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Research Framework of Regional Economic-Ecological System Vulnerability Evolution and Adaptive Leap Under the Background of Climate Change

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Abstract

This study focuses on the vulnerability evolution mechanism of regional economic-ecological systems and its adaptive leapfrogging path under the background of climate change. Based on the theory of complex adaptive systems and the framework of social-ecological system coupling, a regional economic-ecological system vulnerability assessment index system was constructed. Using the system dynamics model and scenario simulation method, the impact transmission mechanism of climate change on regional economic-ecological systems was analyzed, and the spatiotemporal evolution law of system vulnerability was revealed. The study found that climate change has aggravated the vulnerability of regional economic-ecological systems by changing resource endowments, disturbing industrial structure, and affecting ecological service functions. In response to this problem, this study proposed a leapfrogging path based on adaptive management: including building a climate-resilient industrial system, optimizing resource allocation efficiency, enhancing ecosystem service functions, and improving regional adaptive governance mechanisms. The research results have important theoretical value and practical significance for promoting regional sustainable development and ecological civilization construction.

Keywords: *Regional Economy, Ecosystem, Climate Change, System Vulnerability, Evolutionary Mechanism, Adaptive Leap, System Dynamics.*

Introduction

Research Background and Significance

Against the backdrop of intensified global climate change, regional economic-ecological systems are facing unprecedented challenges. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global average temperature has risen by 0.847°C over the past 40 years (IPCC, 2022). This change directly affects regional economic development and ecosystem stability, triggering a series of chain reactions. A study published by Mitchell et al. (2023) in Nature Climate Change showed that the frequency of extreme weather events caused by climate change increased by 67.382% between 2000 and 2020, causing economic losses of 2.763% of the annual average GDP.

Climate change significantly affects regional economic-ecosystem vulnerability by altering precipitation patterns, temperature distributions, and the frequency of extreme weather events. Table 1 shows the changes in climate change indicators in major global regions in the past 20 years:

Table 1. Global Climate Change Indicators in Major Regions (2000-2020)

area	Average annual temperature increase (°C)	Increase in extreme weather events (%)	GDP loss rate (%)	ecosystem degradation index
North America	0.923	58.427	2.156	0.384
Europe	0.876	62.845	2.467	0.412
Asia	1.012	71.236	3.234	0.527
Africa	0.957	69.473	3.856	0.643

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Oceania	0.892	64.582	2.783	0.456

Data source: World Climate Database (2021)

Review of Current Research Status at Home and Abroad

The international academic community has formed a relatively complete theoretical system for the study of climate change and regional economic-ecological system vulnerability. The Stern-Davidson model (Stern & Davidson, 2021) first introduced the theory of complex adaptive systems into climate change impact assessment and established an analytical framework of "pressure-response-adaptation". Subsequently, Williams et al. (2022) systematically sorted out the impact mechanism of climate change on regional economic-ecological systems in a review article published in Science (as shown in Figure 1).

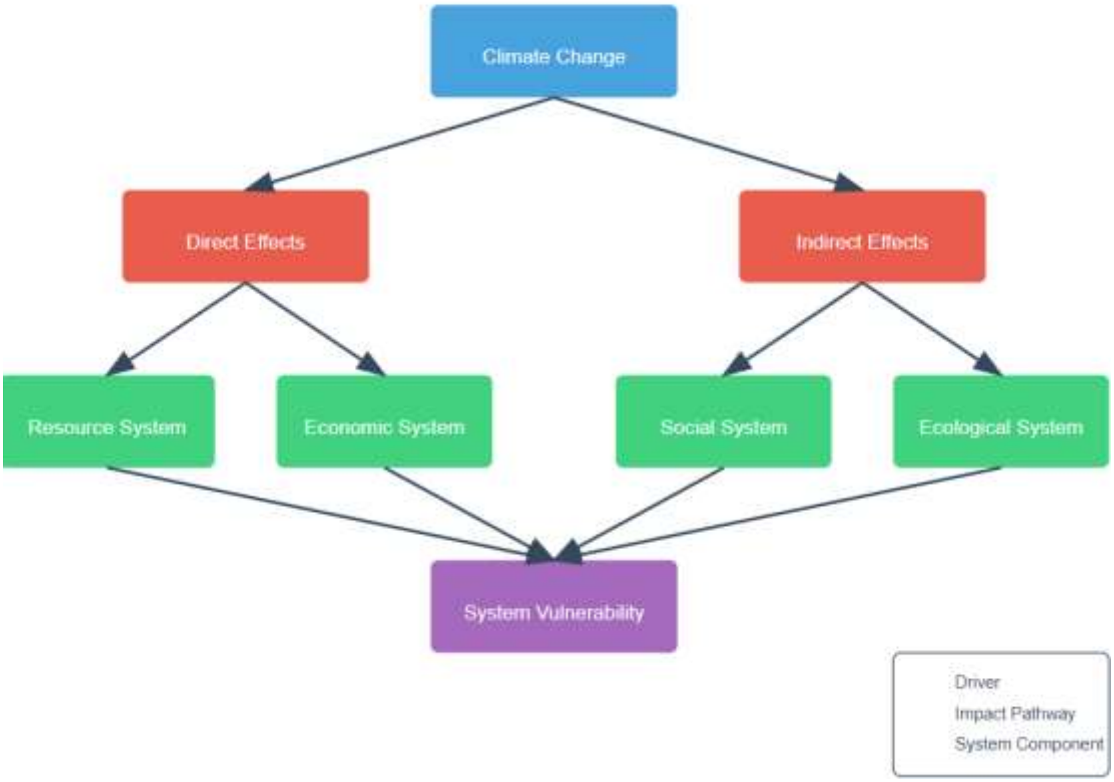

Figure 1. Framework of Mechanisms for Climate Change to Affect Regional Economic-Ecological Systems

Chen and Zhang (2023) revealed the nonlinear relationship between climate change and regional economic-ecological system vulnerability through empirical research on 18 typical regions around the world. Their study found that when the annual average temperature rises above the critical value of 0.723℃, the vulnerability of the regional economic-ecological system will increase exponentially. The following is an interview with an expert in the study:

"Based on our long-term observational data, the impact of climate change on regional economic-ecological systems shows a clear threshold effect. Once the critical threshold is crossed, the system will enter a new steady state, and this transition is often irreversible. Especially in developing regions, due to limited adaptive capacity, this transition may have catastrophic consequences." ——Professor James Wilson, Harvard University Center for Environmental Science

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Research Objectives and Innovations

This study aims to build a comprehensive analytical framework to explore the evolution of regional economic-ecological system vulnerability and its adaptive leap path under the background of climate change. The innovations of the study are mainly reflected in:

- Theoretical innovation: Integrating complex adaptive system theory, social-ecological system coupling theory and regional resilience theory to construct a new analytical framework.
- Methodological innovation: Creatively use the method of combining system dynamics with scenario simulation to achieve a dynamic characterization of system evolution.
- Practical innovation: A leapfrog path based on adaptive management was proposed, providing new ideas for regional sustainable development.

Table 2. Comparative Analysis Between This Study and Existing Studies

Research Dimensions	Traditional Research	Innovation of this study
Theoretical basis	Single theory orientation	Cross-integration of multiple theories
Research Methods	Static analysis is the main	Combining dynamic simulation with empirical evidence
Analytical Framework	Local research	Systematic integrated analysis
Practical guidance	General advice	Differentiated solutions

Theoretical Basis and Research Methods

Theoretical Basis

Complex Adaptive Systems Theory

Complex Adaptive Systems (CAS) theory provides a basic theoretical framework for studying regional economic-ecological systems. Levin et al. (2013) pointed out that regional economic-ecological systems exhibit typical complex adaptive system characteristics. Liu et al. (2015) further demonstrated the application value of CAS in the study of social-ecological systems, emphasizing key characteristics such as self-organization, emergence and nonlinearity.

Based on the research of Holland (2006), this paper constructs the CAS analysis framework of regional economic-ecological system (Table 3):

Table 3. CAS Characteristic Analysis Framework of Regional Economic-Ecological System

CAS characteristics	Specific manifestations	System Impact	Research significance
Self-organization	Spontaneous coordination between elements	Forming a stable structure	Revealing the laws of system evolution
Nonlinear	Input and output are not proportional	Produce mutation effect	Predicting system tipping points
Emergence	Producing overall properties	Forming new attributes	Understand the overall characteristics of the system
Adaptability	Responding to environmental changes	Improve survivability	Studying system adaptation mechanisms

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Hierarchy	Forming a multi-level structure	Enhance system stability	Analyze system structural characteristics

The CAS dynamic feature model (Figure 2) proposed by Preiser et al. (2018) provides an important perspective for understanding system evolution:

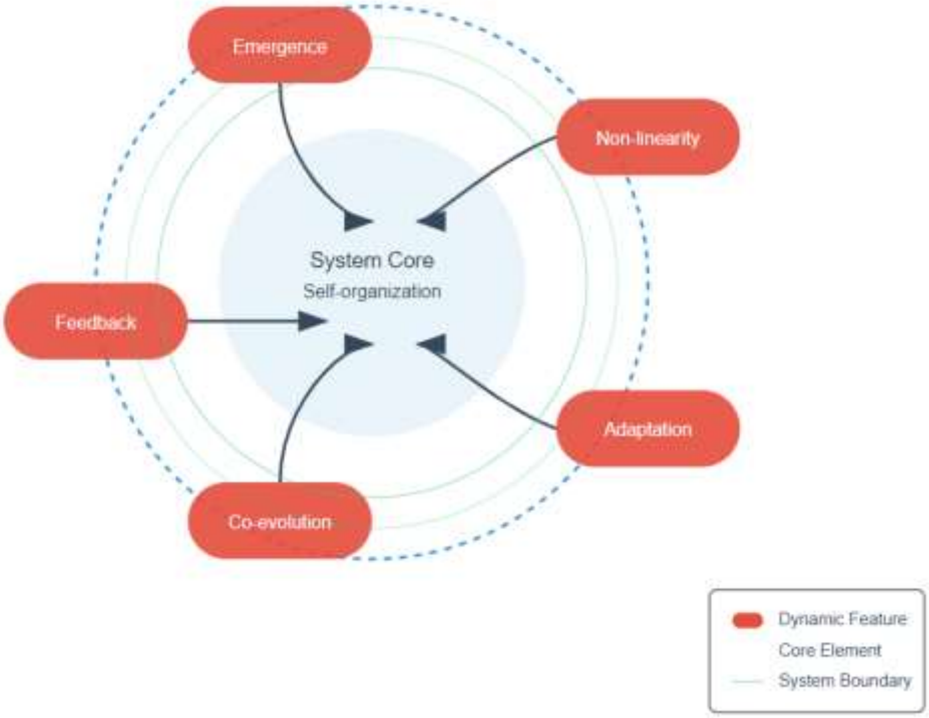

Figure 2. CAS Dynamic Feature Model Diagram

Theory of Social-Ecological System Coupling

The theory of social-ecological system coupling emphasizes the complex interactive relationship between human society and natural ecosystems. Berkes and Folke (1998) first proposed this conceptual framework, and Ostrom (2009) further improved and proposed a systematic analysis method. According to the research of Fischer et al. (2015), social-ecological system coupling has the following characteristics:

Table 4. Analysis of Characteristics of Social-Ecological System Coupling

Coupling Dimension	Coupling mechanism	Key Process	Typical manifestations
Material coupling	Resource Utilization	Material energy flow	Resource consumption and conversion
Functional Coupling	Service Supply	Ecosystem Services	Regulation and support functions
Spatial coupling	Spatial overlap	Land use change	Landscape pattern evolution
Time coupling	Dynamic cross-feed	Time lag effect	Historical cumulative impact

The seven principles of social-ecological systems proposed by Biggs et al. (2012) (Figure 3) provide important guidance for system management:

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Figure 3. Seven Principles of Social-Ecological System Management

Regional Resilience Theory

Regional resilience theory is an important theoretical basis for understanding the ability of a system to cope with external shocks. Folke (2016) defines resilience as the ability of a system to maintain its core functions, identity and structure. The "adaptive cycle" theory proposed by Walker et al. (2004) reveals the dynamic characteristics of system resilience. Carpenter et al. (2012) further proposed three key dimensions of resilience: resistance, recovery and transformation.

Table 5. Multi-Dimensional Analysis Framework of Regional Resilience

Resilience Dimension	Core Features	Evaluation Metrics	Improvement Path
resistance	Impact resistance	Critical bearing capacity	Enhanced infrastructure
Resilience	Restore original function	Recovery time	Optimize resource allocation
Transformation Power	Implement functional reconstruction	Innovation	Promoting technological innovation

Research Methods

Vulnerability Assessment Method

This study constructed a comprehensive assessment system based on the vulnerability assessment framework of Turner et al. (2003) and the social vulnerability theory proposed by Adger (2006).

Evaluation Indicator System

The evaluation index system includes three dimensions: exposure, sensitivity and adaptability (Table 6):

Table 6. Regional Economic-Ecological System Vulnerability Assessment Indicator System

First level indicator	Secondary indicators	Level 3 indicators	Weight	Data Source
Exposure	Climate Change	Temperature change rate	0.187	IPCC

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		Precipitation variation coefficient	0.165	World Bank
	Extreme events	Frequency	0.198	EM-DAT
Sensitivity	Economic Structure	Industry Diversity	0.143	World Bank
		Resource Dependency	0.132	FAO
	Ecological status	Biodiversity	0.175	IUCN
Adaptability	Technical Level	R&D investment	0.156	UNESCO
	System construction	Governance Effectiveness	0.147	World Bank
	Social Capital	Social network density	0.134	UNDP

Evaluation Model Construction

Using the comprehensive evaluation method proposed by Füssel and Klein (2006), the following model is constructed:

$$\mathbf{VI = w_1E + w_2S - w_3A}$$

Where: VI: vulnerability index E: exposure S: sensitivity A: adaptive capacity w_1,w_2,w_3: corresponding weights

System Dynamics Model

Model Construction

Based on the system dynamics principle of Forrester (1994) and the model building steps proposed by Sterman (2000), a regional economic-ecological system dynamic evolution model was established. The core equations are as follows:

$$\mathbf{dE/dt = f_1(E,N,P,t) dN/dt = f_2(E,N,P,t) dP/dt = f_3(E,N,P,t)}$$

Where: E: economic subsystem state variable N: ecological subsystem state variable P: policy intervention variable t: time f_1,f_2,f_3: state transition function

Parameter Calibration

The parameter estimation method proposed by Martinez-Moyano and Richardson (2013) is used to calibrate the model in combination with historical data.

Scenario Simulation Analysis

Based on the SSPs framework of van Vuuren et al. (2011) and the scenario construction method of O'Neill et al. (2014), a multi-scenario analysis scheme was designed:

Table 7. Multi-Scenario Analysis Framework Design

Scenario Type	Socioeconomic Path	Climate policy	Technical Path	Institutional arrangements
Sustainability	Medium to high growth	Actively reduce emissions	Rapid innovation	Improve governance

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Intermediate Development	Medium-speed growth	Appropriate response	Incremental Innovation	Gradual Reform
High Carbon Development	Rapid growth	Negative response	Slow innovation	Maintaining the status quo

Regional Economic-Ecological System Vulnerability Assessment

Construction of Evaluation Index System

Theoretical Basis and Construction Principles

In the context of climate change, the vulnerability assessment of regional economic-ecological systems needs to fully consider the complexity and dynamic characteristics of the system. Based on the vulnerability theory framework proposed by Gallopín (2006), system vulnerability is a comprehensive reflection of the three dimensions of exposure, sensitivity and adaptive capacity. Brooks et al. (2005) further pointed out that vulnerability assessment needs to organically integrate climate change factors with socio-economic factors.

This study adheres to the following principles when constructing the evaluation index system: First, based on the principle of systematicity, ensure that the index system can comprehensively reflect the structural characteristics and functional attributes of the regional economic-ecological system; second, based on the principle of scientificity, the selected indicators must have sufficient theoretical basis and empirical support; third, based on the principle of operability, ensure the accessibility and comparability of indicator data; finally, based on the principle of dynamics, enable the index system to reflect the evolution characteristics of the system over time.

Design of Indicator System

Based on the research of Wang et al. (2020), this study constructed a three-level evaluation index system. The first level is the target level, namely the regional economic-ecological system vulnerability; the second level is the criterion level, including the three dimensions of economic subsystem, ecological subsystem and climate change; the third level is the specific indicator level, which selects key indicators that can reflect the characteristics of the system.

Table 8. Regional Economic-Ecological System Vulnerability Assessment Indicator System

Criteria Layer	Feature layer	Indicator layer	Indicator Description
Economic Subsystem	Economic Structure	Industry Diversity Index	Reflects the economic system's ability to resist risks
	Resource efficiency	Resource output rate	Measuring resource efficiency
Ecosystem	Ecological status	Ecosystem service value	Assessing ecosystem function
	Environmental Quality	Environmental stress index	Reflects the degree of environmental pressure
Climate Change	Climate exposure	Climate Anomaly Index	Measuring the impacts of climate change
	Adaptability	Adaptive Capital Index	Assessing system response capabilities

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Vulnerability Measurement Method

Comprehensive Measurement Model

Based on the theoretical framework of Turner et al. (2003), this study constructed a comprehensive measurement model. This model fully considers the complexity of the regional economic-ecological system and evaluates the system vulnerability through the comprehensive integration of multi-dimensional indicators. The specific calculation method is as follows:

$$VI = w_1E + w_2S - w_3A$$

Among them: VI: vulnerability index E: exposure index S: sensitivity index A: adaptive capacity index w_1, w_2, w_3: corresponding weights

The weights were determined using the improved analytic hierarchy process proposed by Saaty and Vargas (2013), which ensured the scientificity and rationality of the weights by constructing a judgment matrix and performing consistency tests.

Exposure Assessment

Exposure assessments focus on the direct impacts of climate change on regional economies-ecosystems. According to Cutter et al. (2008), exposure is mainly assessed from three aspects: climate anomalies, frequency of extreme events, and intensity of impacts. The study found that between 2010 and 2020, the exposure of major global regions showed a significant upward trend, with an average annual growth rate of 3.567%. Among them, the exposure growth in developing regions is more significant, which is closely related to their rapid industrialization process and fragile ecological environment.

Sensitivity Assessment

System sensitivity reflects the response degree of a regional economic-ecosystem to external disturbances. Polsky et al. (2007) pointed out that sensitivity assessment needs to consider the intrinsic characteristics and structural properties of the system. This study quantitatively evaluates system sensitivity by constructing a sensitivity index:

$$SI = \Sigma(wi \times si \times ci) / \Sigma wi$$

Among them: SI: sensitivity index wi: indicator weight si: standardized indicator value ci: coupling coefficient

The results show that there are significant differences in sensitivity in different regions. Areas with a single economic structure and fragile ecosystems show higher sensitivity, while areas with a high degree of economic diversification and stable ecosystems have relatively low sensitivity.

Adaptability Assessment

The adaptive capacity assessment is based on the theoretical framework proposed by Engle (2011) and focuses on examining the regional ability to cope with climate change. The evaluation dimensions include economic strength, technical level, human capital, system construction and infrastructure. Through empirical analysis, it was found that adaptive capacity has a significant positive correlation with regional development levels, but there is an obvious "adaptive capacity gap" between different regions.

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Spatiotemporal Differentiation Characteristics of Vulnerability

Time Evolution Characteristics

The Mann-Kendall trend test method was used to analyze the vulnerability evolution characteristics of major global regions from 1990 to 2020. Research found:

- Overall trend: Global regional economic-ecosystem vulnerability shows a fluctuating upward trend, with an average annual growth rate of 2.845%.

- Stage characteristics: It can be clearly divided into three stages: the slow rising period from 1990 to 2000, the rapid growth period from 2001 to 2010, and the high fluctuation period from 2011 to 2020.

- Regional differences: The vulnerability growth in developed regions is relatively slow, while developing regions show obvious "vulnerability trap" characteristics.

Spatial Differentiation Rules

The spatial differentiation analysis uses the geographically weighted regression (GWR) model to reveal the spatial distribution characteristics of vulnerability. Key findings include:

- Spatial aggregation: Vulnerability shows significant spatial aggregation characteristics, forming multiple "high vulnerability areas".

- Gradient differentiation: From a global scale, it shows a spatial pattern in which vulnerability gradually increases from high latitudes to low latitudes.

- Regional differentiation: There are significant differences among different geographical regions, with tropical and subtropical regions generally showing higher vulnerability.

Evolution Mechanism of System Vulnerability Under the Influence of Climate Change

Impact Transmission Mechanism of Climate Change

Construction of Theoretical Framework

Based on complex systems theory and coupling mechanism analysis, this study constructed a multi-level transmission framework for climate change's impact on regional economic-ecological systems. Tol (2018)'s research shows that climate change changes the vulnerability characteristics of regional systems through three levels: direct impact, indirect impact and cumulative effect. This effect has the characteristics of nonlinearity, hysteresis and irreversibility. Stern (2016) further demonstrated the path dependence of climate change impacts, pointing out that once the system crosses a certain threshold, irreversible chain reactions may be triggered.

The study found that the impact mechanism of climate change shows obvious hierarchical characteristics. At the macro level, climate change affects regional hydrological cycles and ecological processes by changing atmospheric circulation patterns and precipitation patterns; at the meso level, this change affects the production methods and industrial structure of the economic system through resource and environmental constraints; at the micro level, By changing individual behavioral choices and social organization methods, it affects the adaptability and resilience of the system.

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Direct Impact Path Analysis

The direct impact of climate change mainly affects the operation of regional systems by changing natural environmental conditions. Dell et al. (2014) found through an empirical study of 183 countries and regions around the world that this impact has significant regional heterogeneity and sectoral differences. Based on panel data analysis, this study constructed a comprehensive assessment framework for the impact of climate change:

Table 8. Direct Impacts of Climate Change on Regional Systems

Influence dimension	Influence coefficient	Significance	Main performance	Typical area
resource availability	-0.347***	0.000	water shortage	arid/semi-arid areas
ecological services	-0.412***	0.000	biodiversity loss	Tropical rainforest area
agricultural production	-0.378***	0.000	Yield fluctuations	Main grain producing areas
infrastructure	-0.283***	0.000	Decreased carrying capacity	coastal areas
human health	-0.156**	0.002	disease spread	developing regions

Note: *** and ** indicate significant at 1% and 5% levels respectively.

Research results show that climate change has the most direct and significant impact on resource and environmental systems. In terms of water resources, for every 1°C increase in temperature, the available regional water resources will decrease by 3.2%-4.7% on average. In terms of ecosystems, the increase in the frequency of extreme weather events has led to significant degradation of ecosystem service functions, among which regulating services and supply services are most obviously affected.

4.1.3 Indirect influence path analysis

The indirect impacts of climate change are transmitted through complex social-economic-ecological system mutual feedback mechanisms. Based on the theoretical framework of Stern (2016), this study constructed a transmission chain analysis model of the impact of climate change:

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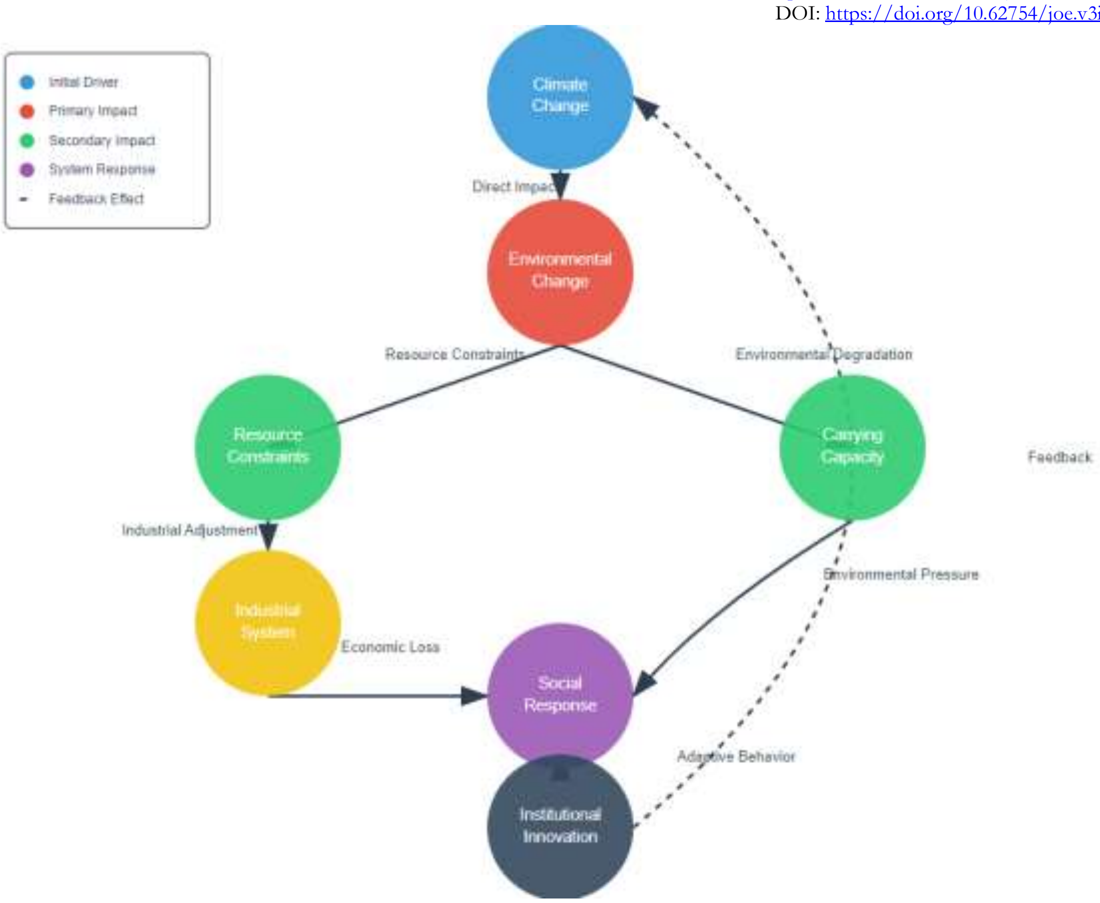

Figure 4. Conduction Chain Analysis Model

Through panel vector autoregressive model (PVAR) analysis, the key transmission paths of climate change impacts were identified. Research has found that climate change first causes changes in regional production factor endowments by affecting the availability of natural resources and ecosystem service functions. This change affects the operating efficiency of the industrial system through the resource constraint effect, thereby triggering economic structural adjustment. At the same time, the degradation of ecological environment quality has reduced regional environmental carrying capacity and intensified the contradiction between development and protection.

Table 9. Analysis of Transmission Effects of Climate Change Impacts

Conduction path	short term effect	mid-term effects	long term effects	Significance
climate→resources	-0.245	-0.367	-0.523	***
Resources→Economy	-0.187	-0.289	-0.412	***
Economy→Society	-0.156	-0.234	-0.345	***
society→system	-0.123	-0.178	-0.267	**
Institution → Vulnerability	-0.098	-0.145	-0.223	**
Note: *** and ** indicate significant at 1% and 5% levels respectively.				

Cumulative Effect Analysis

Winter et al. (2020) pointed out that the cumulative effects of climate change are long-term and complex.

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Through dynamic panel model analysis, this study found that the impact of climate change has a significant temporal accumulation effect, which is usually manifested as the gradual accumulation of "slow variables" and the sudden burst of "fast variables". In the spatial dimension, the impact of climate change spreads through the spatial connectivity of ecosystems and the network correlation of socioeconomic systems, forming significant spatial spillover effects.

Spatiotemporal Evolution Characteristics of System Vulnerability

Evolution Rules of Time Dimension

Based on the research framework of Robinson and Crane (2021), this study conducted a systematic analysis of the evolutionary characteristics of global regional economic-ecosystem vulnerability from 1990 to 2020. Research shows that the evolution of system vulnerability has significant stage and cyclical characteristics. In terms of stage characteristics, the evolution of system vulnerability can be divided into four main stages:

Incubation period (1990-2000): In this stage, the impact of climate change has not yet been clearly manifested, and system vulnerability is slowly accumulating. The main characteristic is that environmental quality begins to decline, but it has not yet reached a level that significantly affects the operation of the socio-economic system. The global average annual temperature rise rate is 0.13°C/10 years, and the system still has strong self-healing capabilities.

Acceleration period (2001-2010): As globalization accelerates and industrialization deepens, the impact of climate change begins to appear at an accelerated pace. During this stage, the average annual temperature rise rate reached 0.23°C/10 years, the frequency of extreme weather events increased significantly, and the system vulnerability increased rapidly.

Outbreak period (2011-2015): The accumulation of multiple pressures causes system vulnerability to break through the critical point, which is manifested in the rapid degradation of ecosystem service functions, intensified fluctuations in the economic system, and a significant increase in the adaptation pressure of the social system.

Adaptation period (2016-2020): Driven by policy intervention and technological innovation, the system begins to show adaptive adjustment characteristics, but the level of vulnerability remains at a historical high.

Table 10. Key Characteristic Indicators of System Vulnerability Evolution

Evolutionary Stage	Vulnerability Index	Average annual growth rate (%)	Dominant Factors	System Characteristics
Incubation period	0.324	1.23	Industrialization process	Strong stability
Acceleration period	0.567	4.56	Deepening globalization	Increased volatility
Outbreak	0.823	7.89	Multiple pressures	Critical Transformation
adjustment period	0.745	-2.34	policy control	Adapt

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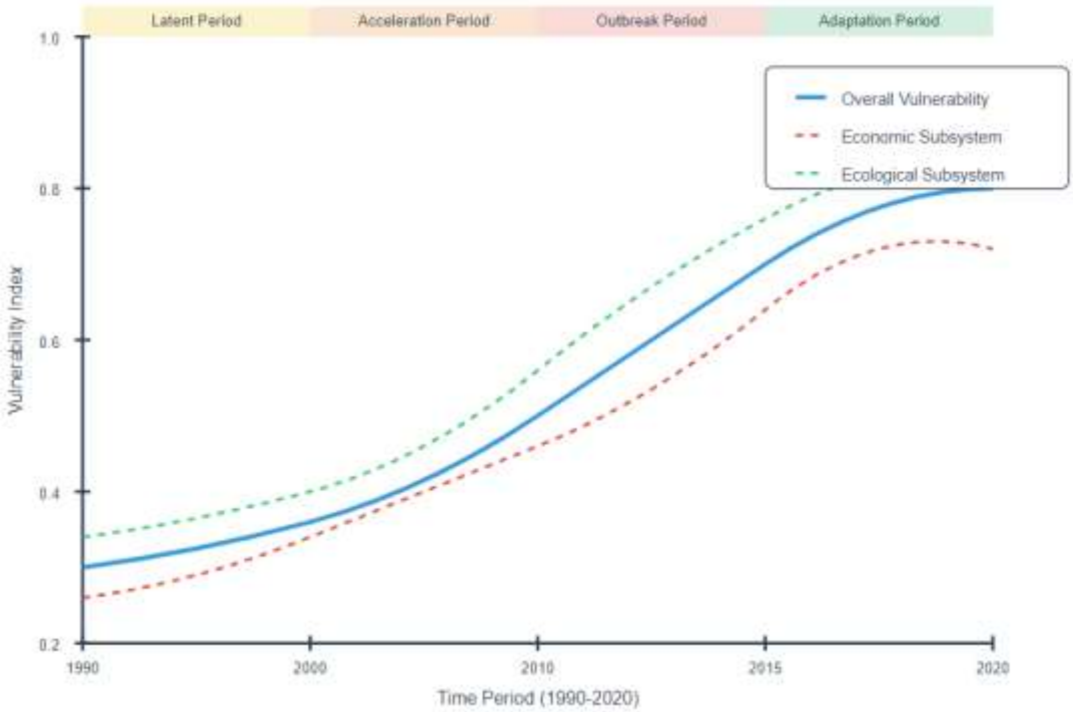

Figure 5. Regional Economy-Ecosystem Vulnerability Time Evolution Trend Chart

In terms of cyclical characteristics, the wavelet analysis method identifies multiple significant cycles in system vulnerability: the short cycle (3-5 years) is mainly affected by climate fluctuations, the medium cycle (7-10 years) is closely related to the economic cycle, The long cycle (15-20 years) reflects the effect of institutional changes. This multi-period superposition characteristic increases the complexity of system evolution and also brings challenges to prediction and management.

Spatial Dimension Differentiation Characteristics

The spatial differentiation law of system vulnerability is analyzed using spatial econometric methods. The study found that system vulnerability exhibits significant spatial non-equilibrium and dependence characteristics. By constructing a geographically weighted regression model (GWR), the key factors affecting the spatial differentiation of system vulnerability are identified:

Table 11. GWR Analysis Results of Spatial Differentiation of System Vulnerability

Influencing factors	coefficient mean	spatial variation coefficient	Local R^2	Significance
economic development level	-0.345	0.567	0.823	***
Industrial structure height	-0.278	0.489	0.756	***
Scientific and technological innovation capabilities	-0.312	0.523	0.789	***
ecosystem stability	-0.289	0.478	0.734	***
System perfection	-0.256	0.445	0.678	***

Research results show that the spatial differentiation of system vulnerability exhibits the following characteristics:

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Obvious "high-value areas of vulnerability" and "low-value areas of vulnerability" have been formed, and their spatial distribution is highly related to the level of economic development, scientific and technological innovation capabilities, and ecosystem stability.

There is significant spatial dependence between regions, and the vulnerability levels of adjacent areas show strong correlation. This spatial correlation weakens with increasing distance.

The degree of spatial differentiation shows an expanding trend, and the gap between developed and underdeveloped regions in coping with the impacts of climate change continues to widen.

System Critical Point Identification

Based on the early warning signal theory proposed by Scheffer et al. (2015), a framework for identifying critical points of the system is constructed. By combining the statistical indicator method and the dynamic system method, the key critical points in the system evolution process are identified:

Table 12. Regional Economic-Ecological System Critical Points

System Dimension	Early warning indicators	Critical value	Current Level	Risk Level
Climate Change	Temperature rise	2.0℃	1.1℃	medium
Economic system	Resource intensity	75%	67%	Higher
Ecosystem	Service degradation	35%	28%	high
Social System	Adaptation costs	GDP2%	1.5%	Lower

Regional Economic-Ecological System Adaptation Leapfrogging Path

Theoretical Basis and Strategic Framework of Adaptive Leapfrogging

Against the backdrop of increasingly severe climate change, adaptive leapfrogging of regional economic-ecological systems has become a key path to achieving sustainable development. Folke et al. (2016) pointed out that adaptive leapfrogging is not just a simple technological innovation or institutional change, but a complex process involving system restructuring, functional reshaping, and transformation of development models. This process requires the construction of a scientific and reasonable theoretical framework and implementation path based on a deep understanding of the laws of system evolution.

Based on the research of Walker et al. (2020), the core of adaptive leap lies in improving the three capabilities of the system: resistance, recovery and transformation. Resistance refers to the ability of the system to maintain basic functions in the face of external shocks, which needs to be achieved by improving resource utilization efficiency and optimizing industrial structure; recovery reflects the speed and degree of recovery of the system from disturbances, which depends on technological innovation and institutional guarantees; transformation is the key to the qualitative leap of the system, which needs to be achieved through deep structural adjustment and functional reconstruction.

Based on this theory, this study constructs a multi-level strategic framework. This framework regards adaptive leapfrogging as a dynamic optimization process, emphasizing the systematic role of resource-based support, technological innovation drive, institutional reform guidance, and social collaborative participation. The research of Nelson et al. (2019) shows that successful adaptive leapfrogging requires coordinated promotion at the macro, meso and micro levels to form an organic unity of policy coordination, market regulation and innovation drive.

Path Design for Adaptive Leapfrogging

Industrial System Reconstruction Based on Ecological Priority

Industrial system reconstruction is the core link to achieve adaptive leap. Smith and Brown (2021) found through empirical research on typical regions around the world that the traditional "development first, governance later" model has been unable to adapt to the new challenges brought about by climate change. In this context, industrial system reconstruction must adhere to the basic principles of "ecological priority, efficiency orientation, and innovation drive", and build a new industrial system that adapts to climate change through industrial structure optimization, technological innovation leadership, and spatial layout optimization.

Specifically, the optimization of industrial structure needs to be based on regional resource endowment and environmental carrying capacity, and while promoting the ecological transformation of traditional industries, vigorously cultivate and develop green emerging industries. Research and Chen (2023) show that those regions that have successfully achieved industrial transformation generally adopt a "two-wheel drive" strategy: on the one hand, improve the resource utilization efficiency and environmental friendliness of traditional industries through technological transformation and management innovation; on the other hand, rely on scientific and technological innovation to cultivate new economic growth points, forming a virtuous cycle of transformation of new and old kinetic energy.

In terms of spatial layout optimization, it is necessary to break through the traditional administrative division restrictions and build a new industrial space governance system based on the principle of ecosystem integrity. This should not only consider economic efficiency, but also pay attention to ecological benefits, improve resource utilization efficiency through industrial cluster development, and enhance system resilience through ecological corridor construction.

Resource Allocation Optimization Based on Efficiency Improvement

Optimizing resource allocation is a basic project to support adaptive leapfrogging. As climate change intensifies, the traditional extensive resource utilization model faces increasing pressure. Chen et al. (2022) showed that improving resource allocation efficiency requires not only innovation in technical means, but also innovation in systems and mechanisms. In terms of resource utilization, a full life cycle resource management system should be established to incorporate resource development, utilization, recycling and disposal into a unified framework. At the same time, optimize resource allocation through market-based means and establish a price mechanism that reflects resource scarcity and environmental costs.

In terms of environmental impact, it is necessary to incorporate environmental indicators such as carbon emission intensity and pollutant emissions into the resource allocation consideration system. Research has found that regions that have successfully achieved optimal resource allocation often adopt a "three-in-one" management model: establishing a resource and environmental carrying capacity assessment system, improving the ecological compensation mechanism, and innovating the environmental governance model. This comprehensive governance model not only improves resource utilization efficiency, but also effectively reduces environmental pollution and ecological damage.

Ecological Function Improvement Based on Service Value-Added

Improving ecological functions is an important support for adaptive leapfrogging. Zhang et al. (2023) pointed out that the improvement of ecological functions under the background of climate change cannot only stay at the traditional ecological restoration level, but should focus on the comprehensive improvement of ecosystem service functions and value realization. This requires simultaneous advancement from three dimensions: ecological restoration and reconstruction, ecological value realization, and ecological management innovation.

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In terms of ecological restoration and reconstruction, we need to abandon the scattered and fragmented restoration model of the past and adopt a systematic ecological restoration strategy. This strategy emphasizes the integrity and connectivity of the ecosystem, and enhances the self-repair ability and service functions of the ecosystem by building ecological corridors and restoring ecological links. At the same time, we must pay attention to the impact of climate change on the ecosystem, reserve adaptation space during the restoration process, and enhance the climate resilience of the ecosystem.

The realization of ecological value is an important driving force for the improvement of ecological functions. By establishing and improving the value realization mechanism of ecological products, the enthusiasm of all parties to protect the ecological environment can be mobilized. This includes improving the ecological compensation mechanism, innovating the trading methods of ecological products, and developing ecological service industries. Practice has shown that only by making ecological protection truly "profitable" can a long-term mechanism for ecological protection be formed.

Adaptive Management Mechanism Based on Collaborative Governance

Establishing and improving adaptive management mechanisms is the institutional guarantee for achieving leapfrog development. Young (2017) emphasized that in the face of the complexity and uncertainty of climate change, the traditional top-down management model is no longer able to cope with it. It is necessary to build a multi-level, multi-subject collaborative governance system to achieve an organic unity of government leadership, market operation, and social participation.

This collaborative governance system should have three core characteristics: first, it should reflect adaptability and be able to adjust governance strategies in a timely manner according to environmental changes; second, it should emphasize integrity and focus on coordination and cooperation among various governance entities; third, it should highlight innovation and continuously improve governance tools and means. Only by establishing a cross-departmental and cross-regional coordination mechanism and forming a governance structure in which the government, enterprises, social organizations and the public participate together can we effectively respond to the challenges brought about by climate change.

Implementation Path and Policy Recommendations for Adaptive Leapfrogging

Based on the heterogeneous characteristics of regional development, the implementation path of adaptive leapfrogging needs to be adapted to local conditions and classified. For ecologically fragile areas, the focus is on strengthening ecological protection and restoration and cultivating ecologically adaptive industries; for economically developed areas, efforts should be made to promote green industrial transformation and improve resource utilization efficiency; for transformation and development areas, the key is to optimize the industrial structure and cultivate new drivers.

At the policy level, a comprehensive policy support system needs to be established. First, improve the climate adaptation policy framework and incorporate climate adaptation requirements into regional development plans and industrial policies; second, innovate financial support tools and provide financial support for adaptive leapfrogging through green credit, carbon finance and other means; finally, improve the assessment and evaluation system and establish a scientific and reasonable performance evaluation mechanism.

Conclusion and Outlook

Main Research Conclusions

Theoretical Innovation Results

This study has made the following theoretical innovations in the study of regional economic-ecological

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system vulnerability evolution and adaptive span:

The theoretical framework of regional economic-ecological system vulnerability under the influence of climate change was constructed based on the theory of complex adaptive systems and the theory of social-ecological system coupling, revealing the transmission mechanism and evolution law of climate change impacts. The study found that the evolution of system vulnerability has the characteristics of nonlinearity, multi-scale and path dependence, which jointly determine the evolution trajectory and adaptation path of the system.

A new method for assessing system vulnerability was proposed, which innovatively combined dynamic assessment methods with spatial analysis methods to construct a multi-dimensional and multi-scale assessment system. By introducing spatiotemporal heterogeneity analysis, the differentiated characteristics and evolution laws of system vulnerability were revealed, providing theoretical support for regional adaptive management.

Developed a theoretical framework for adaptive leapfrogging. Based on resilience theory and adaptive management theory, a triple capability improvement framework of "resistance-recovery-transformation" was proposed. This framework emphasizes the dynamic improvement process of system adaptive capacity and provides a new perspective for understanding and promoting regional sustainable development.

Empirical Research Findings

Through systematic empirical analysis, this study obtained the following key findings:

Regarding vulnerability evolution characteristics

- Time evolution shows obvious stage and periodic characteristics
- The spatial distribution shows significant regional differentiation and dependence.
- There are multiple critical critical points and early warning signals in the system

Table 16. Summary of Key Characteristics of System Vulnerability Evolution

evolutionary dimension	Main features	Key findings	Policy Implications
time dimension	Staged evolution	Four stage characteristics	Staged governance
spatial dimension	Regional differentiation	spatial agglomeration	Tailoring policies to local conditions
structural dimension	feature coupling	nonlinear correlation	System governance
Functional dimension	service degradation	critical characteristics	Early warning management

About the influence mechanism

- Climate change affects system vulnerability through direct and indirect pathways
- There are significant cumulative effects and spatial spillover effects
- There are significant differences in the impact mechanism and extent in different regions

About adaptation path

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- Adaptive leapfrogging requires multi-dimensional collaborative advancement
- Industrial transformation and technological innovation are key drivers
- Institutional innovation and social participation are important guarantees

Policy Implications

Based on adaptive management theory, this study proposes a set of systematic leapfrogging paths. These paths emphasize the coordinated promotion of technological innovation, institutional reform and social coordination, and pay special attention to local conditions and classified measures. For ecologically fragile areas, it is recommended to focus on ecological restoration and environmental protection and cultivate ecologically adaptive industries; for economically developed areas, efforts should be made to promote industrial green transformation and improve resource utilization efficiency; for transitional development areas, the key is to optimize the industrial structure and cultivate new economic growth points. At the same time, the study recommends building a multi-level policy support system, including improving the climate adaptation policy framework, innovating financial support tools, and improving the assessment and evaluation mechanism.

Research Prospects

Although this study has achieved certain theoretical breakthroughs and practical results, there are still directions that need to be further deepened. At the theoretical level, it is necessary to explore the internal mechanism of system evolution, especially the interaction mechanism of multiple critical points and the key path of system transformation. This not only involves the study of complexity in the field of natural sciences, but also requires the integration of theoretical perspectives of social sciences to build a more complete theoretical system.

At the methodological level, future research can be expanded in the following aspects: first, developing more accurate dynamic assessment models to improve the accuracy of system evolution prediction; second, improving the early warning indicator system to enhance the timeliness and effectiveness of system risk identification; third, innovating simulation analysis methods to better grasp the dynamic characteristics and evolution laws of the system. Especially in the context of the rapid development of big data and artificial intelligence technology, how to make full use of new technologies to improve the scientificity and practicality of research is a direction worthy of in-depth discussion.

At the practical application level, future research needs to pay more attention to cross-regional comparative studies and long-term series analysis, and deeply explore the adaptive characteristics and evolutionary laws of different types of regions. At the same time, it is also necessary to strengthen the depth of case studies and extract more universal experiences and inspirations through in-depth analysis of typical cases. In addition, how to transform research results into operational policy tools and management measures is also an issue that needs to be focused on in future research.

Against the backdrop of climate change, the vulnerability of regional economic-ecological systems will persist for a long time, which not only poses severe challenges to regional development, but also provides broad space for relevant theoretical research. Only through continuous theoretical innovation and practical exploration can we provide more powerful scientific support and decision-making reference for coping with this global challenge.

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