

Historical Evolution and Frontier Trends of Research in the Field of Ecological Security Patterns in China

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Abstract: To further explore the scientific research level, research hotspots, and cutting-edge trends in the field of China's ecological security pattern, this paper, based on the China Academic Journal Network Publishing Repository, uses CiteSpace and VOSviewer and the literature from 2002 - 2023 to carry out a visual analysis and knowledge mapping of China's ecological security pattern research. The results show that from 2002 - 2023, publications in the field of China's ecological security pattern have increased; there is close cooperation among authors, and the authors with the first publication and the first citation frequency are Peng Jian and Yu Kongjian from Peking University, respectively. The distribution of the research institutes is concentrated, with the dominant institution being the University of the Chinese Academy of Sciences. This field primarily takes "ecological security pattern," "ecological corridor," "minimum cumulative resistance model (mcr)," and "ecological source" as the hot research content, based on which the research hotspots are classified into five aspects, and "ecological source" and "circuit theory" are the key research frontiers. The robust scholarly interest in China's ecological security pattern underscores its significance, and the comprehensive summary and analysis of research status and application dynamics are poised to foster collaborative advancements in this critical field.

Keywords: China; CiteSpace; ecological security pattern (ESP); VOS viewer; visualization analysis

1 INTRODUCTION

In the 21st century, with the increasing global urbanization, anthropogenic activities such as high-intensity land development and utilization have had a great impact on the connectivity and stability of natural ecosystems, leading to rapid environmental degradation, over-exploitation of resources, and many other ecological problems that are gradually coming to the forefront [1-3]; they also pose a great threat to the national and regional ecological security and the sustainable development of the social-ecological system. In this regard, in the early 1990s, Professor Yu Kongjian and his research team globally proposed the theory and methodology of ecological security pattern [4]. The method integrates ecological landscape elements, spatial location, and linkage strength; it gradually becomes an important way to maintain natural ecological processes and regional ecological security and safeguard ecosystem health and safety [5-8]. For the first time, the report of the 18-th National Congress of the Communist Party of China (CPC) elevated "building an ecological security pattern" to the height of national strategy and integrated the construction of ecological civilization into the overall process of economic, political, social, and cultural constructions. Based on the proposal of ecological civilization construction, how to promote the benign cycle of ecosystems, maintain regional ecological security, and build an ecological security pattern has become one of the hot spots of current research [9, 10].

Early studies on ecological security patterns in China primarily focused on resource management and the basic structure and function of ecosystems [11-13]. Over time, the Chinese government's increasing focus on environmental issues has fuelled the emergence of the field of environmental policy and management. Nowadays, relevant studies primarily focus on the construction, evaluation, and optimization of the ecological security pattern and the optimization of the construction framework [14-16]. There are various research objects, such as cities [17], industrial and mining zones [18], mountains and hills [19], and plateau lakes [20], and the scale of the study has

shifted from a single scale to a multi-scale integration [21]. The field of China's ecological security pattern has further expanded into an inter-scientific field, where ecology, natural resources, urban and rural planning, environmental economics, and many other disciplines are fused to achieve integrated research on ecological issues. In addition, the application of the geographic information system (GIS) and remote-sensing technology to explore the spatial and temporal distribution and dynamic changes of ecosystems in a finer way [22, 23] provides technical support to construct ecological security patterns.

To gain a deeper understanding of the historical evolution and cutting-edge trends in the study of China's ecological security patterns, we will apply VOSviewer and CiteSpace visualization tools to analyze the relevant literature. This will help identify the knowledge structure, academic cooperation networks, and research hotspots in this research area and reveal the development path of China's ecological security pattern. Simultaneously the experience and programs to construct an ecological security pattern have a positive impact on stabilizing the global ecosystem and achieving sustainable development goals, effectively promoting the harmonious progress and sustainable development of the ecological environment and improving the human socio-economic and living standards.

2 MATERIALS AND METHODS

In this article, we primarily use VOSviewer_1.6.18 and CiteSpace 6.1.6. VOSviewer is a bibliometric analysis and visualization software developed by NeesJanvan Eck and Lu-do Waltman [24], and its strength lies in "co-occurrence" network clustering and density analysis. CiteSpace, developed by Dr Chaomei Chen of Drexel University in collaboration with Dalian University of Technology, is a Java-based citation network analysis and visualization tool used for "co-citation" analysis [25, 26], which is primarily used for measuring, analyzing, and identifying data in the scientific literature, as well as for

displaying new trends and dynamics in scientific development.

Based on VOSviewer and CiteSpace, the quantitative analysis and knowledge mapping of China's ecological security pattern-related literature data from 2002 to 2023 were visualized to show the overall research direction of China's ecological security pattern, hotspots, and the cutting-edge direction at each stage. With the help of literature management software EndNote 20 and statistical software Excel software to process the data, we summarize the evolution process of China's ecological security pattern and explore its development hotspots and future development trends. To make it easier to view the keyword clustering, this study imported the data from VOSviewer into Pajek and made the necessary adjustments to the clustering diagrams in "Draw" in Pajek to obtain more uniform and clearer clustering results that could be used for subsequent analyses.

2.1 Data Download

The core collection of the China Academic Journal Network Publishing Database (CNKI) was used as the search base. The process is as follows: Open CNKI, click advanced search, select journal articles, and enter the subject term "ecological security pattern" as the subject of the search; the search condition is "precise," the source category is "all journals," and the period of the data retrieval is 2002 - 2023. A total of 412 documents were obtained with a search date of October 23, 2023. The content format consisted of complete records and cited references, and 412 plain-text files were exported.

2.2 Data Processing

We exported the data of 412 articles on "ecological security patterns" retrieved from CNKI, saved them in Refworks format, and named the file "download.txt". We put it into the input folder, converted the data to CNKI data format recognized by the software through CiteSpace, and set up the parameters according to the required functions, including "Time Slicing," "Years Per Slice," "Node Types," "Top N, Thresholds," "Pruning," and so on.

Next, we selected data in EndNote format and exported them to EndNote 20 for annual publication volume and high-frequency keyword statistics. Through EndNote 20's bibliographic title export function, the output style used is RefMan (RIS) Export; the RIS format is exported so that it can be identified and analyzed for processing by VOSviewer. To better display the results of the analysis, the subject terms were sorted out, and the subject terms with close meanings were merged and processed through the subject term elimination and merging function that comes with VOSviewer and CiteSpace, while the search terms playing an interfering role in the clustering analysis were eliminated.

3 RESULTS

3.1 Trend Analysis of the Volume of Literature

The statistical analyses of the 412 pieces of literature (Fig. 1), show a clear trend of growth in the research on China's ecological security pattern, indicating that the

importance of this field is gradually becoming more prominent in Chinese academia and policy practice. During 2002 - 2013, the number of articles published was in a period of slow growth, which was a stage of exploration in the field of ecological security pattern, and the research results were less presented in the form of academic literature, among which 2009 and 2013 were influenced by the "Bulletin on the State of China's Environment" and the "Twelfth Five-Year Plan for National Ecological Protection," respectively. An increase was observed in the number of research papers to strengthen China's ecological protection work and safeguard the ecological security of the country and the region in the meantime. From 2014 - 2019, the overall volume of articles issued was in a period of steady growth, a growth trend driven by Chinese government policies. The release of "Promoting China's ecological civilization construction to a new stage" has a major significance; through six core principles, six major initiatives, and strengthening the government to comprehensively promote the construction of ecological environmental protection and environmental sustainability, the implementation of policy initiatives has spawned more research to support the development and implementation of policies [9]. Simultaneously, society's rising concern for sustainable development and ecological conservation has prompted academics and research organizations to actively invest more resources in relevant research. However, there is a significant decline in the number of articles in 2020, which primarily stems from the outbreak of COVID-19 restricting spatial movement, resulting in the postponement of ecological security surveys and field research in China in 2020. Since 2021, the number of articles has been in the stage of rapid growth of research depth and stability. In this stage, the state and the government strongly support and lead ecological environmental protection, the establishment of a resource-saving and environmentally-friendly society, and the coordinated development of the economy and ecological environment. This foundation has led to a significant growth in projects. The many and varied academic achievements predict that the research in the field of ecological security pattern will continue to flourish and is expected to have a far-reaching impact on the construction of an ecological civilization and ecological environmental protection in China.

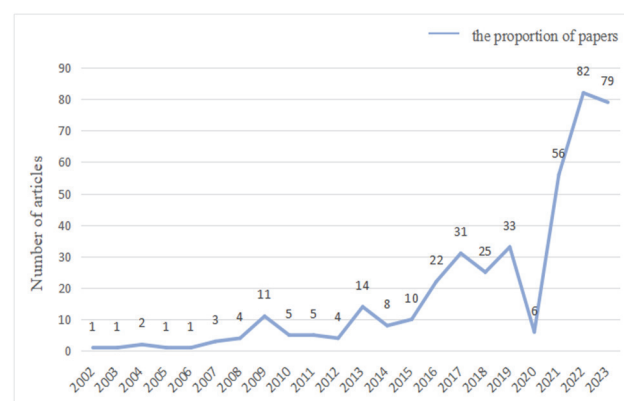


Figure 1 Trends in the amount of research literature on China's ecological security patterns

3.2 Analysis of the Co-occurrence of Author and Institutional Cooperation

3.2.1 Author Analysis

The presence of outstanding scholars in a research field is a key factor in its development, and by analyzing the authors' collaborative networks, representative scholars and core research teams in the field of China's ecological security patterns can be identified [27]. Author co-occurrence analysis using CiteSpace resulted in a total of 404 authors appearing during 2002 - 2023 (as shown in Fig. 2a), and information on the top 10 authors in terms of the number of publications is presented along with the number of articles published (Tab. 1). Among them, Peng Jian has the richest research output in this field with eight published papers and ranks first in terms of the number of publications, followed by Yu Kongjian, Meng Jijun, and Pan Jinghu. Yu Kongjian's paper has been cited up to 1925 times, far more than any other authors, indicating his outstanding academic influence in the field of China's ecological security pattern. Scholar Meng Jijun's research interests involve physical geography, land change science, natural resource evaluation, and utilization planning. Scholar Pan Jinghu is primarily engaged in spatial analysis and perception research, and both of them have excellent research results in the field of ecological security pattern.

Author collaboration networks of more than four published articles were overlaid and visualized using VOSviewer. The cooperation between authors can be derived from the knowledge graph, with larger nodes indicating more publications and greater influence and more connectivity between authors indicating greater intensity of cooperation. Consequently, close cooperation was observed among the group members, consisting of 45 academics in 7 cooperative groups (as shown in Fig. 2b), with the highest number of group members being 12. Five of the groups had six members, and the other group had three members. The research group is centered on Peng Jian, who is a notable contributor to the field of ecological security patterns and ecological restoration of territorial space. Peng Jian's research is concerned with ecological protection and restoration issues in China, with a special focus on constructing an ecological security pattern in Guangdong Province to resolve the contradiction between ecological protection and economic development [28]. In addition, his study emphasizes the basic logic of ecological restoration in national land space, stresses the enhancement of human ecological well-being as the core restoration goal, and constructs a multi-scale synergistic ecological security pattern, which provides guiding principles and goals for ecological restoration in national land space [29].

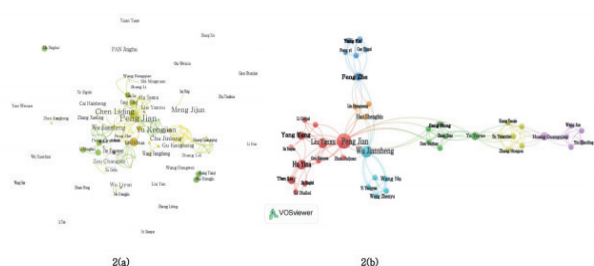


Figure 2 (a) Author co-occurrence map; (b) Author partnership co-occurrence map (small group of 45 people)

Table 1 Frequency of publications by high-yield authors of studies on China's ecological security pattern

No.	Author	No. of Documents	Highest Cited	Author's Unit
1	Peng Jian	7	1615	School of Urban and Environmental Studies, Peking University
2	Yu Kongjian	6	1946	School of Architecture and Landscape Architecture, Peking University
3	Meng Jijun	4	306	School of Urban and Environmental Studies, Peking University
4	Pan Jinhu	4	252	Northwest Normal University
5	Wu Jiansheng	4	565	Peking University
6	Wu Lirun	4	105	Fujian Agriculture and Forestry University
7	Zou Changxin	4	474	Nanjing Institute of Environmental Science, Ministry of Ecology and Environment
8	Chen Lidong	4	1261	Ecological Environment Research Centre, Chinese Academy of
9	Gu Kangkang	4	172	Anhui University of Architecture and Technology, School of Architecture and Planning
10	Chu Jinlong	4	111	Anhui University of Architecture, School of Architecture and Planning

3.2.2 Co-occurrence Analysis of Research Institutions' Collaboration

Co-occurrence visualization analysis using CiteSpace with the research institution as a node yields a knowledge graph of the research institution's collaborative network (Fig. 3). According to the information of the top 10 major research institutions (Tab. 2), the University of Chinese Academy of Sciences (UCAS) published the largest number of articles totalling 9, followed by 8 articles each from the State Key Laboratory of Urban and Regional Ecology of the Ecological Environment Research Centre of the Chinese Academy of Sciences and the Key Laboratory of Science and Technology of Urban Habitat of the School of Urban Planning and Design of the Graduate School of Shenzhen, Peking University. A collaborative research network was formed, with these three institutions as the core. It shows that these research institutions have strong scientific strength and influence in the field of China's ecological security pattern and have attracted the active participation of several universities and research institutions. The UCAS'partner institutions span a wide range of fields, including meteorology, ecological and environmental studies, resources and environment, and geology [30-32]. The UCAS provides a wide range of interdisciplinary support that promotes diversity in research and educational programs and enhances the exchange of knowledge and experience. Notably, the reason for the highest number of publications in the UCAS may be related to the Chinese national context. The reasons are shown below:

- In terms of policy: With the convening of the 18-th National Congress and the clear proposal of "building an ecological security pattern," society as a whole will further understand and implement this spirit.

The theory and construction system of "ecological security pattern" will be further improved and actively put into extensive social practice.

- Ecological and economic perspective: the construction of the ecological security pattern provides paths and techniques for coordinating the relationship between spatial protection and development of the national territory, and provides ecological safeguards and environmental support for rapid economic growth [33].

From a social point of view, China is a large country with a large population, and the continuous increase in human activities has led to an intensification of the urbanization problem; to alleviate and eliminate the negative effects brought about by human activities, an ecological security pattern can maintain the continuity and integrity of the regional landscape process and protect the ability of the region to develop sustainably under different levels of development.

Table 2 Highly productive organizations for the study of ecological security patterns in China

No.	Name of Organization	Volume of Publications
1	University of Chinese Academy of Sciences	9
2	State Key Laboratory of Urban and Regional Ecology, Ecological Environment Research Centre, Chinese Academy of Sciences, China	8
3	Key Laboratory of Urban Habitat Science and Technology, School of Urban Planning and Design, Shenzhen Graduate School, Peking University, China	8
4	College of Land and Resources, Hebei Agricultural University	7
5	Anhui University of Architecture, School of Architecture and Planning	6
6	Key Laboratory of Ground Surface Process Analysis and Simulation, Ministry of Education, School of Urban and Environmental Studies, Peking University, Beijing, China	6
7	Institute of Geographic Sciences and Resources, Chinese Academy of Sciences	6
8	College of Landscape Architecture, Nanjing Forestry University	5
9	College of Geographic Sciences, Inner Mongolia Normal University	5
10	School of Land Science and Technology, China University of Geosciences (Beijing)	5



Figure 3 Distribution of research organizations collaborating on China's ecological security landscape

3.3 Analysis of Research Hotspots

Keywords can distinctly and intuitively express the topic of the literature discourse or thesis, and through the study of keywords in a certain field, we can quickly grasp the research focus and hot topics in the field [34]. VOSviewer carries out the hotspot visualization of co-occurring keywords. In the hotspot knowledge graph, the keywords are represented by circles and labels, the larger the node circle is, the greater the word frequency of its keywords, that is, it is the hotspot research content; the same color represents the same group, that is, the same type of research topic, and the degree of its activity is positively correlated with the size of the circle. By analyzing the keyword co-occurrence knowledge map (Fig. 4), it is concluded that the whole keyword knowledge map primarily focuses on the "ecological security pattern," with

a radial distribution. To avoid the confusion of the direct analysis, the keyword co-occurrence knowledge map was run in Pajek and adjusted appropriately, and, then, imported into VOSviewer to obtain the monochromatic and uniform keyword clustering knowledge map (Fig. 4b). The top 10 keywords of hotspots in the field of China's ecological security pattern since 2002 are shown in Tab. 3. From Fig. 4 and Tab. 3, it can be seen that the high-frequency keywords such as "Ecological Security Pattern (336)", "Ecological Corridor (65)," "Minimum Cumulative Resistance Model (MCR) (65)," "Ecological Source (46)," and "Circuit Theory (36)" constitute the representative terms of the field, which are also the hotspots of China's research on the ecological security pattern in the past 20 years.

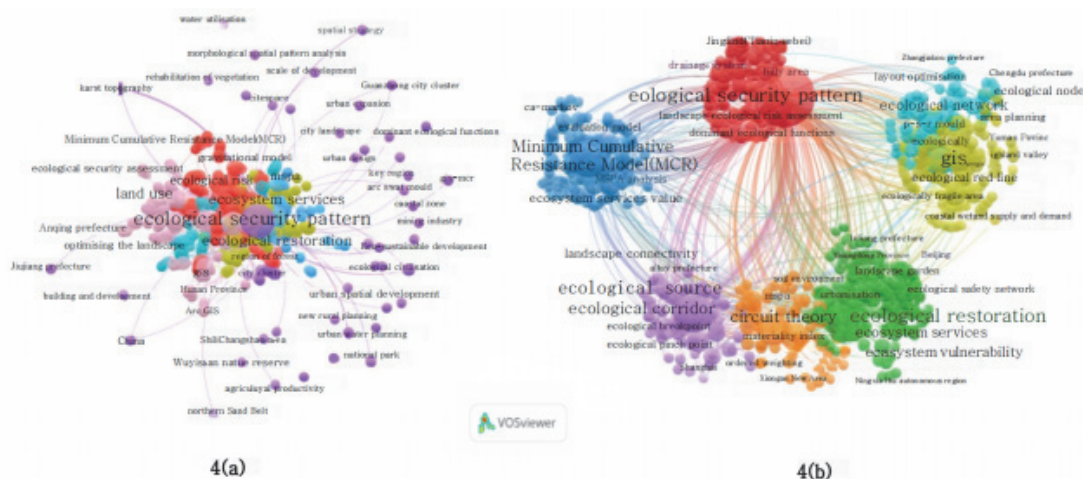


Figure 4 (a) Co-occurrence graph of keyword; (b) keyword clustering map

Table 3 Statistics of high-frequency and medium-center keywords in the field of China's ecological security pattern, 2002 - 2023

Keyword	Occurrences	Total link strength
Ecological security pattern	337	1240
Ecological corridor	65	261
MCR	65	254
Ecological niche	46	192
Circuit theory	36	139
Ecological security	34	110
Ecosystem services	24	96
Ecological restoration	17	76
Land use	16	64
Ecological sensitivity	16	61

Table 4 Clustering of research topics and keyword co-occurrence clustering induction

No.	Research Topic	Main Keywords
1	Ecological security pattern construction and optimization	Ecological spatial structure of urban agglomerations, urban growth boundaries, landscape ecological risk assessment, dominant ecological functions, key sites, morphological spatial pattern analysis (mspa) methodology, risk assessment, dual assessment.
2	Ecological corridor construction	Ecological conservation and restoration zoning, habitat quality, ecological "plus points", zoning management, maximum entropy modeling, ecological safety nets, biodiversity conservation, supply and demand space, ecological resistance surfaces.
3	MCR	Ecosystem service values, gravity modeling, conservation and restoration, zoning, ca-Markov model, mspa analysis.
4	Land use landscape patterns	GIS, urban planning, ecological nodes, built-up land, least-cost pathways, ecologically fragile areas, ecological networks, ecological protection red lines, sensitivity analyses, landscape pattern changes.
5	Ecological restoration of territorial space	Urbanization, security patterns, importance of ecosystem services, "greening of the countryside" data, land use planning, ecological carrying capacity, ecological factors, carbon footprint, urban sprawl, remotely sensed ecological indices.

To discover the research hotspots in the field more intuitively, the keyword clustering density was visualized using VOSviewer (Fig. 5). In the keyword clustering density knowledge graph, the larger the range of the warm circle, the redder the color of the center, which indicates that the greater the density of the clustering, that is, it represents the greater the degree of hotness and concern in

the field [35]. Combining the keyword clustering knowledge map (Fig. 4b) and the keyword clustering density map in Fig. 5 with the learned professional knowledge, five cutting-edge hot topics in the current research field of China's ecological security pattern were extracted (Tab. 4), and the research content and important results of each hot topic were further analyzed and discussed.

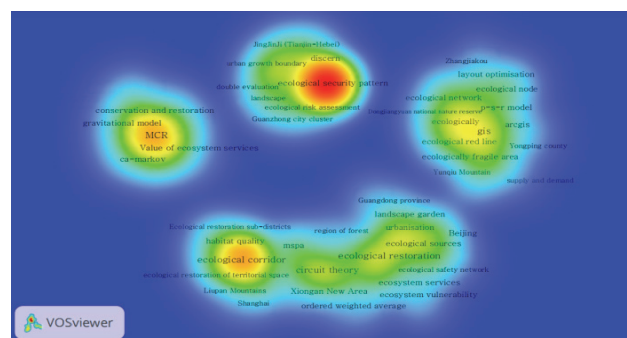


Figure 5 Keyword density visualization

3.4 Construction and Optimization of Ecological Security Patterns

Reasonably constructing and optimizing the ecological security pattern is of great significance for the protection and restoration of biodiversity, the maintenance of ecosystem services, the safeguarding of the ecological function of the regional system, and the building of a firm national ecological security barrier [36, 37]. After Yu Kongjian, a Chinese scholar, explicitly proposed the concept of landscape ecological security pattern, many scholars have conducted related studies and explorations in the fields of ecology, geography, urban planning and their interdisciplinary disciplines [38, 39], which have led to the emergence of the concept of landscape ecological security pattern. The research direction has transitioned from the early focus on quantitative pattern analysis of ecological processes to introducing spatio-temporal pattern scenario decision-making with many ecological theories and models and, then, to the current focus on pattern dynamic simulation prediction and comprehensive optimization analysis [40-42]. The research methods have also changed from the initial single land use pattern analysis to the introduction of rich scenario simulation and decision-

making analysis methods, such as the Landscape Pattern Index [43], InVEST Model [44], Minimum Cumulative Resistance (MCR) Model [45], and Circuit Theory [46], which have significantly improved the reliability of constructing ecological security patterns. Findings show that the construction of China's ecological security pattern is now more concerned with the dynamic simulation of ecological processes, dynamic games, and the comprehensive optimization of ecological space expansion and pattern [42]. For example, Bao Yubin et al. (2023) combined the advantages of ecological service evaluation of the InVEST model and the advantages of corridor identification of the circuit-theoretic landscape model, adopting the study of "source-corridor-node" [44]; Ma Caixue et al. (2022) emphasized the energy-value ecological footprint model combined with the knowledge of the night-lighting data and the MCR model [47], and Chen et al. (2017) prioritized the theory of "importance-sensitivity-connectivity"[48]. Research on the construction and optimization of ecological security has been carried out in Ningxia, Yangtze River Delta, Guangdong, and other places, and good decision-making support effects have been achieved. The establishment of an ecological security pattern with regional characteristics through dynamic pattern simulation and prediction will be the primary focus of future research.

3.4.1 Ecological Corridor Construction

Ecological corridor construction is mostly based on MSPA and MCR models, with "source-corridor-point" forming an ecological network. The research perspectives are primarily based on the Habitat Evaluation Procedure [49], ecological risk evaluation [50], ecological protection red line [51], and ecological sensitivity and ecological service system evaluation [52]. Yanget al. (2023) used the main line of "source identification-corridor construction-ecological network optimization" to build an ecological network pattern of mountains and water [53]. Lianget al. (2023) constructed an ecological corridor system by removing redundancy based on the MCR model and the least-cost path method, which is important for protecting biodiversity and improving ecological environment quality [54]. Findings show that China is now shifting from building ecological corridors at the city or community scale to building ecological barriers at large scales such as urban agglomerations. For example, Houet al. (2022) identified potential corridors at multiple scales in the region using the LCP and SLEUTH models and incorporated corridor protection with a certain buffer width into urban spatial planning [55]. Donget al. (2020) extracted core habitat patches based on habitat quality, fused MCR, SCWT(Short Circuit Withstand Time), and KDE (Knee Point Voltage) methods to quantitatively identify ecological corridors and key restoration areas [56], clarified spatial boundaries, and provided effective spatial guidance for landscape and urban planning in Beijing. Nanjing also proposes to construct multi-scale characteristic ecological corridors in accordance with the spatial pattern of mountains, water, roads, forests, and fields for cities, functional areas, and communities [57]. Therefore, multi-scale integration of urban ecological corridors has become an important trend in China to

comprehensively improve the construction of urban ecological corridors.

3.4.2 MCR Model

The MCR model can better simulate the relationship between potential trends in spatial movements of organisms and changes in landscape patterns, taking into account the horizontal linkages of landscape units and well simulate the disturbance of ecological flows by heterogeneous landscape units, identifying least-cost pathways [58, 59]. Yang et al. (2023) identified potential ecological corridors and nodes through the MCR and gravity models and constructed a regional ecological security pattern by combining with the watershed integrated management project of mountains, water, forests, fields, lakes and grasses [58]. Zhang et al. (2023) used the MCR model and ant colony algorithm combined with kernel density analysis to identify the extent of ecological corridors [60]. The MCR model is an important method for scholars to extract ecological corridors based on the theory of "source area-resistance surface." However, in the specific implementation process, such as source identification, resistance surface construction, corridor node extraction, and so on, there is no unified standard [61].

3.4.3 Ecological Restoration of Territorial Space

Land consolidation and ecological restoration are committed to optimizing land space and improving ecological functions, maintaining a good natural background, and focusing on reducing the encroachment of human activities on ecological space and the coercion of ecological functions [62]. The 19-th National Congress of the CPC put forward the national strategy of "uniformly exercising the responsibility for the use control and ecological protection and restoration of all national land space, and integrating the systematic governance of mountains, waters, forests, fields, lakes and grasses"; it inextricably links the use control of national land space with ecological protection and restoration, establishes the concept of national land ecological space based on ecological restoration, and integrates the management of natural resources on a larger spatial scale to construct regional ecological security and the ecological security pattern of "overall protection, systematic restoration and comprehensive governance" [63]. Currently, most of the research on spatial ecological restoration in China's national territory focuses on projects and pilots that are carried out at a single point, a single target, or a specific environment at the small-scale level [63, 64]. Learning how to accurately identify the key areas of land space restoration and construct the ecological restoration pattern of land space from a holistic, systematic, and comprehensive perspective is worthy of further scholarly exploration and research.

3.4.4 Land Use Landscape Patterns

Changes in land use lead to changes in landscape patterns, and the combination of the two responds to the heterogeneity of the landscape and is the result of various

ecological processes [65, 66]. To achieve sustainable development goals, understanding land use change in landscape ecology from the perspective of landscape pattern is one of the research hotspots, which mainly focuses on the changes and drivers of land use and landscape pattern, simulation of landscape ecological risk assessment, and dynamic evolution of landscape pattern [67-69]. For example, Liu et al. (2022) analyzed the characteristics of spatial and temporal changes in land use landscape patterns and their drivers in Ruixing and the surrounding area [67]. Han et al. (2023) simulated land use in Zhengzhou City in 2030 [70] and analyzed the changes in land use shifts and landscape patterns. Qiao et al. (2023) analyzed the characteristics of the spatio-temporal evolution of land use and spatio-temporal differentiation of ecological risks of landscapes in Xining City [71]. In general, most of the previous studies are about large-scale study areas, while relatively few studies have been conducted on land use landscape patterns in small-scale rapidly urbanizing areas.

3.5 Frontier Trend Analysis

The VOSviewer keyword co-occurrence density map can only qualitatively show the research hotspots of China's ecological security pattern, and cannot reflect its temporal change pattern, while CiteSpace's keyword emergence analysis can quantitatively represent the heat of different research hotspots and their temporal change pattern [72]. The time region is determined as 2002 - 2023, and each year is set as a time slice, and the emergent keywords are detected in each slice, which finally results in Fig. 6 and Fig. 7.

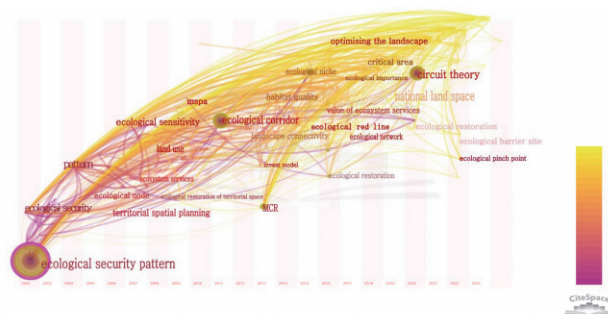


Figure 6 Time zone map of the evolutionary path based on CiteSpace



Figure 7 The top four burst keywords detected using CiteSpace

Combined with Fig. 6 and Fig. 7, the development trends in the field of China's ecological security pattern research are summarized below, based on the temporal distribution of key nodes:

- Research in the field of China's ecological security pattern began with the study of ecological security, and to promote ecosystem services and seek a path to

ecological security, the construction of an ecological security pattern was proposed.

- From 2004 to 2022, there were more key nodes related to the theme of China's ecological security pattern, including key nodes of land use, ecological corridor, ecological source, circuit theory, ecological restoration, and homeland space. During this period, research on China's ecological security pattern was in a phase of rapid development, reflecting the fact that research on this topic has attracted sustained attention from scholars.

- In addition, scholars prefer to construct the ecological security pattern through evaluation methods and models, such as critical area identification, the importance of ecosystem services, ecological sensitivity evaluation, the InVEST model, the MCR model, and so on.

- Since 2022, ecological security patterns and regional restoration have been primarily studied with the keywords "ecological obstacle points" and "ecological pinch points," combining the circuit theory to identify ecological "pinch points" to be protected, "obstacle points" to be removed, and ecological rupture points based on ecological corridors constructed, which are priority areas for ecological restoration of national land space, and the removal of which can increase the possibilities of ecologically important spatial connectivity [73, 74].

A burst word is a keyword that has a sudden increase in frequency of use within a short period of time, and the mutation rate shows the intensity of the sudden increase in the frequency of use of the word within a short period of time, and the analysis of keyword bursts is used to explore the trend of research frontiers in a particular field [75]. Research on the field of ecological security patterns includes four of the most popular emergent keywords: 'security patterns', 'land use', 'ecological corridors', and 'circuit theory' (Fig. 7). Research on "security patterns" has increased significantly since 2004, a response to the Chinese Government's growing awareness of ecological security issues. From 2000, when the goal of "safeguarding national ecological and environmental security" was explicitly stated, to 2002, when it was proposed that ecological security is an important component of national security, along with national defence security and economic security, to 2004, when the maintenance of ecological security was written into national law as a legislative purpose, establishing it as a legal concept. The interplay of research directions and policies during this period has promoted the study of ecological security patterns [76]. In 2008, the keyword "land use" was a hot research topic. It reflects the rapid development of urbanisation and industrialisation in China, which has led to changes in land use and tensions between demand and conservation of resources. Researchers have focused on land use change to better manage resources and ecosystems [77]. In 2021 and 2022, the keywords "ecological corridor" and "circuit theory" become new research hotspots and continue to this day. The focus on multi-scale integration of urban ecological corridor construction, circuit theory ecological security network, ecological restoration and protection of the red line and other directions indicate that ecological corridors and circuit theory will become the hotspot and trend of future research in the field of ecological security pattern.

4 DISCUSSION AND CONCLUSION

In this study, the field of China's ecological security pattern was analyzed by the VOSviewer and CiteSpace visualization software, and we can draw the following conclusions:

- The field of ecological security patterns in China has achieved remarkable development in the past two decades. From the perspective of the quantity of research literature, the research in the field of ecological security patterns has experienced rapid growth from the initial start-up development to the subsequent rapid growth, especially since 2021, with a significant increase in the number of published articles. This trend reflects China's policy priorities in ecological security protection and sustainable development, as well as the continued attention and investment in this field by academics, and signals that research in the field of ecological security patterns will continue to flourish.
- The main authors in the field of ecological security patterns are Peng Jian, Yu Kongjian, Meng Jijun, and Pan Jinghu, all of whom have produced important research results. There is close collaboration among the authors, with the largest group consisting of 12 scholars, centered on Peng Jian of Peking University, China, whose main research areas are ecological security patterns, landscape ecology and land use, and integrated ecosystem assessment.
- Closer cooperation between the UCAS and its partner institutions across several fields, in particular, in the field of China's ecological security pattern, has strong scientific research strength and influence; it has attracted the active participation of many colleges and universities and scientific research organizations.
- The keywords "ecological corridor," "minimum cumulative model," "ecological source," and "circuit theory" are analyzed through the keyword co-occurrence diagram of VOSviewer, which highlights the core elements of the study of ecological security patterns. Five frontier hotspots in this research field were distilled through the clustering results and density maps based on the clustering results: construction and optimization of ecological security patterns, the construction of ecological corridors, the MCR model, the ecological restoration of national land space, and the landscape pattern of land use.

These results show a trend of cross-fertilization with the disciplines of ecological environment, geographic sciences, urban and rural planning, and natural resources, indicating that the research in this field is expanding. In terms of research methodology, satellite remote sensing technology, theoretical modelling, evaluation methods and other research systems. In addition, after analyzing and summarizing the recent relevant literature, findings show that scholars mainly focus on the fusion of multiple scales and dynamic pattern simulation to predict the establishment of an ecological security pattern with regional characteristics. The research covers different areas such as nature reserves, major project areas, rapidly urbanizing areas, and ecologically fragile areas and applies the ecological security pattern to the delineation of ecological protection red line, precise identification and control of natural resources space, and ecological restoration of national land space.

In conclusion, research in the area of ecological security patterns in China has made significant progress, but some challenges remain. China needs to recover quickly from the new coronavirus epidemic and achieve sustainable development and management. The Fourteenth Five-Year Plan for the National Economic and Social Development of the People's Republic of China and the Outline of the Vision for 2035 include the promotion of green development for the harmonious coexistence of human beings and nature as an important task and strengthen efforts to conserve biodiversity and natural resources, reconcile human beings with nature, and enhance ecological and environmental regulatory capacity. Therefore, the findings of the visualization analysis were integrated with China's regional development policies:

At present, China has carried out work on the construction of an ecological security pattern at the territorial scale and has achieved remarkable results, maintaining important ecological elements and processes in ensuring the operation of key ecosystems in territorial space. With the deepening of regional cooperation and international exchanges, as well as the implementation of the "Belt and Road" strategy, cross-regional and national strategic cooperation on ecological security will provide a good opportunity to solve global ecological and environmental problems.

Future researchers and staff should follow the world and China's national development strategies and ideas, focus on core scientific mechanisms, and optimize key technologies to promote the systematization of the content of China's ecological security landscape and enhance the overall level and impact of scientific research.

Researchers should identify the opportunities and challenges in the field of ecological security patterns, construct an effective spatial identification system and control transmission rules, form a continuous, complete, and systematic ecological protection pattern and open space network system, and establish an ecological security pattern with multi-scale integration of regional characteristics through dynamic pattern simulation and prediction.

Some research limitations in this paper need to be improved in the future. First, the data used in the study do not include all the literature as only the CNKI database was chosen as the data source for the bibliometric analyses in this study, and no other databases (Web of Science, Scopus, etc.) were selected. However, as a major research country in ecological security pattern, China's CNKI database contains high-quality literature, which can represent the research hotspots and frontiers in this field. Second, in the future, we can comprehensively analyze the most influential papers in the database to dig out the latest and cutting-edge hotspot information, which will bring new ideas and scientific research directions for research in this field.

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