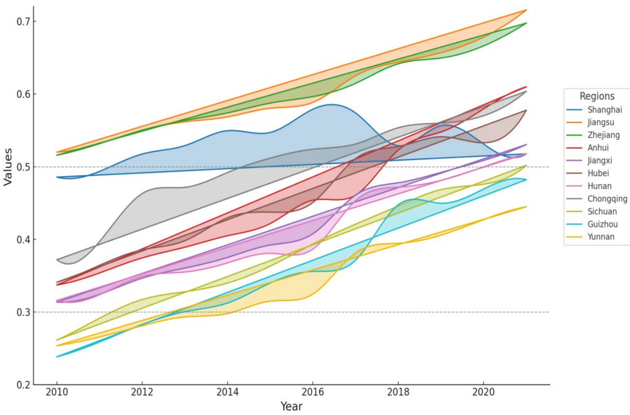

Figure 3- Coupling coordination degree between regional ecological and economic resilience.

4.3 Ranking of Core Driving Factors Influencing Regional Resilience Coordination

This study utilized a grey relational analysis model to rank the associations between key indicators within the six subsystems of ecological and economic resilience and the regional resilience coordination level (see Fig. 4), aiming to clearly identify core driving factors that promote coordinated regional development. This analysis provides valuable theoretical insights not only for the Yangtze River Economic Belt (YREB) but also broadly for resilience coordination challenges commonly faced by developing countries.

Ecological resilience comprises three subsystems: ecological support capacity, ecological pressure perception, and ecological recovery capacity. Specifically, green space coverage, sewage pipeline density, and rural renewable energy utilization significantly enhance regional ecological support capacity, offering stable environmental and resource conditions for economic activities. Conversely, increases in electricity consumption intensity, carbon emission intensity, and population density amplify ecological pressures, thus reducing the overall ecological resilience of the region. Furthermore, higher rates of industrial solid waste treatment and wastewater treatment notably enhance ecological recovery capacity, ensuring rapid ecosystem restoration following external disturbances. These findings underscore the necessity for developing countries with constrained resources to comprehensively coordinate resource support, ecological pressure management, and recovery capabilities to establish a stable and sustainable ecological foundation.

Economic resilience, meanwhile, consists of three subsystems: economic risk resistance, economic recovery momentum, and economic renewal capacity. The analysis revealed that higher levels of per capita disposable income and urbanization significantly enhance economic risk resistance capabilities. Additionally, increased transport network density and higher per capita GDP effectively drive economic momentum recovery and vitality improvement. Furthermore, the industrial upgrading index and levels of green technological innovation substantially contribute to regional economic structural transformation and sustained innovation. These results suggest that developing countries pursuing economic growth must place greater emphasis on optimizing economic structures and bolstering innovative capacities, thereby strengthening their long-term resilience against external shocks.

Overall, core driving variables within ecological and economic systems jointly shape regional resilience coordination levels. This study not only clarifies the roles of critical indicators within each subsystem but also emphasizes their synergistic effects. Consequently, this research provides systematic theoretical and empirical support for improving coordinated ecological and economic development in developing countries. By focusing on key driving factors, this study further extends policy perspectives and offers valuable experiences and insights for international research on regional resilience.

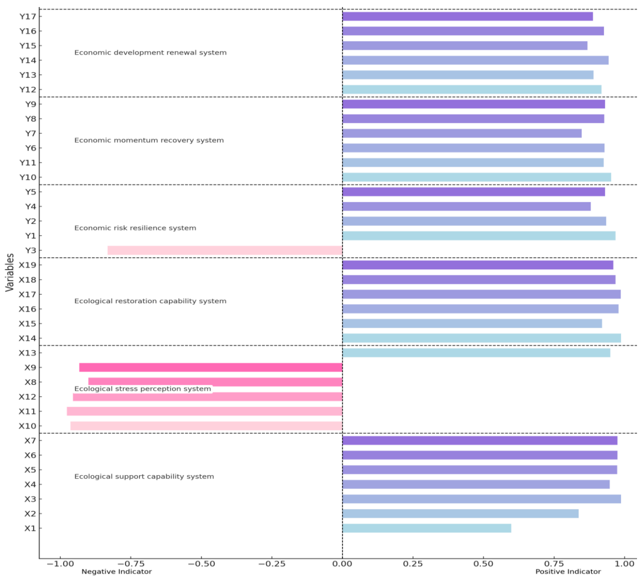

Figure 4- Ranking of influencing factors for coupling coordination degree of regional resilience.

4.4 Policy Simulation and Scenario Analysis

Policy simulation for coordinated regional resilience development consists of two main steps. The first step involves identifying core influencing factors based on the results from Section 4.3, "Ranking of Core Driving Factors Influencing Regional Resilience Coordination," and subsequently setting up policy simulation scenarios. The second step involves adjusting parameters within the system dynamics model based on these policy scenarios, conducting simulations to analyze policy effectiveness, and ultimately determining the efficacy and direction of policy interventions.

4.4.1 Construction of Policy Simulation Scenarios

Based on the ranking of core influencing factors, this study identified critical variables significantly impacting coupling coordination degree and established a baseline scenario (PSS_0), which extends historical development trends from 2010 to 2021 without additional policy interventions. Subsequently, seven distinct policy simulation scenarios (PSS_1 to PSS_7) were designed, specifically targeting six dimensions: ecological support, ecological pressure, ecological recovery, economic risk resistance, economic momentum recovery, and economic renewal capacity (see Fig. 5).

In scenarios PSS_1 through PSS_6, each scenario incorporated five influential factors, with those positively affecting coupling coordination increased by 20%, while those with negative impacts were decreased by 20%. For example, in the ecological pressure perception scenario (PSS_2), four factors negatively impacting coupling coordination (X9, X10, X11, X12) were each decreased by 20%, whereas one positively influencing factor (X13) was increased by 20%. Scenario PSS_7, by contrast, selected the most impactful indicator from each of the six subsystems, specifically increasing five positive indicators by 20%—namely, green space coverage (X3) from the ecological support subsystem, industrial solid waste treatment rate (X14) from the ecological recovery subsystem, urban residents' disposable income per capita (Y1) from the economic risk resistance subsystem, transport network density (Y10) from the economic momentum recovery subsystem, and industrial upgrading index (Y14) from the economic renewal subsystem—while reducing the negatively impactful indicator of electricity consumption intensity (X11) from the ecological pressure subsystem by 20%. This scenario design ensures logical consistency within the theoretical framework and provides quantitative foundations for policy simulation, thus expanding the research perspective from single-indicator adjustments to systematically integrated policy combinations.

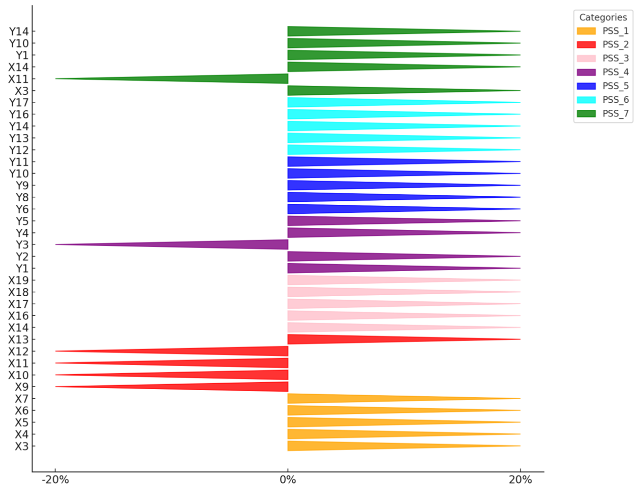

Figure 5- Construction of policy simulation scenarios for coordinated regional resilience development.

4.4.2 Discussion of Policy Simulation Results

By comparatively analyzing the coupling coordination degree across seven distinct policy scenarios (see Fig. 6), this study highlights three core conclusions. These conclusions not only validate the effectiveness of the theoretical model but also illuminate key challenges commonly encountered by developing countries in their efforts to achieve coordinated regional economic and ecological development, offering valuable insights and novel perspectives for international academia.

In the baseline scenario (PSS_0), representing a continuation of the existing development trajectory, the regional coupling coordination did not improve substantially, although it was not the worst among all scenarios. This result implies that while the regional system maintains a certain inherent resilience under natural development conditions, it faces structural bottlenecks that cannot be resolved merely through the existing economic growth pattern. Further simulation results indicate that although approximately 80% of the policy scenarios outperformed the baseline in annual performance, only a select few scenarios (such as PSS_4, PSS_3, and PSS_5) achieved significant long-term improvements in coordination levels. This outcome underscores the critical importance of precise and targeted policy design within complex systems. Consequently, developing countries aiming for regional sustainable development must emphasize scientific rigor and meticulous policy management, avoiding broad, unfocused policy combinations that risk falling into inefficient development traps characterized by rapid growth without structural advancement.

The multi-dimensional composite policy scenario (PSS_7) exhibited lower overall performance compared to single-focused policy scenarios and consistently ranked lowest throughout the simulation period. Although this result appears initially at odds with system dynamics theory, which stresses interactive effects in complex systems, it actually demonstrates the model's sensitivity in capturing potential issues of insufficient policy coordination and resource dispersion. In developing countries, constraints in resource endowments and administrative capacity frequently impede effective coordination across multiple policy dimensions, leading to negative interactions among policies that ultimately diminish their collective effectiveness. For instance, in Bangladesh (South Asia), ineffective internal coordination among multiple development policies has resulted in resource competition and reduced overall effectiveness. Similar issues have been observed in Uganda and Zimbabwe (Sub-Saharan Africa), where simultaneous implementation of various sectoral policies incurred high administrative costs and fragmented resource allocation, diminishing policy performance. Therefore, policymakers should prioritize internal coherence and coordination within policy packages, selectively implementing fewer but clearly prioritized, precise, and effective policies rather than broadly defined, ambiguous multi-dimensional approaches.

Finally, economic policy scenarios demonstrated substantially greater long-term effectiveness than ecological policy scenarios. Although ecological policies yielded quicker improvements in ecological conditions in the short term, economic risk resistance and economic momentum recovery policies (such as PSS_4 and PSS_5) significantly outperformed them in terms of enhancing regional coupling coordination in the long run. This finding supports the core argument of ecological economics theory: a stable and resilient economic foundation is the fundamental prerequisite for sustained ecological protection. Enhanced economic resilience provides continuous financial, technological, and institutional support for ecological restoration, creating a long-term positive feedback loop between economic and ecological systems. International experiences substantiate this conclusion. In Latin America, countries such as Chile and Colombia have effectively strengthened economic resilience through industrial upgrading and technological innovation policies, subsequently fostering sustained ecological-economic coordination. Similarly, India (South Asia) has substantially improved regional coordination between economic growth and ecological protection through infrastructure investments aimed at strengthening industrial resilience. These international cases align with the simulation outcomes of this study, collectively emphasizing the superior long-term efficacy of economic policies. Thus, establishing a robust economic foundation emerges as a critical breakthrough point for achieving coordinated regional economic-ecological development.

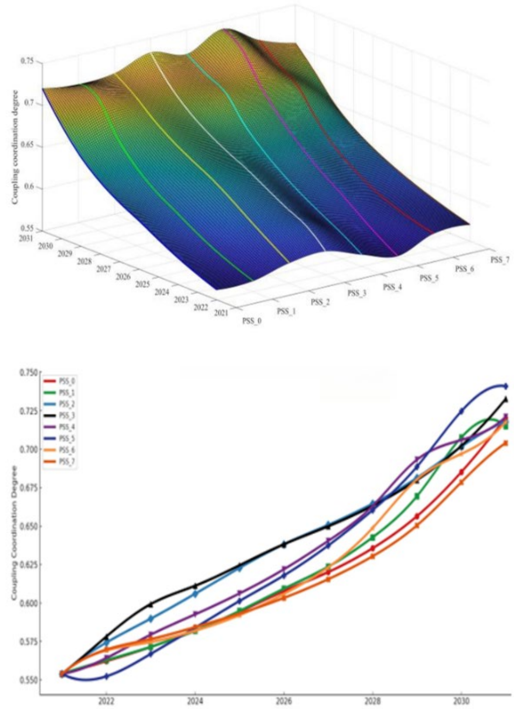

Figure 6- Analysis of regional resilience coordination under multiple policy simulation scenarios.

In summary, this study's policy simulations deepen our theoretical and practical understanding of mechanisms underlying regional resilience coordination. The findings highlight that developing countries must specifically emphasize building economic resilience, complemented by targeted ecological support and recovery policies, to effectively achieve long-term coordinated economic and ecological development. This study not only contributes new perspectives to international discussions regarding regional coordination and sustainable development but also provides substantial empirical references and policy insights for developing countries pursuing green, resilient development pathways.

4.5 Comprehensive Discussion

Drawing on the proposed research framework, this study identifies a set of broadly applicable patterns evident within the Yangtze River Economic Belt (YREB), which hold significant implications for developing countries. Overall, the study offers comprehensive insights from three key dimensions: dynamic processes and long-term effects, contradictions between economic and ecological resilience, and the synergistic effects of multi-policy combinations, thereby enriching international theoretical discourse on coordinated economic-ecological development.

Simulation outcomes reveal that policy scenarios exhibit varying dynamic patterns over time, and the ultimate effectiveness of a policy is not solely determined by intermediate fluctuations. For instance, while the ecological recovery scenario (PSS_3) demonstrated superior performance from 2022 to 2025, and the ecological pressure reduction scenario (PSS_2) performed well from 2026 to 2028, the economic momentum recovery scenario (PSS_5) ultimately yielded the most substantial improvement in coupling coordination over the long term. This dynamic disparity indicates that comprehensive evaluations of policy effectiveness in complex systems must consider long-term trends, as short-term advantages do not always translate into lasting systemic breakthroughs. This finding is especially critical for developing countries, which typically confront persistent economic fragility alongside ecological pressures, necessitating nuanced policy strategies that balance immediate gains with sustainable long-term outcomes.

Within the YREB, economic resilience markedly lags behind ecological resilience, particularly in economically weaker upstream regions. Despite their relatively abundant ecological resources, these areas struggle to effectively translate ecological advantages into economic growth due to weak economic foundations, inadequate infrastructure development, and incomplete market mechanisms, all of which impair their economic recovery and adaptation capacities. This imbalance significantly constrains improvements in regional coupling coordination. This issue also prevails in regions within Latin America, Sub-Saharan Africa, and South Asia, where despite relatively abundant ecological resources, economic transformation challenges persist, compounded by underdeveloped market structures and insufficient infrastructure investment, leading to mismatches between ecological conservation and economic growth. Consequently, a widespread challenge faced by developing countries is effectively overcoming structural economic constraints through targeted policy interventions, actively facilitating the economic utilization of ecological resources, and fostering virtuous cycles between economic and ecological systems.

The relatively poor performance of the multi-dimensional composite policy scenario (PSS_7) reflects inherent difficulties in coordination and resource dispersion during the design and implementation of multi-faceted policies. Although theoretically capable of comprehensively addressing critical aspects of economic and ecological development, multi-dimensional policies often inadvertently generate negative interactions among variables, resulting in unintended trade-offs, unclear policy objectives, increased administrative costs, and inefficient resource allocation. The simulation results clearly identify and illustrate these potential conflicts and inefficiencies, demonstrating the capability of the system dynamics approach to sensitively capture and analyze intricate policy coordination issues. For developing countries with limited resources and governance capacities, precise policy design is crucial. Policymakers must clearly define policy priorities and weights, carefully avoiding broadly conceived, unfocused policy packages, to enhance resource efficiency and achieve clear, measurable policy outcomes.

5. Model Validation and Robustness Tests

To ensure the constructed system dynamics model accurately reflects the dynamic behaviors of ecological and economic resilience systems and effectively predicts the impacts of policy interventions, this study conducted comprehensive validations through five procedures: system boundary verification, theoretical verification, goodness-of-fit analysis, stability testing, and sensitivity analysis. These rigorous validation steps not only reinforce the scientific rigor and reliability of the model but also provide a solid theoretical foundation for interpreting the policy simulation results. Additionally, these validation procedures offer valuable methodological references for international academia and developing countries focusing on regional coordinated development.

5.1 System Boundary Verification

The primary objective of the system boundary verification is to confirm that the selected model variables comprehensively represent the essential dynamic characteristics of the studied system. Through an extensive literature review combined with a clearly articulated theoretical framework, this study meticulously selected critical indicators representing economic resilience (such as urbanization rate and GDP per capita) and ecological resilience (such as green space coverage and wastewater treatment capacity). Simultaneously, secondary indicators with minor impacts or those with limited data availability were systematically excluded. This rigorous selection process ensures the completeness of the model structure and the scientific rationality of the boundary settings, allowing the model to accurately and comprehensively reflect interactions and dynamic characteristics between regional economic and ecological systems.

5.2 Theoretical Verification

Theoretical verification primarily involves constructing and analyzing causal relationship diagrams to ensure the rationality and logical coherence of causal interactions among model variables. This study clearly defined core pathways; for instance, green space coverage substantially enhances ecological support capacity, and urbanization rates significantly improve economic risk resistance capabilities. These relationships align closely with existing regional development logic and established academic literature. The outcomes of theoretical verification further solidify the academic validity of the model, endowing it with robust theoretical interpretability when describing complex system dynamics, thus reinforcing the theoretical soundness of the model.

5.3 Goodness-of-Fit Analysis

Goodness-of-fit analysis involves comparing historical data with simulation outputs to assess the model's precision in replicating historical trends. As depicted in Fig. A4 (in Appendix 4), this study performed detailed comparative analyses on twelve key indicators from the six ecological and economic resilience subsystems. All simulation errors were strictly controlled within a 10% margin, with the maximum deviation recorded at 6.75% and the minimum approaching zero. These results strongly indicate that the constructed system dynamics model possesses high predictive accuracy and reliability, effectively capturing historical trends of the regional systems and providing robust data support for subsequent policy scenario simulations.

5.4 Stability Testing

The stability testing evaluates the consistency and robustness of the model's behavior under varying parameter settings and time-step adjustments. As demonstrated in Fig. A5 (in Appendix 5), this study selected several core variables—including forest coverage rate, population density, and urban sewage treatment rate—and conducted simulations under different time steps (1 year, 0.5 years, and 0.25 years) as well as varying initial conditions. Results indicated no significant deviation in the predicted trends of these variables across scenarios, confirming the model's stable and consistent dynamic characteristics. These findings further validate the model's robustness, ensuring its ability to consistently and accurately simulate the long-term dynamics of regional systems under diverse conditions .

5.5 Sensitivity Analysis

Sensitivity analysis primarily assesses the responsiveness and sensitivity of dependent variables in the model to changes in critical independent variables. As illustrated in Fig. 7, this study adjusted key independent variables such as population size, GDP, and per capita green space area by ±10%. Results showed corresponding dependent variables (such as per capita water resources and green coverage rate) exhibited nearly proportional changes around 10%, highlighting the model's high sensitivity to these variables. Further multi-factor sensitivity analyses indicated that GDP, population density, and energy consumption intensity exerted the most pronounced influence on the model outcomes. These sensitivity analysis results not only confirm the model’s accurate representation of real-world dynamics but also provide clear insights into key influencing factors and critical intervention points for subsequent policymaking.

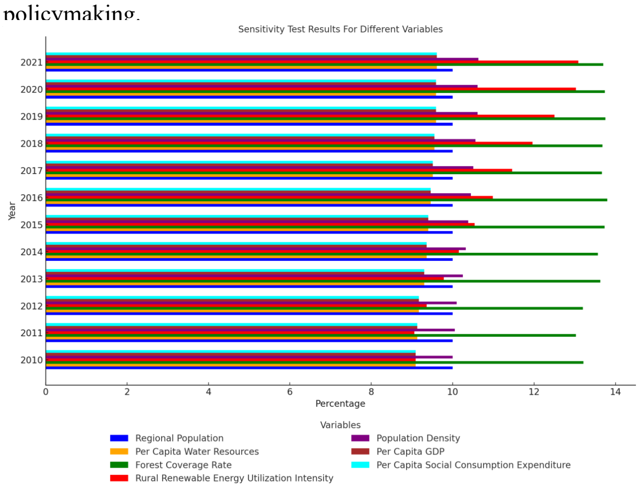

Figure 7- Sensitivity testing results of the system dynamics model.

Overall, through comprehensive model validation and robustness testing procedures, the constructed system dynamics model demonstrated a robust theoretical foundation, high goodness-of-fit accuracy, strong stability, and pronounced sensitivity to key variable changes, substantially enhancing the overall credibility of the model. This robust validation provides solid scientific evidence for subsequent policy scenario analysis and effective formulation of regional economic-ecological coordination strategies. Moreover, the validation framework offers internationally relevant comparative research methods and practical experiences for developing countries seeking to address similar challenges within their green and sustainable development pathways.

6.Conclusions and Policy Recommendations

6.1 Conclusions

This study focuses on the issue of coordinating regional economic and ecological resilience, developing an integrated analytical framework that encompasses resilience evaluation, coupling coordination measurement, influential factor identification, and policy simulation. Based on an empirical analysis of the Yangtze River Economic Belt (YREB), the following key conclusions are drawn:

A clear imbalance between economic and ecological resilience commonly exists in developing countries. Specifically, ecological systems typically demonstrate relatively strong support and recovery capabilities, especially following the implementation of ecological protection measures. However, economic resilience consistently lags behind, particularly in regions with weaker economic foundations, forming a significant bottleneck that constrains overall regional resilience and coordinated development. This phenomenon reflects the broader neglect in building economic resilience during economic growth processes in many developing countries, resulting in ineffective coordination between economic and ecological systems.

Significant regional disparities exist within the YREB in terms of resilience coordination. Economically developed regions demonstrate higher synergy between economic and ecological resilience, thus exhibiting stronger overall sustainability. In contrast, economically underdeveloped areas, particularly in upstream and midstream regions of the Yangtze River, show a marked lag of economic resilience relative to ecological resilience. Due to insufficient economic foundations, inadequate infrastructure development, and poorly developed market systems, these regions experience difficulties in rapid economic recovery, limiting productive interactions between economic and ecological systems. This regional divergence indicates that ecological protection measures typically achieve rapid outcomes, whereas economic recovery and resilience enhancement require more time and solid economic foundations.

The core driving factors influencing regional resilience coordination have been clearly identified. Ecological support capacity, ecological recovery capability, economic risk resistance, and economic recovery momentum all play decisive roles in coordinated regional development. Specifically, ecological variables such as green space coverage and wastewater treatment capacity significantly enhance ecological resilience, while economic variables like per capita disposable income and transportation network density effectively improve economic resilience. Clearly identifying the roles of these key factors enables developing countries to design and implement targeted policy interventions more effectively.

Policy simulations conducted through the system dynamics model further revealed varying degrees of policy effectiveness. The baseline scenario (PSS_0), which follows historical development trends, failed to significantly enhance coordination but was not the worst scenario; meanwhile, targeted policy interventions considerably improved regional resilience coordination. Policy effectiveness heavily depends on precision in policy design. Single economic-focused policies exhibited superior long-term outcomes compared to multi-dimensional composite policies, primarily because the latter often suffer from internal conflicts among variables, reducing their overall effectiveness. Furthermore, economic policy scenarios demonstrated superior long-term performance compared to ecological policy scenarios, reinforcing a central tenet of ecological economics: a stable economic foundation is a fundamental prerequisite for sustained ecological protection. Enhanced economic resilience provides continuous and stable financial and technological support for ecological restoration, promoting a long-term positive feedback loop between economic and ecological systems.

6.2 Policy Recommendations

Based on the above conclusions, this study proposes four specific policy recommendations aimed at effectively guiding developing countries towards coordinated regional economic and ecological development:

Developing countries should implement differentiated and precise policies tailored to the specific stages of regional economic and ecological development. In regions with weak economic resilience, priority should be given to infrastructure construction, industrial structure upgrading, and green technological innovation to enhance the regional economic system's capacity to withstand external risks, laying a solid foundation for coordinated economic and ecological development. For instance, Indonesia successfully enhanced the economic resilience of Java and Sumatra through sustained infrastructure improvements and industrial park developments, effectively promoting regional coordination between economic and ecological systems.

Policy design should focus on core variables to avoid potential conflicts inherent in multi-dimensional policy approaches. Economic momentum recovery policies should form the central focus, complemented by necessary ecological support and recovery measures. This combination significantly enhances economic resilience and provides resources for ecological protection, thus preventing resource waste caused by overly dispersed policy objectives. For example, Chile effectively strengthened its economic resilience through targeted support policies for copper mining and agricultural industry upgrading, accompanied by ecological restoration measures, thereby achieving dual objectives of economic stability and ecological improvement.

Policy interventions must fully consider regional differences. In economically disadvantaged regions, priority should be placed on single-focused economic policies such as enhancing fiscal self-sufficiency, boosting market activity, and promoting industrial upgrading. These policies have demonstrated stronger long-term impacts on regional economic resilience. Concentrating resources to restore and strengthen economic momentum is therefore crucial. Ethiopia, for example, substantially enhanced its economic resilience through fiscal investment and industrial support policies prioritizing the manufacturing and export processing sectors, thereby providing a robust economic foundation for ecological protection and sustainable development.

During policy implementation, it is essential to establish and reinforce a dynamic monitoring and adjustment system based on adaptive governance theory. Specifically, the central government should set overall strategic objectives, prioritize policies, and coordinate interregional policies, while local governments should manage phased policy implementation, real-time monitoring, and feedback. Employing quantitative analytical tools such as system dynamics allows timely policy adjustments and optimization, ensuring flexibility and effectiveness during policy implementation. South Africa, for instance, has established a nationwide, cross-departmental policy monitoring system, enhancing coordination and communication between central and local governments. Regular policy assessments and dynamic adjustments have ensured the long-term effectiveness and coordination of economic and ecological policies.

7. Author contributions

All authors contributed significantly to the conception and design of the study. Conceptualization, methodology development, and preparation of the original draft were performed by Yifan Wang. Data curation, editing, and grammar reviewing of this manuscript were done by Zihui Han. Bing Wang designed the research framework, supported funding, and was responsible for determining the study's research priorities.

8. Acknowledgments

This work is supported by the major project of the National Social Science Fund, Research and Interpretation of the Spirit of the 20th National Congress of the Communist Party of China: "Research on the Economic Development Level and Social Development Characteristics of Moderately Developed Countries from the Perspective of Public Value" (Grant No.: 23AZD013). We would also like to thank the anonymous reviewers very much for their constructive suggestions and valuable feedback on the initial draft of this paper, which greatly helped in improving the content.

9. Conflict of Interest Statement

The authors declare that they have no known competitive economic interests or personal relationships that may affect the research work.

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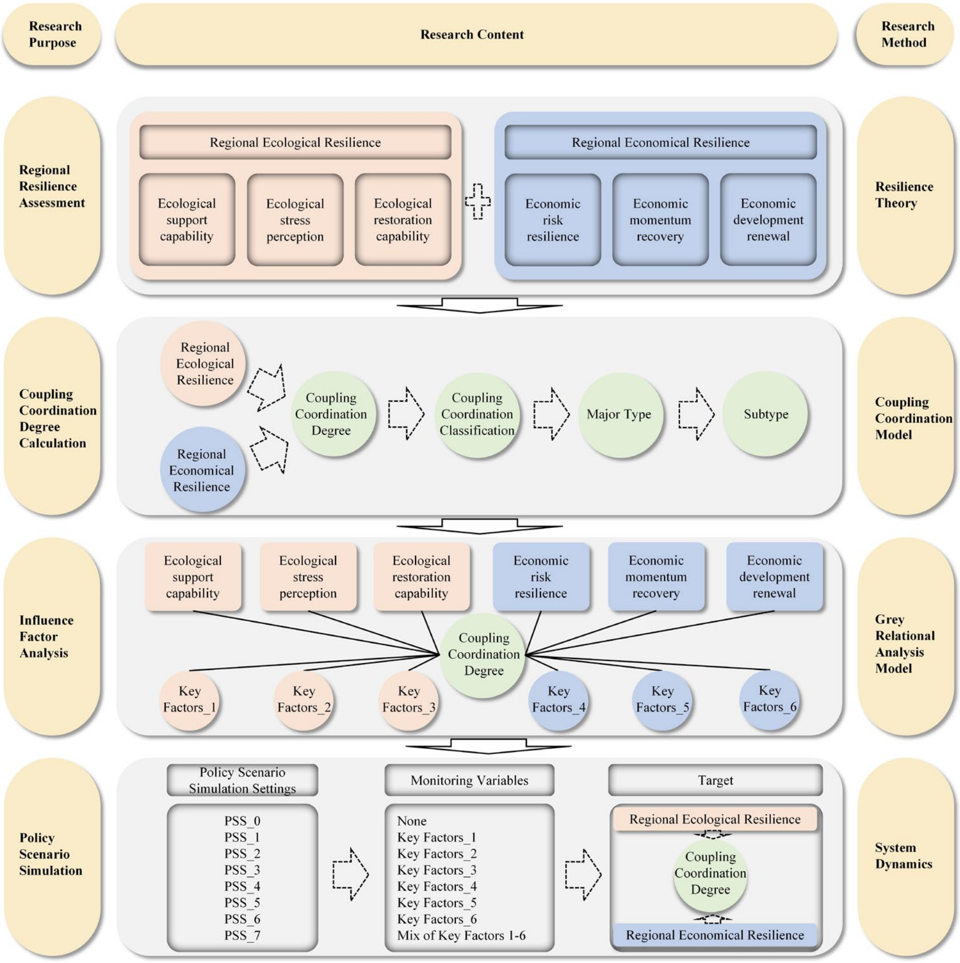
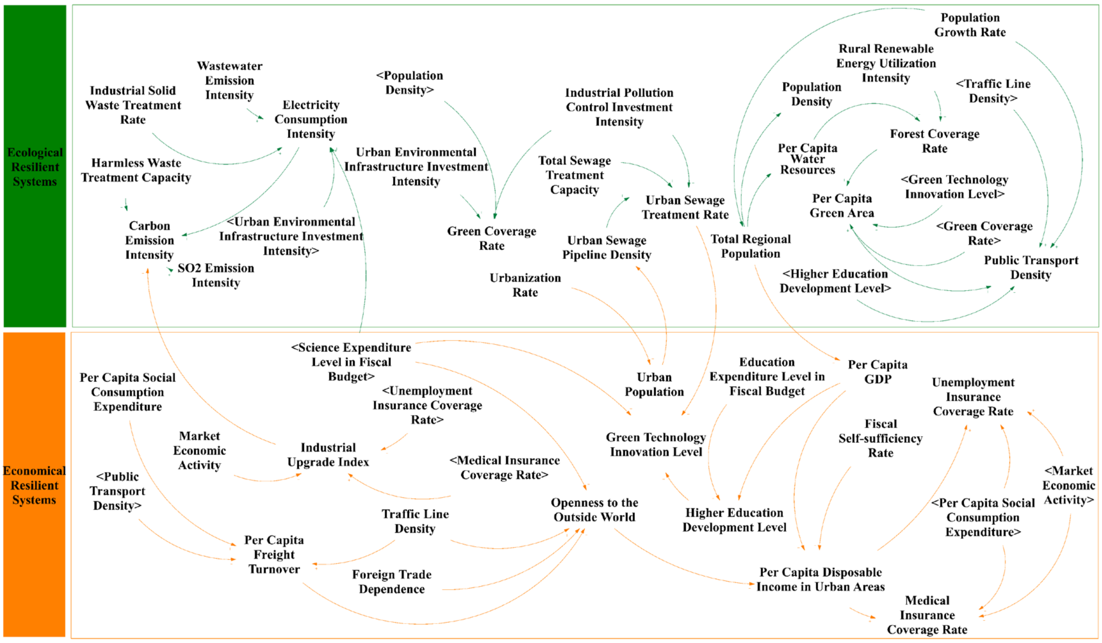
Appendix 1- The Research Framework



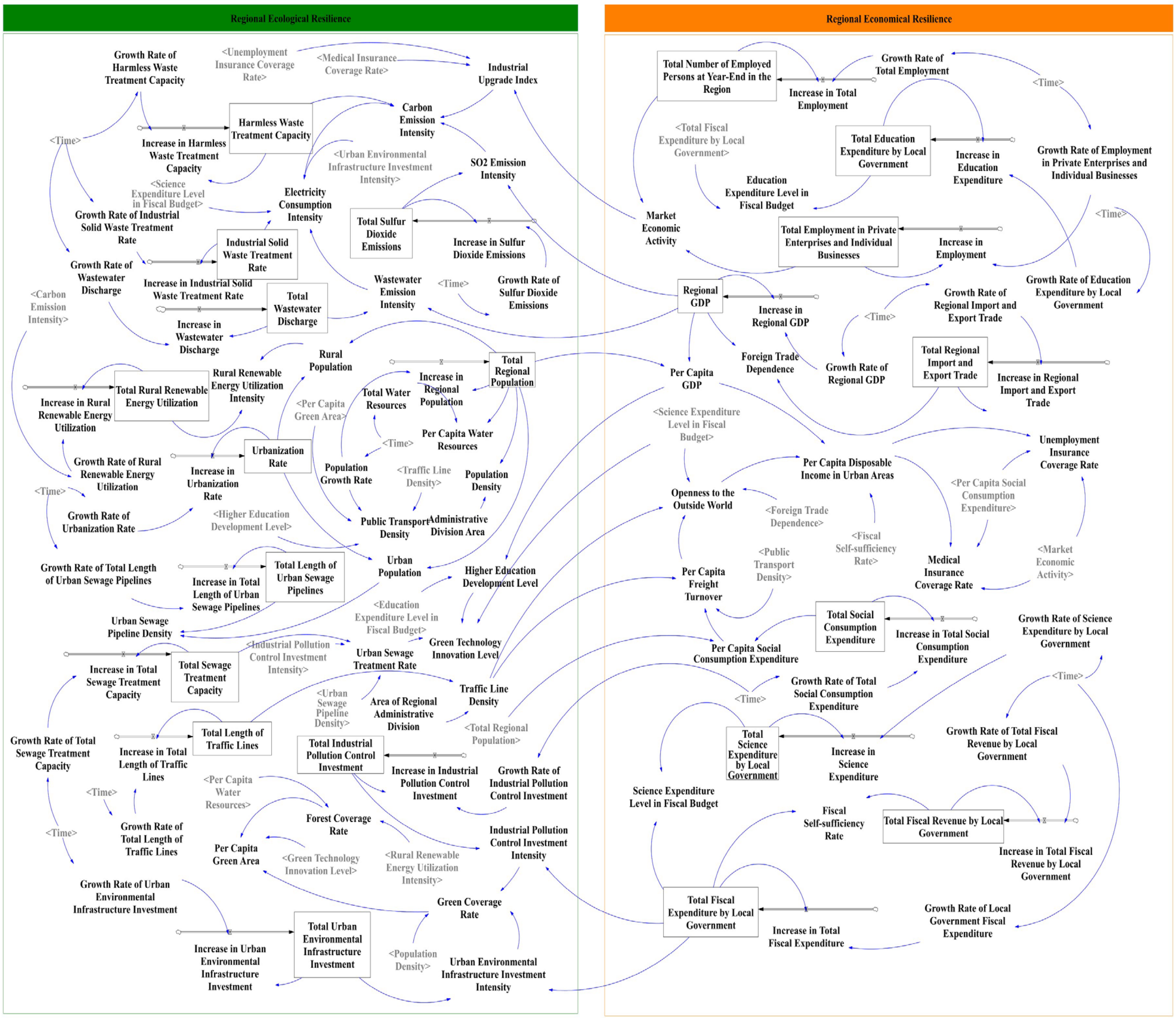
A 1- The Research Framework

Appendix 2- Causal Feedback



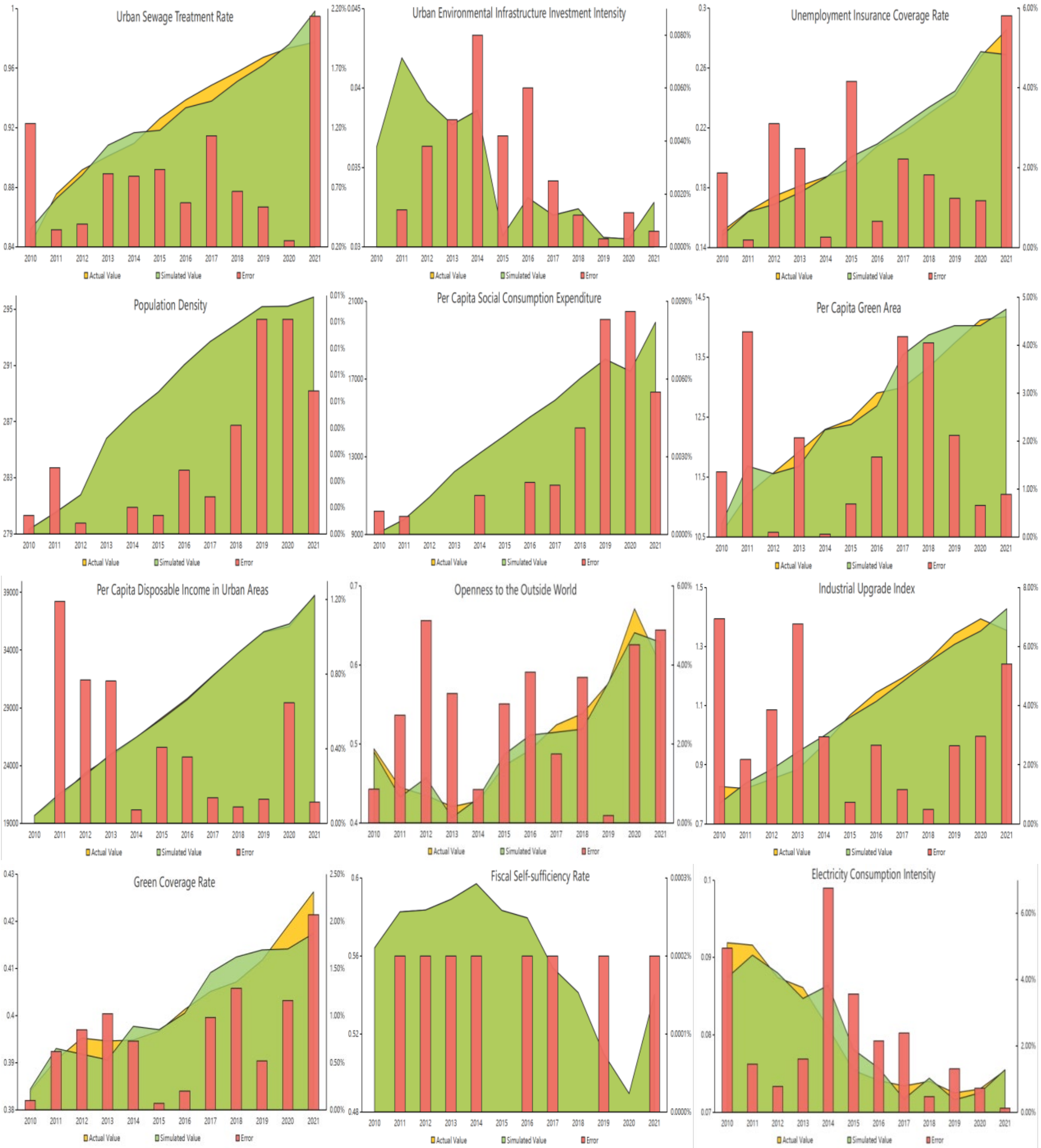
A 2- Causal feedback diagram of the regional resilience system.

Appendix 3- Stock-flow diagram of the regional resilience system



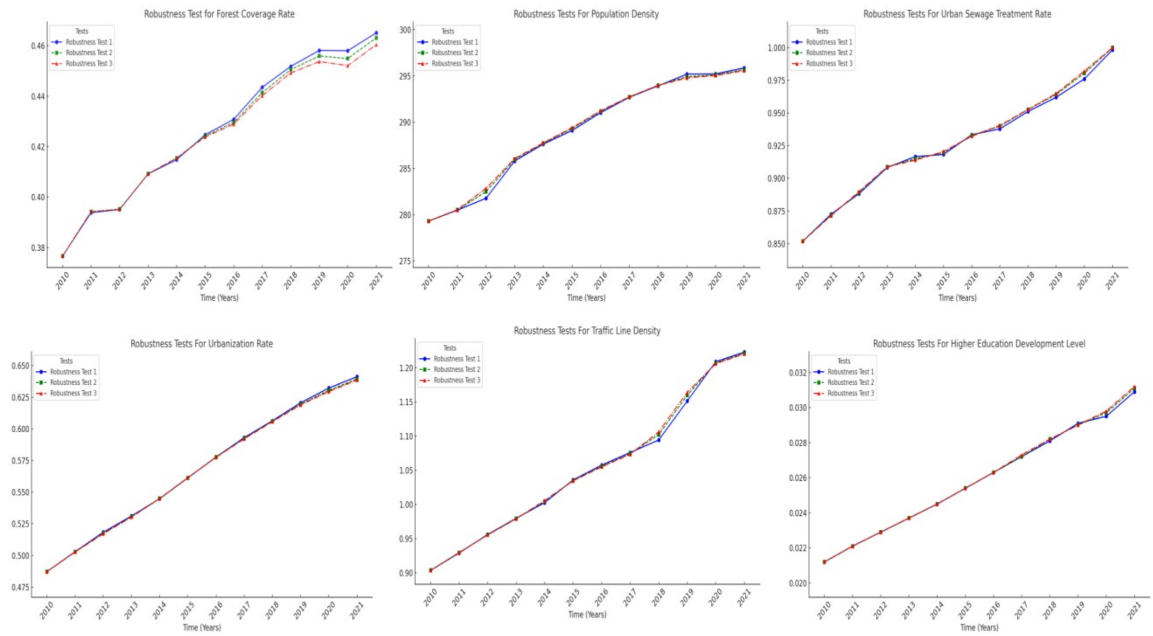
A 3- Stock-flow diagram of the regional resilience system

Appendix 4- Goodness of Fit Analysis



A 4- Results of goodness-of-fit analysis for the system dynamics model.

Appendix 5- Robustness Test Results



A 5- Robustness Test Results of the System Dynamics Model