Main Content and Progress of Ecological Security Pattern Research: Postprint

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Abstract

Ecological security patterns constitute an important component of China' s territorial spatial development strategic framework. The effective construction and maintenance of regional ecological security patterns not only facilitates the integrity of ecosystem structure and function, biodiversity conservation, and the sustenance of ecosystem services, but also enhances human well-being, achieves sustainable development, and ultimately safeguards regional ecological security. The complexity and interdisciplinary nature of ecological security have resulted in diverse research content in existing studies, yet these lack interconnection and comparison, leading to multiple patterns under varying regional and methodological research conditions. Therefore, systematic analysis and synthesis are necessary to enable comprehensive analysis and integration, and to implement regulation, management, and decision-making for ecological security patterns. Drawing upon major research findings on ecological security patterns both domestically and internationally, this study elaborates on the key content requiring focused attention in ecological security pattern research and the interrelationships among them. Based on the relationship of "pattern formation and evolution mechanisms - impacts - key area identification - construction and optimization - regulation and management" , specific research contents and related methodologies are discussed. By strengthening research on the interrelationships and mechanisms among the main research contents of ecological security, improving and optimizing assessment and early warning method models, and developing regulation technologies and safeguard policies for coordinated development, important support is provided for the decision support system of ecological security pattern management.

Full Text

Preamble

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Main Research Contents and Advances in the Ecological Security Pattern

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Abstract

Ecological security pattern constitutes a crucial component of China's territorial development strategy. Effective construction and maintenance of regional ecological security patterns not only contributes to maintaining ecosystem structure and function integrity, biodiversity conservation, and ecosystem service provision, but also enhances human well-being, promotes sustainable development, and ultimately safeguards regional ecological security. Due to the complexity and interdisciplinary nature of ecological security research, previous studies have generated diverse content but lack interconnections and comparisons, leading to multiple patterns identified through different methods across different regions. Therefore, systematic analysis and synthesis of these studies are essential to inform management decisions for ecological security patterns. This paper illustrates key research subjects and their relationships in ecological security pattern studies, discusses main research contents and methods within the logical framework of pattern formation and evolution mechanisms, pattern impacts, key area identification, pattern construction and optimization, and regulation and management. Decision support systems for ecological security pattern management can be improved by strengthening research on mechanisms of key ecological security processes, optimizing evaluation and early warning methods and models, and developing regulation technologies and safeguarding policies for coordinated ecological security and socioeconomic development.

Keywords: ecological security pattern; ecosystem services; biodiversity; key

areas; ecological protection redlines

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1. International Research on Ecological Security Patterns

Since the concept of land health was proposed in 1941, issues concerning ecosystem health and environmental risk have gained global attention. In 2005, the Millennium Ecosystem Assessment report highlighted that ecosystem service degradation would severely impact human well-being. The International Institute for Applied Systems Analysis (IIASA) formally proposed ecological security monitoring systems. In 2012, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established under UNEP to serve policy decision-making through scientific assessment, demonstrating international commitment to ecosystem services related to human welfare.

International ecological security pattern research has primarily focused on protected area systems, classified by protection strictness from strict preservation to sustainable use types. Global terrestrial and inland water protected area coverage reached 15.4% by 2014, double the 2000 figure. Priority conservation areas have been identified at regional and global scales, such as the 200 priority regions identified by WWF, biodiversity hotspots, and Key Biodiversity Areas (KBAs) by IUCN. Early pattern construction mainly targeted biodiversity conservation, but has gradually shifted toward coupled natural-social-economic systems with the development of ecosystem service assessment and growing recognition of socioeconomic dimensions in ecological security. Current research emphasizes biodiversity and ecosystem service assessment and synergies, ecological protection and restoration, coupled analysis of natural and socioeconomic systems, and ecological security policy studies under the context of regional ecological problems caused by global change and human expansion.

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2. Domestic Research on Ecological Security Patterns

Domestic ecological security research has evolved from early conceptual discussions to ecological risk and ecosystem assessment, becoming a hotspot for applied and management-oriented studies. Ecological security pattern refers to the spatial configuration of landscape elements—specifically the shape, proportion, and spatial arrangement of land use types—at macro scales. Certain critical spatial relationships among points, lines, and planes form potential patterns that are vital for maintaining and controlling ecological processes, protecting ecosystem structure and function integrity, and sustaining ecosystem services. China has conducted ecological zoning, major function zoning, and protection priority zoning at national scales, with particular emphasis on ecological security pattern research.

In 2012, the Ministry of Environmental Protection launched a major project on

key technologies and protection strategies for national territorial ecological security pattern construction. Based on fundamental theoretical and methodological research, ecological protection redline delineation studies were conducted, providing foundations for ecological region protection and management. The revised Environmental Protection Law in 2014 mandated strict control through policies and regulations to strengthen ecological security maintenance.

Current domestic research primarily focuses on pattern identification and construction, such as spatial ecological security grading based on case evaluations, and pattern construction using spatial overlay and objective optimization methods. However, in-depth studies on formation mechanisms, security early warning, and regulation remain needed. Mechanism research is relatively weak: ecology-focused studies often lack macro-level ecological considerations, while socio-ecological studies insufficiently address ecological processes. No unified evaluation system or criteria have been established, with most research remaining theoretical and evaluative, resulting in multiple coexisting patterns that hinder management application and strategic decision-making.

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2. Review of Ecological Security Pattern Research Contents

Ecological security pattern construction and improvement occur against socioeconomic development backgrounds, targeting key ecological problems and integrating ecological protection and restoration activities with different demand levels. The main research contents include: (1) pattern formation, evolution, and impact mechanisms; (2) ecological process-based patterns; (3) multi-objective pattern optimization; (4) ecological protection redline-based pattern construction; and (5) ecological security prediction, early warning, and regulation management.

2.1 Pattern Formation, Evolution, and Impact Mechanisms

Understanding historical pattern formation helps identify current problems. This involves analyzing historical evolution processes, identifying potentially vulnerable areas, and examining driving mechanisms affecting regional ecological environments through multi-scale surveys and multi-factor analysis. Human activity impacts on patterns must be assessed, forming the foundation for ecological security evaluation frameworks and indicator systems.

2.2 Ecological Process-Based Ecological Security Patterns

Ecological processes refer to material, energy, and information flows and transformations within and between ecosystems. Landscape patterns and ecological processes are closely interrelated and mutually influential. When ecological processes exceed carrying capacity, old balances are broken, creating new patterns.

Research must consider both pattern quantification and ecological processes to enhance ecological significance.

2.3 Multi-Objective Ecological Security Pattern Optimization

Land use management often prioritizes visible economic benefits over invisible ecological ones, or certain ecosystem services over others. Ecosystem service trade-offs and synergies have become research hotspots. The UK National Ecosystem Assessment identified ecosystem protection and multifunctional landscape development as optimal approaches. Multi-objective optimization aims to comprehensively optimize patterns based on regional ecological contexts, national and regional positioning, and industrial development, considering interactions among ecosystem services, biodiversity, and socioeconomic development.

2.4 Ecological Protection Redline-Based Pattern Construction

China has established protected area systems including nature reserves and scenic areas, but management lacks unified planning with overlapping spatial layouts and insufficient legal frameworks. The ecological protection redline concept integrates existing important protection areas and key areas with protection gaps to improve efficiency and form a regulable system. Redlines represent the bottom line for national and regional ecological protection, providing the strictest protection boundary for constructing national ecological security patterns.

2.5 Ecological Security Prediction, Early Warning, and Regulation Management

Effective pattern regulation requires ecological monitoring, assessment, and early warning technologies. Key aspects include predicting ecosystem pattern changes, simulating driver impacts, and developing early warning systems. Model and scenario analyses for different regional ecosystem characteristics are current research priorities and important tools for theoretical and applied integration.

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3. Research Methods

3.1 Pattern Formation Mechanisms

Research requires constructing spatiotemporal pollen databases using pollen data, quantitative reconstruction of paleovegetation patterns at different scales using pollen-biome and landscape reconstruction algorithms, and revealing historical ecosystem changes. Combining paleoclimate data helps identify dominant environmental factors and biological mechanisms (e.g., origin of constructive species from paleobotanical fossils), providing crucial support for identifying key areas in ecological security patterns.

3.2 Pattern Evolution, Drivers, and Evaluation Systems

With rich data sources, change detection has evolved from single to multi-source remote sensing data fusion. Remote sensing monitoring establishes quantitative analysis methods for pattern evolution, revealing areas of dramatic change requiring attention. Landscape pattern indices quantitatively describe spatial structure and heterogeneity across time and regions.

Drivers can be categorized as natural, technological, institutional, political, and cultural, interacting complexly across spatiotemporal scales. Land use change research often employs driver-land use change frameworks. Socioeconomic factors are primary drivers in ecological restoration areas, while annual precipitation also significantly influences land use change.

Evaluation indicator systems are crucial for ecological security assessment and key area identification. International frameworks include the PSR (Pressure-State-Response) model by OECD and DPSIR (Driving-Pressure-State-Impact-Response) by the European Environment Agency. Domestic indicators primarily target environmental quality evaluation, but establishing universally accepted systems remains challenging due to interdisciplinary complexity. Some propose indicators based on ecosystem functions and processes, particularly recovery capacity after disturbance.

3.3 Factor Impact Analysis on Patterns

Human activities: Construct human activity databases through data collection, analyzing urbanization and resource development impacts using urban development indices, breakpoint analysis, and spatial regression models. Build databases for major construction project disturbance intensity and environmental risk indices to assess positive and negative impacts on ecological security patterns.

Natural factors: At long time scales, use variogram and spatial statistics methods for climate change characteristic analysis. Combine ecosystem process models with meteorological data to determine climate change sensitivity points and key areas, identifying ecosystem vulnerability to climate change.

Socioeconomic aspects: Research focuses on socioeconomic development impacts on ecological security patterns, examining trade-off relationships and development patterns that maintain ecological security. Coordination analysis between socioeconomic development and ecological security patterns needs strengthening.

3.4 Pattern Construction Methods and Principles

Landscape ecological planning offers valuable insights. Forman's "concentration and dispersion" model ensures large natural vegetation patch integrity through landscape pattern adjustment and concentrated land use, maintaining biodiversity and ecological functions. Landscape planning emphasizes spatial context,

ecosystem integrity, and surrounding landscape impacts—consistent with protected area planning principles.

Regional ecological security pattern construction should follow these principles: (1) Protect natural landscape resources and maintain natural functions and processes as the foundation; (2) Integrate ecological, social, and economic impacts comprehensively; (3) Employ targeted analysis indicators and methods based on specific regional problems; (4) Address multi-scale issues since disturbances have scale-dependent effects; (5) Use active interventions like ecological restoration and engineering to gradually improve patterns.

3.5 Multi-Objective Pattern Optimization Methods

Ecosystem service trade-offs are central to optimization. Ecological restoration enhances regulating and cultural services while supply services (e.g., food production) may decrease, but overall ecosystem service capacity increases. Quantitative analysis among multiple services remains limited, with root-mean-square deviation being a simple practical method. Tools like InVEST, ARIES, and SAORES integrate scenario analysis, ecosystem service trade-offs, and spatial optimization for decision-making.

Biodiversity and ecosystem services are intrinsically linked and vital for human well-being. While most protected area management focuses on biodiversity, some studies analyze spatial congruence between biodiversity and ecosystem services. However, debate continues on whether ecosystem services should substitute for biodiversity conservation. Multi-objective optimization must balance ecological, social, and economic benefits, particularly in China' s context of uncoordinated industrial development and resource-environment constraints.

3.6 Redline-Based Pattern Construction Methods

The technical process includes: identifying redline delineation scope, assessing ecological importance (ecosystem services, sensitivity, vulnerability), determining redline schemes, and verifying boundaries. Redlines integrate existing important protection areas and key gaps rather than creating new ones. Construction based on redlines resembles protected area planning, using multi-scale importance and degradation assessments to build patterns with redlines as the core and external extensions, analyzing coupling between socioeconomic development and ecological protection patterns for industrial layout planning.

3.7 Ecological Security Prediction and Management

Model simulation and scenario analysis are primary prediction methods. Representative models include Cellular Automata (CA), Markov models, and Agent-Based Models. CA-Markov models simulate urban and land use spatial patterns. Population and economic growth impacts on habitats, urban expansion effects on biodiversity, and sea-level rise impacts on coastal ecosystems have been predicted.

For ecosystem services, models include environmental, social, and coupled models. Early warning methods include set pair analysis, Markov chains, and spatial pattern indicators as early warning signals for ecological state transitions. However, pattern models have limitations as they don' t simulate dynamic mechanisms, depending mainly on transition probabilities and neighborhood rules. Future research should strengthen coupling between pattern-process models and spatial statistical models.

Ecological security management requires performance assessment of ecological protection redlines, clear accountability mechanisms, and establishing multi-angle feedback systems linking policy formulation, regional sustainable development, and human well-being enhancement.

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4. Key Issues

4.1 Pattern Construction, Maintenance, and Supervision

The theoretical framework for ecological security pattern construction remains weak and exploratory. Different research directions lack systematic integration. Evaluation methods and indicator systems lack universally accepted criteria, causing deviations among results. Without binding protection and supervision mechanisms, patterns remain merely boundaries on paper. Effective construction and management at regional and national levels require improved theoretical methods and decision-support technologies.

4.2 Scale Effects

Different spatial scales have different priorities. At national and global scales, biodiversity conservation and climate regulation services are emphasized, while at provincial and municipal scales, regional ecological problems and protection capacity enhancement are the focus. Cross-scale uncertainties and heterogeneity increase difficulty, requiring special attention to functional zone boundaries and cross-scale integration. Temporal scales also matter as ecological security patterns change with productivity, natural conditions, and human activities.

4.3 Mechanism Research and Interdisciplinary Integration

Ecological security is a comprehensive issue involving ecology, geography, and ecological economics. Strong theoretical foundations are needed for pattern assessment, particularly regarding formation mechanisms and relationships between ecosystem services and patterns. Interdisciplinary integration remains a challenge.

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5. Outlook

Ecological security pattern research has evolved from qualitative to quantitative, static to dynamic, and rigid constraints to flexible optimization. The focus has shifted from structural optimization (e.g., forest coverage) to process-based spatial pattern effects, and from species protection to ecological restoration and national/regional sustainability. Future priorities include:

1. Improving ecological security pattern assessment methods and model optimization
2. Better integrating pattern construction with land development planning and management
3. Developing and implementing regulation technologies and policies for coordinated ecological security and socioeconomic development
4. Building decision support systems integrating monitoring, databases, and model libraries
5. Establishing national ecological security early warning systems and maintenance systems to address ecological crises

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References

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Note: Figure translations are in progress. See original paper for figures.