

ORIGINAL RESEARCH ARTICLE

Research progress of China's grassland ecosystems in the 21st century based on bibliometric analysis

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Abstract

Grasslands are critical ecological barriers and carbon sinks, and research on China's grassland ecosystems has expanded in response to climate change, ecological restoration, and carbon-neutrality goals. This study conducted a systematic bibliometric analysis of the research progress of China's grassland ecosystems from 2000 to 2025. The results show that publication output increased slowly before 2020 and then rose exponentially thereafter. A total of 18 countries and regions participated in this field, with China ranking first, followed by the United States. Keyword co-occurrence analysis identified five thematic clusters, from which three major evolutionary research trajectories were further distilled: (i) driver attribution and remote-sensing diagnosis; (ii) carbon cycling and the re-evaluation of "vegetation–soil–microbe" mechanisms; and (iii) ecosystem services and spatial governance. The study further identifies that the field continues to face several challenges, including weak integration of cross-scale and multi-process analyses, insufficient mechanistic interpretation, limited quantification of uncertainty, and obstacles in translating research outcomes into policy. Overall, the findings indicate that, supported by multi-source data fusion, research on China's grassland ecosystems is shifting from change monitoring and attribution toward mechanistic explanations of stability and responses to extreme events. In addition, workflows such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and Patch-generating Land Use Simulation (PLUS) show considerable potential for incorporating carbon sequestration and ecosystem service assessments into verifiable scenario comparisons and spatial governance decision-making.

Keywords: China's grassland ecosystem; Bibliometric analysis; Data-driven analysis; Knowledge visualization; Research evolution

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1. Introduction

Grasslands are an indispensable component of the Earth's ecosystems and are often described as the "skin of the Earth." If forests can be regarded as a three-dimensional ecological barrier, grasslands function as a horizontal ecological barrier. They perform essential ecological functions, including windbreak and sand fixation, soil and water conservation, water retention, climate regulation, and biodiversity maintenance.¹ China is the world's second-largest grassland country.² Its natural grasslands account for 12% of the global total and cover 41.7% of China's land area.³ Therefore, grasslands are a vital ecosystem supporting China's ecology, economy, and society, as well as an irreplaceable strategic resource. Since the launch of the Grain for Green Program in 1999, China has implemented ecological protection compensation projects on a large scale. In the grassland sector, ecological protection compensation can be traced back to the Returning Grazing Land to Grassland Program established in 2003. Thus, China's earliest ecological protection compensation mechanisms were first developed in the forest and grassland sectors.⁴

Over the past two decades, extensive research has been conducted on China's grassland ecology. A systematic synthesis of these diverse studies can help scholars identify current research hotspots more quickly and accurately, while also clarifying future development directions. Quantitative analysis and statistical inference based on mathematical models provide an effective means of achieving this goal. Bibliometrics is a data-driven method that applies statistical techniques to scientific outputs and provides knowledge-oriented quantitative analysis.⁵ Existing reviews on China's grassland ecosystems mainly adopt the following perspectives:

- (i) Studies limited to specific regions of China. Some reviews examine the developmental trajectory, current understanding, and latest advances in grassland research, while discussing future research opportunities and their scientific, environmental, and socioeconomic significance.⁶ Others focus on northern China's grasslands and the Qinghai-Tibetan Plateau, providing systematic and internationally accessible reviews of the effects of livestock grazing on vegetation and soils.
- (ii) Studies focusing on specific fields or disciplines. Some reviews examine the theory and practice of grassland ecological compensation by exploring its conceptual connotations in China and evaluating its implementation effects.⁷ Others review research in classical ecology and ecological principles applicable to grassland conservation and management, and

discuss the challenges and opportunities facing grassland ecology as a field.⁸

- (iii) Studies addressing multiple ecological elements, including grassland ecology, within a defined time frame. For example, one bibliometric study analyzed 167 publications from 2013 to 2022 and concluded that policy management and environmental science are the two major research domains in addressing rural ecological and environmental crises in China.⁹

Overall, existing studies have mainly focused on grassland ecosystems in specific regions of China, with relatively limited disciplinary coverage. Some studies have also examined grassland ecosystems only within broader discussions of multiple ecosystem types, rather than focusing on grasslands themselves. In addition, recent literature has not been sufficiently incorporated into existing analyses.

To address these limitations, this study adopts a longer time span, from 2000 to 2025, and a broader scope covering research outputs across China. It focuses specifically on the evolutionary mechanisms and interdisciplinary collaborative patterns of grassland ecosystem research. By combining bibliometric methods with an assessment of the field's development potential, this study aims to provide predictions and proposals for the future development of ecosystem research in China. This study covers only the English-language literature indexed in international databases. Chinese domestic journals and policy reports constitute an important additional knowledge base.

2. Methods and data

A descriptive and evaluative bibliometric analysis of articles on strategies and pathways for the restoration and conservation of China's grassland ecosystems was conducted. A bibliometric analysis provides researchers with a broader profile of the literature through performance analysis, visualization, and relationship analysis.¹⁰ In this study, bibliometric methods were used to monitor research trends and to examine the relationships within research networks.

2.1. Data source and retrieval

This study searched the Web of Science Core Collection (WoSCC) of Clarivate Analytics¹¹ for English-language academic journal articles published between 2000 and 2025 containing the keywords: "China's Grassland Ecology" OR "China's Grassland Ecosystem" OR "China's Steppe Ecology." Regarding document type, this study focused on journal articles indexed in the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI), with no restrictions on source journals or subject categories.

These databases provide comprehensive records of article types, authors, institutional addresses, and bibliographic references.¹²

The WoSCC database was selected as the data source because of its academic authority and suitability for bibliometric analysis. It includes major citation indexes, such as Science Citation Index Expanded (SCIE), SSCI, Arts & Humanities Citation Index (AHCI), and Emerging Sources Citation Index (ESCI), and is widely used for knowledge mapping, collaboration network analysis, and research trend studies.

A topic search (TS) was used to improve coverage of literature related to the research topic. In WoSCC, the Topic field covers titles, abstracts, author keywords, and Keywords Plus, making it suitable for the initial retrieval of relevant publications. Since WoSCC does not adopt a unified controlled vocabulary like some medical databases, the search terms were manually designed by combining subject terms, synonyms, and related expressions to reduce omissions.

Based on the research topic, China's Grassland Ecosystems in the 21st Century: A Data-Driven Analysis of Collaborative Visualization, Research Frontiers, and Future Trends, the search strategy included two groups of terms. The first group described the research object, including "grassland," "grassland ecosystem," "steppe," "meadow," and "rangeland." The second group defined the geographic scope, including "China," "Chinese," "Inner Mongolia," "Tibet," "Xinjiang," "Qinghai," "Gansu," "Ningxia," and "Sichuan." These terms were combined using the Boolean operators AND/OR and truncation symbols to comprehensively cover the main expressions used in studies on China's grassland ecosystems.

2.2. Data preprocessing

After preliminary screening and duplicate removal, this study further used the Co-Occurrence 9.9 software (COOC 9.9; COOC development team, China) for data extraction and cleaning to ensure the authenticity and reliability of subsequent data computation and processing (Figure 1). First, after data extraction, a second round of refined deduplication was conducted. All records were compared using COOC, and duplicate publications and records with severe data deficiencies were removed. As a result, 590 duplicate records were excluded, leaving 1,094 valid publications.

Second, detailed data cleaning was conducted on these 1,094 publications. Specifically, missing information was supplemented by tracing back to the original texts; records with unresolved missing fields were deleted; publications with low relevance to grassland ecosystem research

were excluded; and data coding was standardized for subsequent statistical analysis. Synonym merging was then performed according to the following principles: First, terms referring to the same concept within the context of this study were merged into a single keyword. Second, the abbreviated and full forms of the same concept were unified. Third, keywords denoting concepts that were too broad in meaning or scope were removed. Since the same keyword could appear repeatedly within a single article after synonym merging, author keywords in the database were further deduplicated.

Ultimately, 1,077 publications were included in the formal bibliometric analysis. The deduplicated dataset was then exported for subsequent data computation and processing in VOSviewer (1.6.20, Leiden University, The Netherlands) and CiteSpace (6.4.R2 Advanced, Drexel University, United States of America [USA]).

2.3. Bibliometric analysis methods

The concept of scientific knowledge mapping originated from an academic workshop organized by the USA National Academy of Sciences in 2003. With the development of information visualization, an increasing number of tools for generating scientific knowledge maps have gradually emerged.¹³ In this study, COOC 9.9, VOSviewer,¹⁴ and CiteSpace¹⁵ were selected to analyze the bibliographic dataset and construct knowledge maps. Based on the respective strengths of each software package and method, this study employed the following approaches for each tool:

- (i) COOC has been widely adopted in bibliometric research because of its distinctive capabilities in raw data extraction and its detailed functions for knowledge map generation. In this study, COOC was first used to organize and clean pre-analysis data using its data extraction functions. It was then used for frequency statistics and for visualizing temporal trends and the relationships among country/region distributions. Specifically, this software was used to generate Figures 1, 2a, 3a, and 3b.
- (ii) CiteSpace can systematically organize bibliometric data by using time as the main analytical clue, and is therefore a highly practical tool for identifying research trends and supporting trend prediction. In this study, CiteSpace was used to generate the following figures and to present the detailed k-values: Figure 2b, Figure 4 (k = 25), Figure 5 (k = 25), Figure 6 (k = 10), Figure 7 (k = 5), and Figure 8 (k = 15).
- (iii) VOSviewer pays special attention to the graphical representation of bibliometric maps in an easy-to-interpret way. It can also handle large-scale computations involving up to 5,000 publications and

Original	Frequency	Preprocessed	Original	Frequency	Preprocessed	Original	Frequency	Preprocessed
Climate change	103	Climate change	Inner mongolia	14	Inner mongolia plateau	Grassland	55	Grassland ecosystems
Climate-change	6		Inner mongolia plateau	3		Grasslands	13	
Land use type	6		Geodetector	10		Grassland ecosystem	19	
Land use types	4		Geographical detector	3		Grassland ecosystems	4	
Land use	47	Land use	Net ecosystem productivity	9	NEP	Ecosystem services	49	Ecosystem services
Land-use	6		NEP	4		Ecosystem service	16	
INVEST Model	42	INVEST Model	Mongolia	4	Mongolian plateau	Ecosystem service value	30	ESV
INVEST	4	Land use change	NDVI	24		Ecosystem service values	11	
Land use change	38		Normalized difference vegetation index	6	NDVI	Ecosystem service value (ESV)	5	
Land-use change	8		Normalized difference vegetation index (NDVI)	3		Ecosystem services value	3	
Human activities	25		Alpine grassland	11		ESV	3	
Human activity	5	PLUS	Alpine grasslands	3	Alpine grasslands	Net primary productivity	16	NPP
PLUS Model	24		Temperate grasslands	5		NPP	10	
PLUS	4	Drivers	Temperate grassland	5	Temperate grasslands	Net primary production	10	
Driving factors	22		FVC	3		Net primary productivity (NPP)	6	
Drivers	6		Fractional vegetation cover	3	FVC	Land use and land cover change	6	LUCC
Driving forces	5		LULC	6		Land use/ Land cover change	3	
Driving factor	4	Soil moisture	Land use/ Land cover	4	LULC	Land use and cover change	3	
Soil moisture	18		Land use and land cover	3		Land use/ Cover change	4	
Soil water	4	Drylands	Land cover change	7	Land cover change	LUCC	8	Remove
Drylands	9		Cover change	6		China	58	
Dryland	4	C	Conservation	4	Ecological conservation	Influencing factors (Sic)(Sic)(Sic)(Sic)	7	
Carbon	8		Ecological conservation	3		Trend analysis	6	
C	3	Nature reserves	Vegetation restoration	7	Revegetation	Patterns	5	
Nature reserves	5		Revegetation	4		Model	5	
Protected areas	3	Ecosystems				Impact	4	
Nature reserve	3					Trend	3	
Ecosystem	7	Carbon stocks				Responses	3	
Ecosystems	3							
Carbon stock	6	Climatic factors						
Carbon stocks	3							
Climatic factors	6	Grassland types						
Climatic factors	4							
Grassland type	4	Species diversity						
Grassland types	4							
Species diversity	13	GPP						
Species richness	8							
Gross primary productivity	10	Ecological restoration						
GPP	4							
Ecological restoration	21	Restoration						
Restoration	5							

Figure 1. Data cleaning process

Abbreviations: InVEST: Integrated Valuation of Ecosystem Services and Tradeoffs; PLUS: Patch-generating Land Use Simulation.

provides strong clustering capabilities for multiple types of bibliometric data. In this study, VOSviewer was used to generate Figure 9.

3. Results

3.1. General analysis

3.1.1. Global distribution of China's grassland ecosystems in the 21st century

This study uses COOC and CiteSpace to analyze publication output in China's grassland ecosystem research since the beginning of the 21st century and to construct knowledge visualization maps. To ensure consistency with WoSCC statistics, the full publication counting method was adopted. Although this method may overestimate the contributions of certain countries or regions, it helps identify collaboration patterns and relationships among

them, thereby supporting the development of emerging research perspectives and fields.

We used full counting to capture participation (presence/visibility) in collaborative publications. To mitigate potential inflation due to multi-entity co-authorship, we performed a fractional-counting robustness check. Under the full-counting method, each country appearing in the address information of a collaborative publication receives one full count; therefore, country-level counts may exceed the number of unique publications.

The results show that global research on China's grassland ecosystems has generally increased since 2000. From 2000 to 2019, the field remained in a slow-growth stage, with annual increases typically ranging from one to three publications, and even a decline between 2013 and 2017. In 2020, however, publication output increased

sharply, rising from 37 to 73 publications. From 2021 to 2025, the cumulative publication output continued to grow rapidly, increasing from 198 to 1,072 by 2025. This trend is closely related to the contributions of different countries, several of which showed notable increases.

This study identified 18 countries and regions with more than 6 publications. As shown in Figure 2, China dominates the field with 1,051 publications, ranking first globally in research on China's grassland ecosystems. The USA ranks second with 89 publications. Since the 21st century, countries and regions with more than 10 publications include Australia (28), the United Kingdom (UK; 25), Germany (24), Canada (19), the Netherlands (13), and Switzerland (12), most of which are located in Europe. In contrast, Asian countries other than China have contributed relatively fewer publications than European countries.

Since 2000, publication output across countries and regions has continued to increase. As shown in Figure 2a, Region 1 represents the slow-growth period from 2000 to 2019, during which all regions showed gradual increases. The USA was the earliest contributor and maintained steady but slow growth. China entered the field in 2002 and gradually surpassed the USA, although its growth remained slow, with no publications recorded for either country in 2010. From 2011 onward, Germany, Canada, and Japan began contributing. After 2012, more countries entered the field, and Mongolia, Denmark, and Switzerland published their first studies in 2014. Belgium and Russia began contributing in 2018 and maintained continuous growth thereafter. China contributed the most publications during this stage.

Region 2 marks the initial phase of rapid growth from 2020 to 2022. During this period, more countries began publishing, while China maintained the highest output and entered a phase of rapid expansion from 2022 onward. The USA, Australia, the UK, Germany, and Canada continued to grow steadily, while other countries also became more active. For example, Belgium and Scotland entered the field in 2020, and Italy and Sweden began contributing in 2021, showing sustained growth thereafter.

Region 3 represents the rapid-expansion stage, characterized by a sharp increase in research output. China's publication volume was particularly prominent during this stage. Many European countries also showed increasing output; although their growth was slower than China's, it was much faster than in the previous two stages.

3.1.2. Influential countries/regions analysis and global collaboration

In research on China's grassland ecosystems, co-authored

publications between China and the USA in 2004 marked the beginning of international academic collaboration in the 21st century. Another notable point was in 2011, when collaborative publications appeared among China, Germany, Canada, and Japan. This also marked the first period in which Chinese institutions established academic ties with research institutions in these countries and regions (Figure 2b).

Thereafter, collaboration between China and the USA continued to deepen. In 2014, more countries entered the field through joint publications. Although annual output was only four papers, academic exchange between China and the USA became increasingly close. In the same year, several countries that had not previously published in this field also contributed through collaboration, including Denmark–China–USA, USA–Mongolia, Switzerland–China–Austria–Germany, and Canada–China. These collaborations indicate the further expansion of international academic exchange in this field.

Compared with 2014, collaboration among countries and regions became closer in 2016. Although annual output was only three papers, China and the USA showed higher total link strength and broader international collaborative ties. From 2017 to 2021, China's international collaboration network became increasingly prominent. From 2022 onward, academic exchange between China and the USA continued to occupy a central position. Moreover, compared with academic exchanges within Asia, China's exchanges with Europe were more extensive. This may be related to China's efforts to learn from and test ecological restoration measures, methods, and advanced technologies developed in European countries.

3.1.3. Overall trend of scientific outputs of China's grassland ecosystems in the 21st century

Changes in the quantitative distribution of disciplines and fields revealed the developmental trends, knowledge accumulation, and research priorities of China's grassland ecosystem research since the beginning of the 21st century. Based on the WoS subject–category classification, this study examined the top 50 high-frequency disciplines and fields involved in this field since 2000. Using time as the reference axis, it traced yearly disciplinary perspectives and research patterns, analyzed their developmental characteristics and trends, and generated knowledge visualization maps using COOC.

As shown in Figure 3, from 2000 to 2025, Environmental Sciences was the only field with more than 500 publications, accounting for the largest share with 539 papers. Fields with more than 100 publications included Environmental Studies (166), Ecology (162),

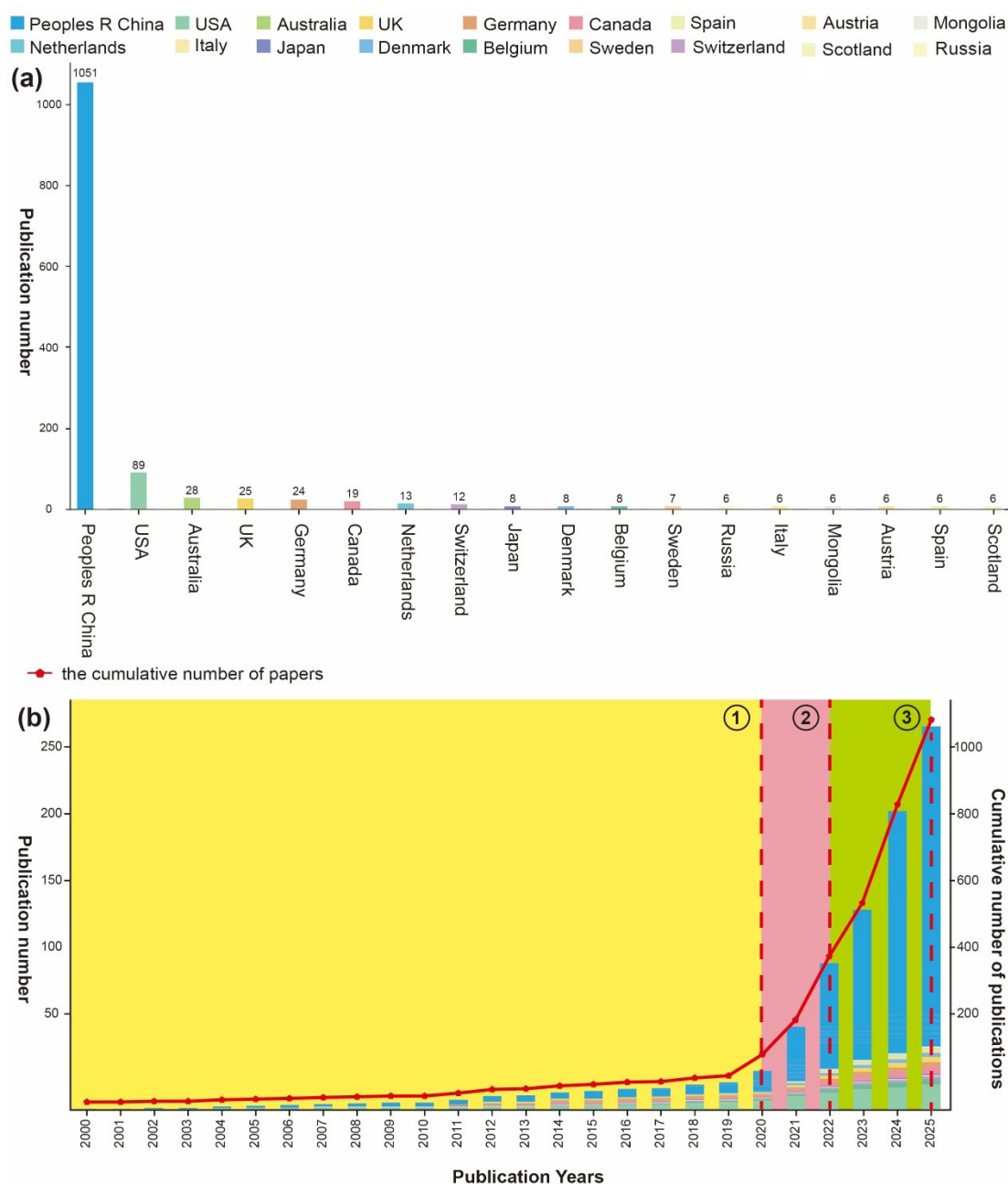


Figure 2. Publication trends and country distribution of China's grassland ecosystem studies. (a) Annual publication trends by country/region in research on China's grassland ecosystems, 2000–2025. (b) Cumulative annual publication output and trend by year in research on China's grassland ecosystems, 2000–2025.

Abbreviation: USA: United States of America.

Geosciences (162), and Biodiversity Conservation (124), all of which occupied relatively central positions in China's grassland ecosystem research. Fields with 70–100 publications included Soil Science (90), Remote Sensing (87), Water Resources (77), Green & Sustainable Science & Technology (75), Plant Sciences (73), and Imaging

Science & Photographic Technology (72). Other fields, such as Forestry, Meteorology & Atmospheric Sciences, and Agronomy, contributed approximately 50 or fewer publications.

Building on the overview of publication frequencies

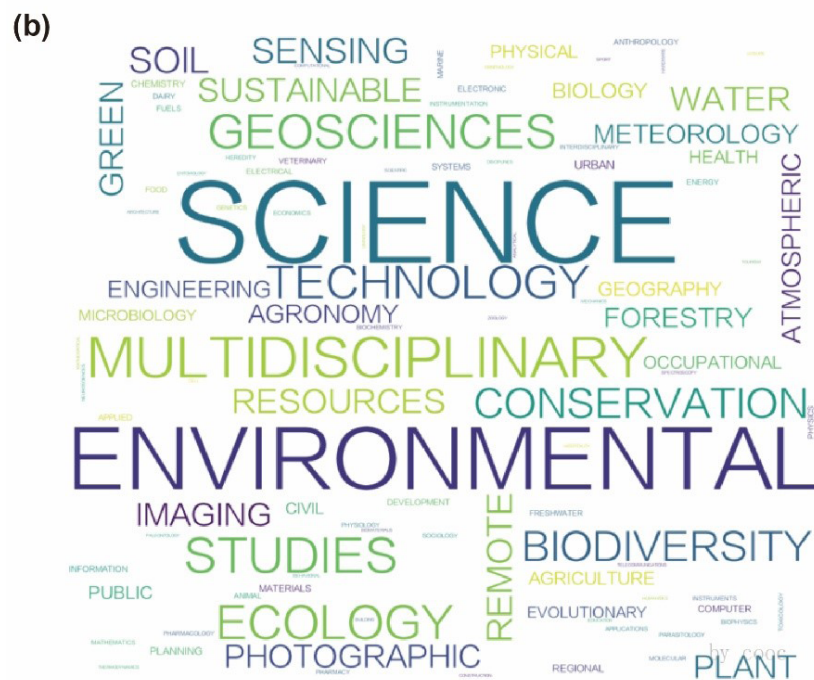
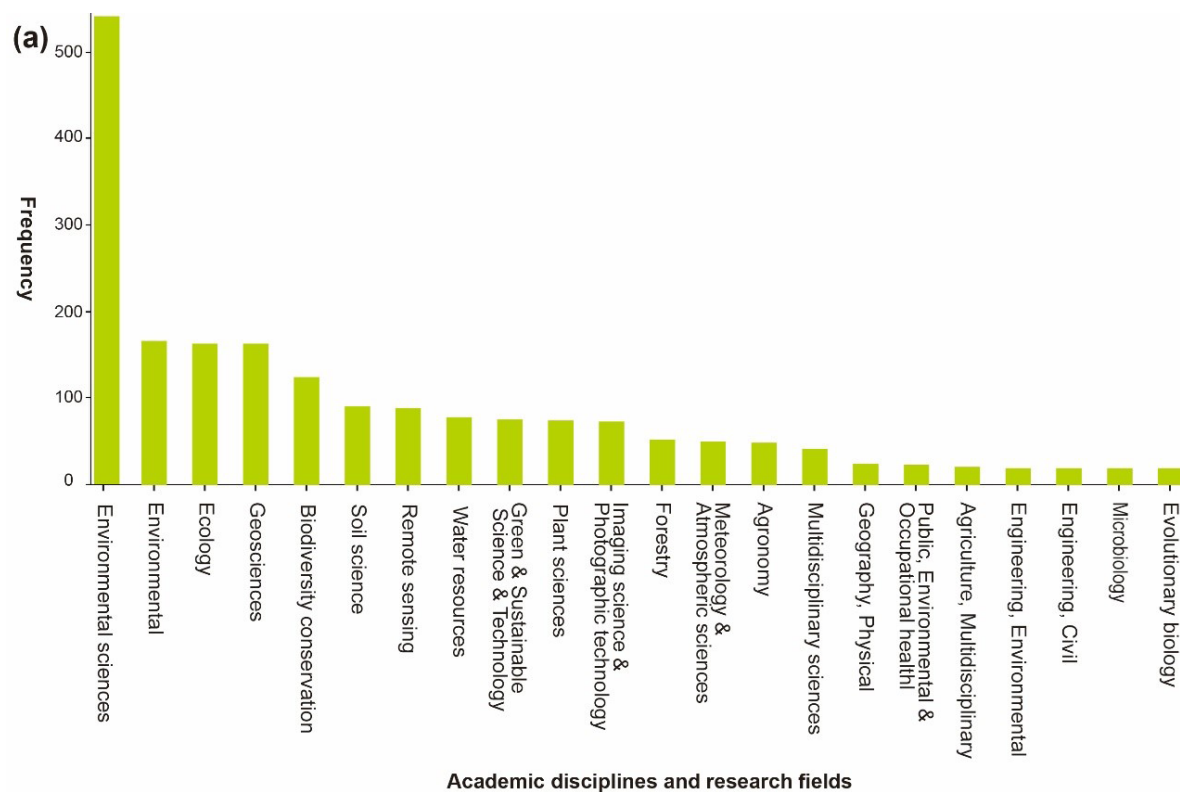
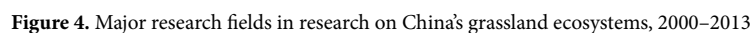


Figure 3. Major research fields in research on China's grassland ecosystems, 2000–2025. (a) Frequency distribution of major research fields in research on China's grassland ecosystems, 2000–2025. (b) Word cloud of major research fields in research on China's grassland ecosystems, 2000–2025.

During this stage (Figure 4), although research output on China's grassland ecosystems was relatively limited, several high-quality studies with foundational significance were published. Overall, the field was characterized by the dominance of a single leading discipline. For example, from the perspective of Environmental Sciences, some studies offered new insights into the scientific management and ecological restoration of rapidly degrading grasslands in Inner Mongolia.¹⁶ Within the framework of Geography, others examined China's national policies and their local implementation in Inner Mongolia, as well as the ecological conceptions of nature underlying both levels.¹⁷ From the perspectives of Plant Sciences and Ecology, some studies explored whether grassland litter, namely dead leaves and stems, affects forage productivity in China's grasslands,

In addition, from the perspective of Biodiversity



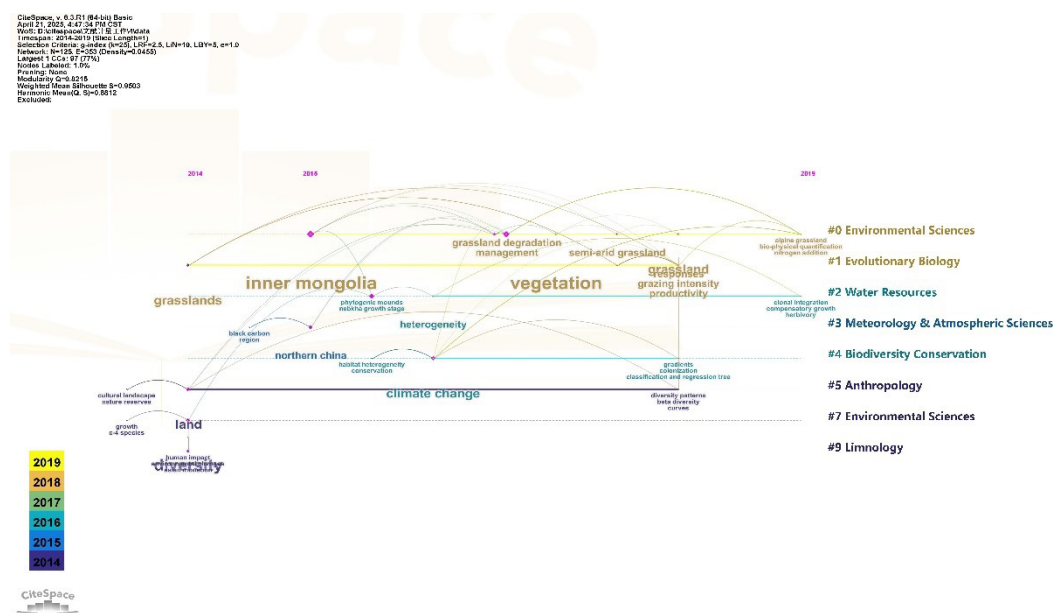


Figure 5. Major research fields in research on China's grassland ecosystems, 2014–2019

Conservation, some studies used the universal soil loss equation (USLE) to analyze the spatiotemporal characteristics of soil erosion from 1985 to 2015. By monitoring land-cover change and climatic variables, they revealed the drivers affecting soil stability and transport processes. During this stage, many emerging disciplines and new fields entered China's grassland ecosystem research, while Environmental Sciences continued to play a leading role.

(iii) Rapid growth stage dominated by emerging and more specialized disciplines (2020–2025)

Between 2020 and 2025 (Figure 6), disciplinary collaboration became more frequent, and the scope of research expanded considerably, with Environmental Sciences continuing to play a leading role, emerging and more specialized fields increasingly engaged in research on China's grassland ecosystems, resulting in more diverse perspectives and methodologies.

For example, from the perspective of Environmental Sciences, studies continued to examine the impacts of drought on vegetation in China's pastoral regions, clarifying the roles of vegetation community type and soil type in vegetation responses to drought across multiple timescales.²¹ From the perspective of Public, Environmental & Occupational Health, field-based observational and experimental research in the *Leymus chinensis* meadow steppe of the Songnen Plain in northeastern China revealed the characteristics of mercury exchange in grassland ecosystems.²² From the perspective

of Agriculture, Multidisciplinary, studies using the desert steppe of northern China as the study area argued that species asynchrony and species stability play key roles across spatial scales in grazing-mediated regulation of ecosystem stability. They further suggested that, in arid grassland ecosystems, biodiversity and grazing intensity should be balanced as spatial scale increases to achieve high ecosystem functioning and stability.²³

During this stage, research on China's grassland ecosystems entered—and remains in—a period of broad multidisciplinary attention. Although Environmental Sciences, Ecology, and Biodiversity Conservation still dominate, more specialized fields such as Forestry, Soil Science, Development Studies, and Regional & Urban Planning have also become highly active. In addition, emerging fields in the broader academic landscape, including Green & Sustainable Science & Technology, Agronomy, and Energy & Fuels, entered this research area for the first time. Therefore, Environmental Sciences will likely continue to play a leading role due to its close relevance to China's grassland ecosystems. Meanwhile, interdisciplinary and more specialized fields, with their distinctive perspectives and methods, are also likely to become important directions for future research.

3.2. Global publication source distribution of China's grassland ecosystems in the 21st century

Inter-institutional collaboration helps clarify interaction patterns in the production of academic outputs within a specific field. Using a bibliometric approach, this study

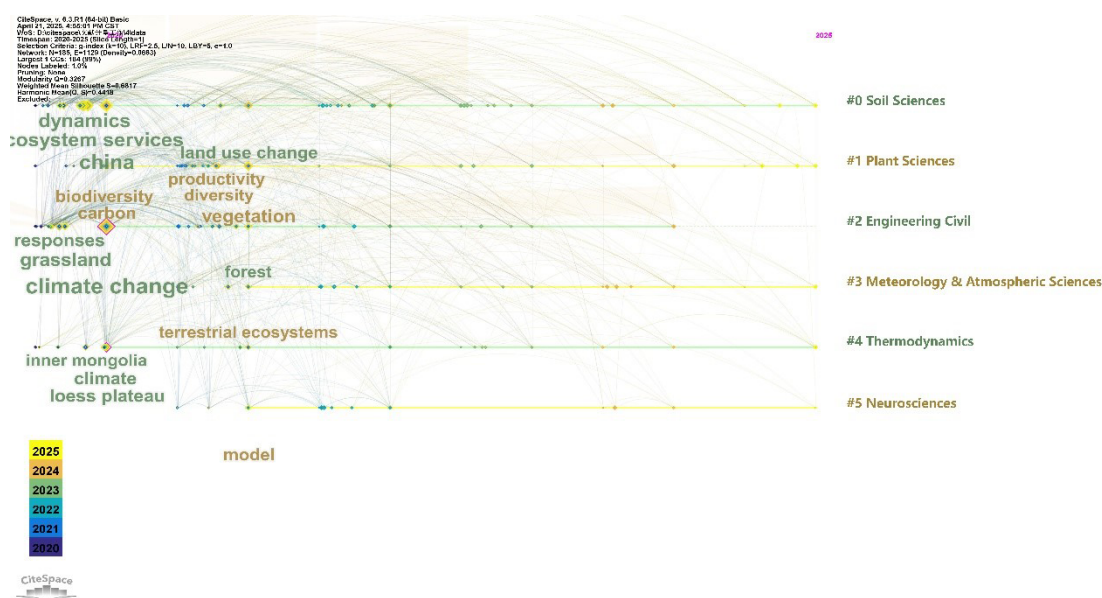


Figure 6. Major research fields in research on China's grassland ecosystems, 2020–2025

analyzed inter-institutional citation links and collaboration relationships in China's grassland ecosystem research since the beginning of the 21st century. It generated a knowledge map showing institutional publication output, the frequency and structure of citation/collaboration links, institutions with more than five occurrences, and a time-based institutional collaboration network (Figure 7). Based on this, the study examined institutional publication patterns, collaboration relationships, collaboration dynamics, and future trends in this field.

Since the beginning of the 21st century, China has attached great importance to the restoration of grassland ecosystems, sustainable development, and the utilization of grassland resources. As shown in Figure 7, the Chinese Academy of Sciences has the highest publication output in this field, with 358 papers, followed by the University of Chinese Academy of Sciences with 178 papers, Beijing Normal University with 136 papers, and the Institute of Geographic Sciences and Natural Resources Research with 66 papers. These institutions have maintained continuous scholarly output in China's grassland ecosystem research from 2000 to the present. In addition, the institutions shown in Figure 7 have more than five publications in recent years.

As shown in Figure 7, institutions with high publication output also show frequent collaboration and broad collaborative reach. Multi-institutional collaboration is common, and institutions further expand academic exchange by working with additional partners. For example, the University of Chinese Academy of Sciences collaborates

with the Cold and Arid Regions Environmental and Engineering Research Institute, which in turn collaborates with the Chinese Academy of Sciences, the most prolific institution in this field. The Chinese Academy of Sciences also maintains academic exchanges with the University of Chinese Academy of Sciences. In the figure, thicker lines indicate more frequent inter-institutional exchanges; for example, Northeast Normal University and the Northeast Institute of Geography and Agroecology show 22 instances of academic exchange. Overall, Chinese research institutions maintain close academic exchanges with one another, and highly productive Chinese institutions also sustain frequent collaboration with European institutions.

This study also examined the temporal evolution of inter-institutional collaboration. As shown in Figure 7, the link colors, from yellow to blue, indicate the progression from 2000 to 2025. In recent years, institutions connected by cyan and blue links generally show close collaboration, represented by thicker lines, and high publication output, represented by larger nodes. The Chinese Academy of Sciences, the Institute of Botany, and the China Institute of Water Resources & Hydropower Research have maintained close recent collaboration and substantial output, making them key actors in the network.

Although leading institutions such as the Chinese Academy of Sciences, Beijing Normal University, and the Institute of Geographic Sciences and Natural Resources Research have contributed substantially and maintained broad collaborative ties, direct collaboration among them remains limited. Therefore, stronger cross-disciplinary and

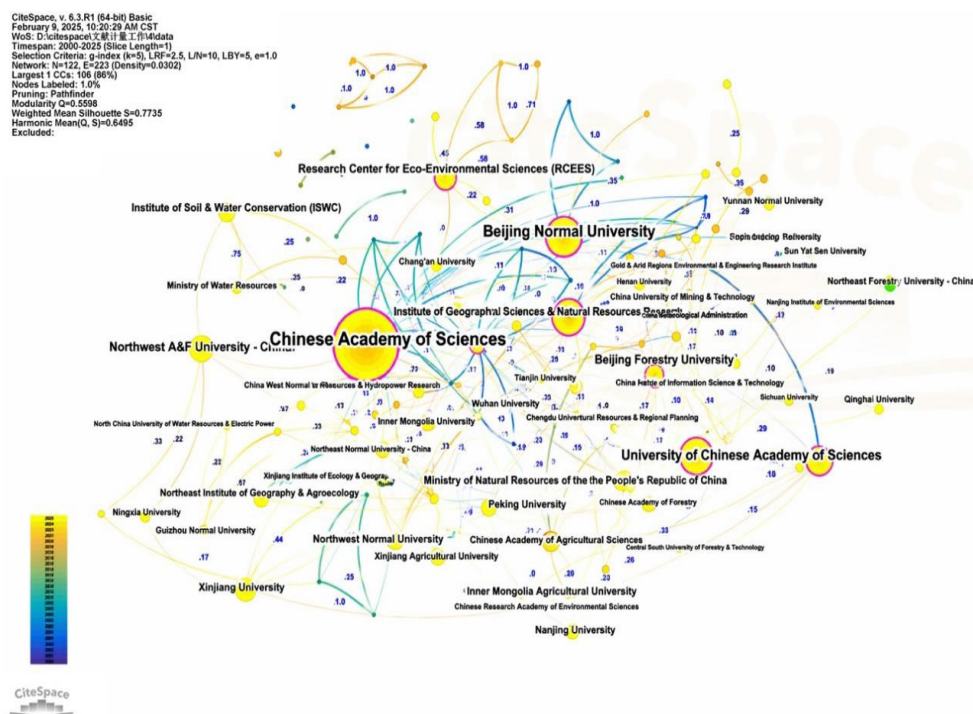


Figure 7. Knowledge map of the institutional collaboration network

cross-institutional collaboration among leading Chinese institutions should be an important future direction for this field.

3.3. The core area differentiation of China's grassland ecosystems in the 21st century

A review of existing research outputs helps current and future researchers more clearly understand the research perspectives currently emphasized across different research directions, their developmental dynamics, and future trends. To systematically reveal the major research domains in research on China's grassland ecosystems since the beginning of the 21st century, and the relationships and coupling among these domains, this study used VOSviewer to conduct a clustering analysis of author keywords (Figure 9).

The analysis identified five major clusters. These five clusters are not merely distinct from one another; rather, they are mutually connected and interact through extensive inter-cluster linkages. This indicates that research outputs on China's grassland ecosystems in the 21st century are largely oriented toward a multidisciplinary and interdisciplinary research paradigm. Moreover, by examining these inter-cluster linkages, it is possible not only to gain a clearer understanding of the current major research domains but also to identify more peripheral areas connected to the major clusters that may serve as potential

entry points for emerging research perspectives.

3.3.1. Cluster 1, characterized by grassland, remote sensing, and Inner Mongolia

The research perspectives represented by Cluster 1 are among the most central in China's grassland ecosystem research since the beginning of the 21st century, indicating that this cluster occupies a core position in the overall knowledge structure. Although "grassland" is a high-frequency research topic, "remote sensing" serves as a key connecting node. "Inner Mongolia" is also a prominent keyword, suggesting that studies on grassland ecosystems in this northern Chinese region have focused on both ecosystem functions and the use of remote sensing technologies to monitor detailed grassland system information.

Within this cluster, "grassland" is the most frequent keyword and occupies a relatively central position in linking with other clusters. It is strongly connected with keywords such as "carbon storage," "biomass," "soil organic carbon," "biodiversity," and "ecosystem stability." For example, some studies have examined shifts in biomass temporal patterns caused by climate change and suggested that such changes have important implications for grazing management. They further indicate that existing grazing strategies should be adjusted under climate change to maintain ecosystem stability.²⁴ Other studies have used

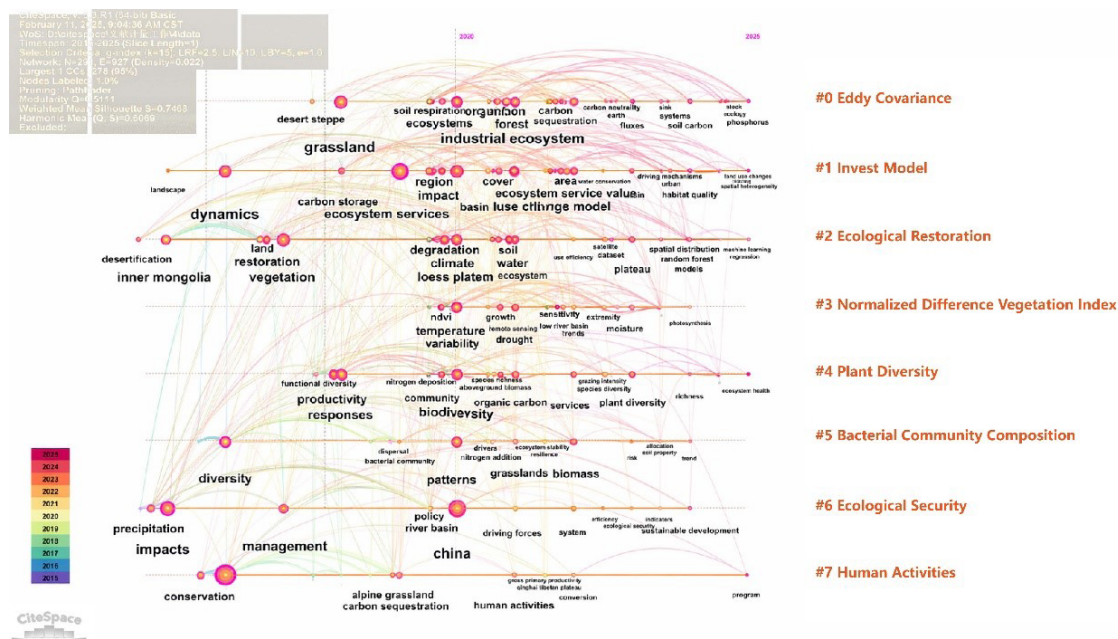


Figure 8. Fish-eye diagram of research trends in the field of China's grassland ecosystems, 2015–2025

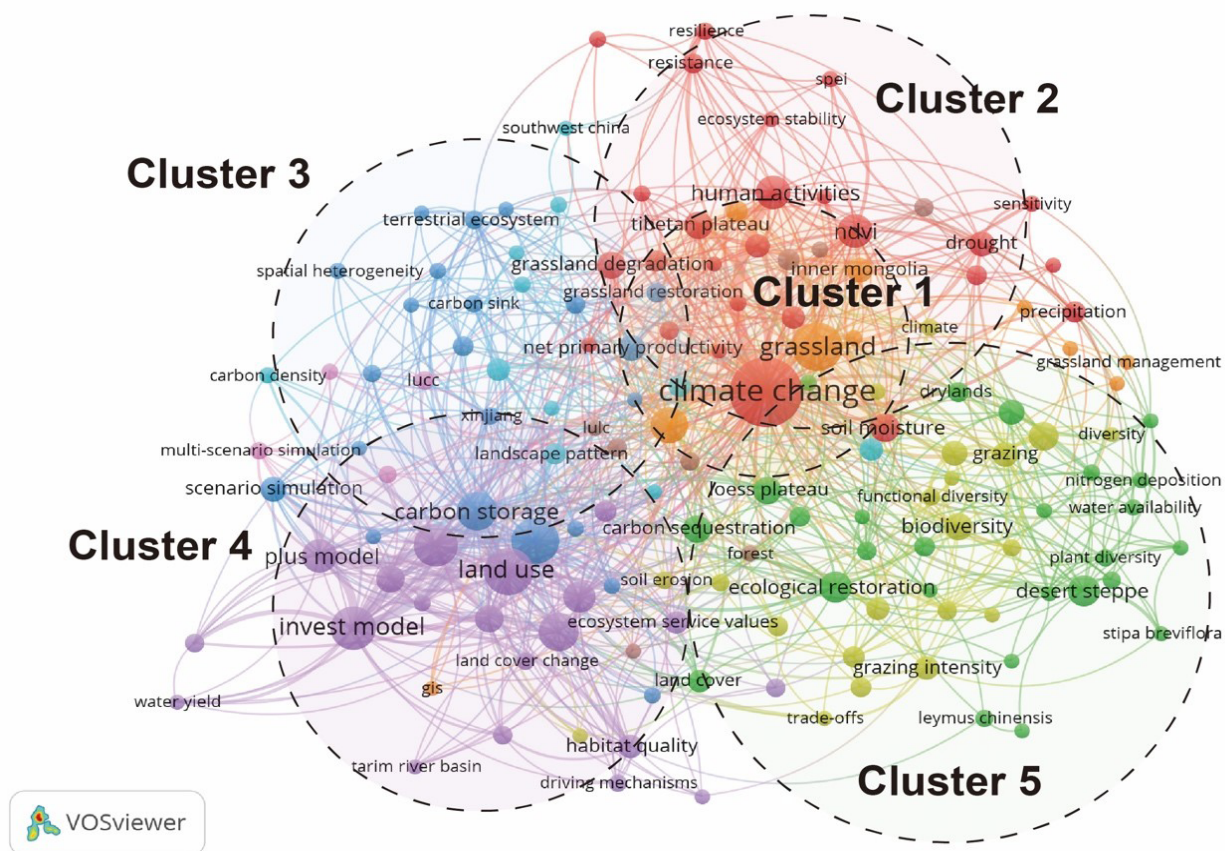


Figure 9. Author keyword co-occurrence knowledge graph and domain segmentation in research on China's grassland ecosystems, 2000–2025

remote sensing, land-use, and meteorological data, together with the Carnegie–Ames–Stanford Approach (CASA) model, to reveal the spatial variation of grassland net primary productivity (NPP) and its influencing factors in northwestern Tibet, northwestern Qinghai, and central Inner Mongolia, China.²⁵ To examine the factors limiting grassland restoration and its restoration potential, other studies employed a process-based agricultural production systems simulation model. Using observational data from typical and meadow steppes under natural conditions, a previous study evaluated simulations of phenology, aboveground biomass dynamics, and soil moisture, and further analyzed the restoration gap of grassland ecosystems and its controlling factors from 1969 to 2018.²⁶

Against this background, multidisciplinary approaches and advanced technologies have become increasingly important for addressing the challenges faced by grassland ecosystems. Research on policy effects in grassland regions is also shifting toward more professional and data-driven methods. In addition, Cluster 1 occupies a relatively central position because of its broad connections with other clusters, especially Cluster 2. As shown in the figure, the yellow nodes are closely linked to the red nodes, indicating that studies on China's grassland systems are often closely linked to perspectives on ecological and climatic change and grassland primary productivity.

Therefore, remote sensing has become a core node in Cluster 1 because large-scale and long-term monitoring of grassland ecosystems requires advanced remote sensing technologies as essential technical support. Meanwhile, Inner Mongolia, as one of the most concentrated regions of typical grassland ecosystems in China and one of the most active areas for ecological degradation and restoration efforts, has naturally become a key carrier for studies such as remote sensing monitoring and carbon storage assessment. The overall development process and internal logic of this cluster clearly reflect a shift in research from the identification of regional grassland change to ecological assessment supported by multi-source data.

3.3.2. Cluster 2, characterized by normalized difference vegetation index, climate change, and human activities

The research perspectives represented in Cluster 2 constitute one of the most common research domains and analytical perspectives in China's grassland ecosystem research since the beginning of the 21st century. Within this cluster, "climate change" serves as the core perspective, driving the development of other high-frequency themes, including "normalized difference vegetation index (NDVI)," "human activities," and "soil moisture." This

indicates that contemporary researchers regard climate change as a critical contextual framework. Against this background, advanced monitoring and detection technologies are used to identify the causes and states of ecosystem change more directly and efficiently.

Under the climate-change context, changes in ecosystem stability further affect ecological functions and the positioning of grassland ecosystems within the broader global ecological system. Human behavior may play either a negative or positive role in these changes, and studies in this cluster have focused particularly on the production and livelihood patterns of nomadic populations living in grassland ecosystems.

For example, based on Landsat remote sensing images from 1979 to 2020, one study used the support vector machine (SVM) classification method to analyze land-use/land-cover change and urban expansion in Hyderabad, Pakistan, over more than four decades. The results showed a significant increase in built-up areas, while agricultural land, vegetation, water bodies, and bare land continuously declined. This reflects the spatial process of transformation from a rural to an urban landscape in the region and provides a reference for future urban planning.²⁷

In addition, ecological change has become a major challenge for humanity, while emerging detection technologies have become highly advantageous research methods. These two dimensions are therefore likely to intersect extensively with research perspectives across other clusters. Nevertheless, particular attention should be paid to the intersections between "human activities" and other cluster domains. Specifically, "human activities" is linked not only to "land use and sustainable development," which occupy central research positions, but also to "deep learning," which remains relatively peripheral at present.

For example, a study analyzed the relationships among vegetation density, urbanization, drought, land surface temperature (LST), and surface urban heat island (SUHI) effects in Prague using summer Landsat-8 imagery from 2015 to 2022 and the Google Earth Engine (GEE) platform. The results showed that NDVI was negatively correlated with LST. In contrast, the normalized difference built-up index was positively correlated with LST, indicating that vegetation provides a cooling effect. At the same time, built-up area expansion intensifies surface warming and SUHI effects. These findings offer a reference for sustainable urban and landscape planning.²⁸

Over the past decade, the evolution of research hotspots has not merely been reflected in the increased frequency of technical indicators but has also been driven by their close connection with national ecological engineering

policies, the restoration of degraded grasslands, adaptation to climate change, and the assessment of human impacts within these processes. This suggests that researchers focusing on human behavior are increasingly examining how nomadic populations coordinate production and livelihood practices to achieve sustainable and efficient land use. Meanwhile, newer methodological approaches are becoming important catalysts for encouraging people to engage with and respond to their surrounding environments through behavioral change.

3.3.3. Cluster 3, characterized by ecosystem services and scenario simulation

The research perspectives represented in the third cluster are characterized primarily by the keywords “ecosystem services” and “scenario simulation.” Other related perspectives in this cluster include studies focusing on Xinjiang, China, as the study area, as well as themes such as carbon storage, bioengineering, and land resource storage. This indicates that current scholars are paying increasing attention to the ecosystem service capacity of China's grassland ecosystems and are analyzing or enhancing the specific values that grassland ecosystems, as one of the indispensable ecosystem types, can provide from these perspectives.

For example, some studies suggest that existing research is beginning to explore the multiple functions of grassland ecosystems and how humans can use them efficiently, thereby providing perspectives and directions for future studies on grassland ecosystem service functions. At the same time, this line of research also underscores the importance of protecting grassland ecosystems from another perspective.

In addition, although “ecosystem services” does not show an especially high frequency, it has a very broad range of connections and extends to nearly all other clusters. It is widely associated with key research domains such as land cover, NDVI, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, ecosystem conservation, biodiversity, and sustainable development. This suggests that the scope covered by grassland ecosystem services is extensive and that researchers have increasingly recognized the latent potential of the ecosystem service capacity of grassland ecosystems.

The growing academic attention to Cluster 3 indicates that it is closely linked to the broader national policy context of the “dual-carbon” strategy, ecological civilization construction, and the realization of ecological product value. In this context, grassland ecosystems are no longer regarded merely as objects of protection, but are increasingly becoming important targets for policy

evaluation in terms of carbon storage, ecological security, and habitat quality.

3.3.4. Cluster 4, characterized by land use

The research perspectives represented in Cluster 4 are centered on “land use.” The related perspectives developed from this research also show relatively high frequencies, including the Patch-generating Land Use Simulation (PLUS) model, the InVEST model, ecosystem service value, and land-cover change. This indicates that scholars have become increasingly aware of the substantial pressure that rapid urban population growth and accelerated industrial development place on ecosystems, especially in China's medium-sized and large urban areas. In this context, the complex relationships between land-use patterns and ecosystem service value require close attention, and optimizing land-use structure and promoting the sustainable development of large cities are of important research significance.

For example, during 2001–2010, China began to place greater emphasis on land cover and adopted a series of measures to improve coverage, which led to land-cover type conversion and changes in carbon storage density in the northern Qinghai–Tibetan Plateau. The results showed that carbon storage increased during this period, low-carbon-density land types decreased, high-carbon-density land types increased, sparse vegetation areas were converted to grassland, and grassland carbon density increased significantly.²⁹ Approaches to efficient land use can therefore take land-cover type conversion as an entry point, and methods such as the InVEST model, which are used to monitor and evaluate land-type change, are highly effective. For example, by comparing a linear regression model with multivariate nonlinear regression models, including random forest, support vector machine, decision tree, and artificial neural network, the best-performing random forest model was selected to estimate grassland aboveground biomass (AGB) from 2015 to 2020, predict AGB over the following 20 years, and further analyze and forecast its changing trends.³⁰

Another study using MODIS NDVI data from 2000 to 2020 examined the relationship between urbanization and vegetation growth across 35 typical Chinese cities of different sizes. The results showed that urban NDVI was generally lower than that of surrounding areas, while megacities and super-large cities had more concentrated greening pixels in their urban cores. This suggests that appropriate urban planning and city-size management may help promote vegetation growth and support sustainable urban development.³¹

Cluster 4 reflects a shift in land-use change research

from the description of static spatial patterns toward scenario simulation and spatial optimization. Through the integration of different models, studies are now able to further assess carbon storage, ecosystem service value, and ecological risk under different land-use scenarios, thereby strengthening the capacity of grassland research to support territorial spatial planning and decision-making.

In addition, Cluster 4 is closely connected with Clusters 2, 3, and 5. The research perspective of “land use” shows strong associations with “climate change,” “human activities,” “ecosystem services,” and “ecosystem conservation.” This suggests that research in the land-use domain remains strongly focused on the land-use practices of people living within grassland systems, while the methods and directions of land-resource transformation—as one functional dimension of ecosystem services—also deserve further exploration.

3.3.5. Cluster 5, characterized by soil properties, desert steppe, and ecological restoration

Cluster 5 is mainly characterized by the keywords “soil properties,” “desert steppe,” and “ecological restoration.” Among them, “ecological restoration” shows relatively high frequency and strong associations with land cover, biomass, and plant diversity, while “desert steppe” is closely linked to “soil properties.” These two major perspectives also extend to areas such as nitrogen deposition, productivity, and vegetation.

For example, to clarify the effects of grazing intensity on soil physicochemical properties and bacterial communities, one study used field surveys and 16S ribosomal RNA sequencing to compare soil bacterial community structures under different grazing intensities and analyze their correlations with soil nutrient factors.³² This indicates that the research covered by this cluster is relatively specialized. Although it does not occupy a central position in the overall landscape of China's grassland ecosystem research in the 21st century, it represents a promising research perspective. Grassland ecosystem research has also begun to show a methodological shift toward interdisciplinary integration between biological sciences and data-statistical or computational disciplines.

In addition, “ecological restoration” in this cluster is broadly connected to several high-frequency keywords in other clusters, such as “land use” and “ecosystem service value.” It is also linked to lower-frequency but central keywords in other clusters, such as “NDVI” and “functional diversity.” This suggests that ecosystem conservation has remained a sustained concern in established research areas while receiving increasing attention in emerging domains. For example, by integrating remote sensing data with

field-survey biomass data, one study corrected habitat-quality estimates for the Altai region over the past three decades based on the InVEST model and compared results from the uncorrected, NDVI-corrected, and biomass-corrected models.³³ New research methods and paradigms are continuously expanding the boundaries of grassland ecosystem research, with research perspectives increasingly shifting toward the construction and application of new models.

In summary, Cluster 5 indicates that grassland ecosystem research is expanding toward deeper mechanistic domains, such as soil processes, microbial mechanisms, and restoration-effect assessment. With the development of multi-omics technologies, long-term plot monitoring, and ecological restoration evaluation, this cluster is likely to become an important growth area for future mechanistic research.

3.4. The theme trend evolution and prediction of China's grassland ecosystems

Among the studies related to China's grassland ecosystems collected for the period 2000–2025, research is concentrated primarily in the following disciplines and fields: Environmental Sciences, Environmental Studies, Ecology, Geosciences, Biodiversity Conservation, Soil Science, Remote Sensing, Water Resources, Green & Sustainable Science & Technology, Plant Sciences, and Imaging Science & Photographic Technology. Among these categories, Environmental Sciences, Environmental Studies, and Ecology are the principal fields and disciplines of focus.

After clustering author keywords in existing studies on China's grassland ecosystems in the 21st century, this study further used CiteSpace to reveal the field's developmental patterns and trends. Based on year-by-year time slicing, author keyword co-occurrence analysis was conducted, and a knowledge map was generated.

Drawing on the five keyword clusters, this study summarized the coupled evolutionary trajectories of existing research into three main lines: (A) driver attribution and remote sensing diagnosis, (B) process mechanisms and the carbon cycle evidence chain, and (C) ecosystem service assessment and spatial governance. Line A is mainly supported by clusters centered on NDVI/remote sensing monitoring, climate change, and human activities, and characterizes the relationship between the spatiotemporal patterns of grassland change and anthropogenic contributions. Line B focuses on soil-vegetation processes, microbial processes, and carbon sinks, including flux observations, carbon storage, and carbon sequestration. It reflects a shift from “phenomena–

drivers" toward a deeper mechanistic chain of vegetation input, soil environment, microbial processes, and carbon exchange/carbon pools. Line C centers on ecosystem services, InVEST/scenario simulation, ecological security, and governance optimization, emphasizing the linkage between ecosystem service indicators, such as carbon storage and habitat quality, and ecological decision-making.

By constructing an author keyword co-occurrence map and a temporal evolution map (Figure 8), this study identified eight keyword cluster labels and, on this basis, summarized three representative hotspot themes in the field. To further clarify the overall structure of research hotspots and the characteristics of keyword clustering, the representative themes and their corresponding cluster numbers, high-frequency terms, and research scales are summarized in Table 1.

3.4.1. Research Line A: Driver attribution and remote-sensing diagnosis

The hotspots of this line of research focus on the impacts of climate change and human activities on grassland dynamics, as well as the quantitative decomposition of NPP. The two major clusters, NDVI and human activities, constitute the core keywords of this research line. As shown in Figure 8, nodes such as climate change, impacts, precipitation, management, human activities, and NDVI exhibit highly dense connections, indicating that a major hotspot in this field is the use of remote sensing and statistical decomposition within ecological analytical frameworks to attribute grassland change to two major drivers: climatic forcing and anthropogenic forcing. As shown in Table 1, this line of research was particularly concentrated during 2020–2021. For example, in studies on the Inner Mongolian Plateau, some researchers explicitly proposed evaluating, at the 2001–2014 scale, the impacts of land-use/land cover change, human activities, and climate on grassland NPP simultaneously, and reported that human activities were the dominant driver of grassland degradation, while also exerting positive effects on NPP in multiple areas; they further noted that policies and ecological engineering projects generated more positive impacts in Inner Mongolia.³⁴

In addition, along the research line of driver attribution and remote-sensing diagnosis, climate stability gradually entered the central research agenda during 2018–2021, and the field showed a transition from assessing climate stability using single indicators to evaluating it through multi-indicator approaches and even framework-based models. For example, some studies used NDVI to define the beginning and end of the growing season and the mean

NDVI during the growing season, tested whether grassland vegetation activity experienced "temporal destabilization" during 1983–2015, and attributed this pattern to factors such as climate warming, aridification, and interannual climate variability.³⁵ In 2023, discussions of large-scale causal chains involving policy instruments—such as grazing prohibition and increased fencing—became more specific. Using the grazing-ban project in northern China as an example, one study reported that grazing prohibition "significantly increased grassland area, but did not significantly improve grassland quality (aboveground net primary productivity, NDVI)" and emphasized clear spatial heterogeneity and differences associated with levels of economic development.³⁶ By 2024, research on climate stability began to move toward two directions: multidimensional analysis and regionally differentiated recovery. For instance, researchers increasingly decomposed climate stability into three dimensions—resistance, resilience, and temporal stability—and used their correlations to characterize "stability dimensions," explicitly identifying regional differences such as stronger drought resistance on the Qinghai–Tibetan Plateau and the Inner Mongolian Plateau, and faster recovery on the Loess Plateau.³⁷ In addition, research has also expanded to the monitoring of gross primary productivity,³⁸ landscape ecological risk,³⁹ and land use/land cover,⁴⁰ with these studies increasingly moving toward more precise and in-depth monitoring approaches.

Based on developments over the past two years, one frontier direction in this field may be a shift from asking whether climate and anthropogenic factors have driven change to asking whether such changes will persist or lead to more unstable conditions—that is, toward examining post-change climate stability and resilience. A second frontier direction is a shift from mean-trend analysis toward the exploration of multidimensional responses under extreme-event forcing. A third direction is a transition from single-indicator NDVI analysis toward multi-source data coupling to support zoned optimization of management strategies (for example, incorporating grazing-ban implementation conditions, subsequent management, and ecological compensation into a unified causal chain).

3.4.2. Research Line B: Reassessing carbon-cycle processes and the "vegetation–soil–microbe" mechanism

As shown in Figure 8 and Table 1, the hotspots of this research line are concentrated primarily in #0 eddy covariance, #4 plant diversity, and #5 bacterial community. The focus of Research Line B no longer remains at the level of merely "observing and quantifying carbon sinks and

Table 1. Author keyword clustering results and hierarchical classification of research scales

Cluster No.	Cluster keywords	High-frequency terms	Time period	Corresponding research scale	
#3	Normalized differential vegetation index (NDVI)	Temperature	2020–2022	Research Line A: Driver attribution and remote-sensing diagnosis	
		Variability			
		Remote sensing			
		Drought			
#7	Human activities	Conservation	2015–2016		
		Climate change	2017–2019		
		Alpine grassland			
		Carbon sequestration			
		Program	2023–2025		
#0	Eddy covariance	Desert steppe	2017–2019	Research Line B: Reassessing carbon-cycle processes and the “vegetation–soil-microbe” mechanism	
		Terrestrial ecosystem	2020–2022		
		Soil			
		Organic carbon			
		Forest			
		Carbon	2023–2025		
		Soil carbon			
		Stock			
		Phosphorus			
#5	Bacterial community	Dispersal	2017–2019		
		Bacterial community	2020–2022		
		Patterns			
		Nitrogen addition			
		Ecosystem stability resilience			
		Biomass			
#4	Plant diversity	Functional diversity	2017–2019		
		Productivity			
		Responses			
		Biodiversity	2020–2022		
		Deposition			
		Community			
		Biodiversity			
		Organic carbon			
		Aboveground biomass	2023–2025		
Ecosystem health					

(cont'd...)

Table 1. (Continued)

Cluster No.	Cluster keywords	High-frequency terms	Time period	Corresponding research scale
#1	Invest model	Carbon storage	2017–2019	Research Line C: Ecosystem service assessment and spatial governance
		Ecosystem service		
		Land use change	2020–2022	
		Ecosystem service value		
		Model		
		Land use		
		Land use change	2023–2025	
		Urban		
		Habitat quality		
Spatial heterogeneity				
#6	Ecological security	Precipitation	2015–2016	
		Impacts		
		Management	2017–2019	
#2	Ecological restoration	Inner Mongolia	2015–2016	
		Desertification		
		Restoration		
		Vegetation		
		Degradation	2020–2022	
		Loess plateau		
		Soil		
		Water		
		Spatial distribution	2023–2025	
		Random forests		
		Models		
		Machine learning		
		Regression		

carbon sources”; instead, it has gradually developed into a chain-structured hotspot framework in which climate–hydrological fluctuations and management disturbances act as joint external drivers, vegetation input and allocation serve as the bridge, and soil nutrients together with microbial assembly and diversity act on carbon pools and carbon exchange. From 2015 to 2019, this line focused on flux observations and the relationships between seasonal and interannual differences in carbon exchange, with emphasis on identifying the environmental factors controlling these differences. In this stage, flux-tower observations served as the primary evidentiary basis. For example, in alpine meadows on the southeastern Qinghai–Tibetan Plateau, long-term net ecosystem exchange observations covering 2014–2019 clearly showed that the wet season functioned as a carbon sink, whereas the dry season fluctuated

between a weak source and a weak sink; at the monthly scale, carbon exchange was dominated by air temperature and soil moisture. At the same time, differences in the seasonal distribution of precipitation significantly shaped the intensity and duration of interannual carbon uptake.⁴¹

Between 2020 and 2023, this research line shifted from “phenomenon interpretation” toward the exploration of a coupled management–vegetation structure–soil environment framework. After 2020, studies in this cluster no longer focused solely on flux responses to climatic fluctuations; instead, they more systematically incorporated management disturbances—such as strengthened enclosure/fencing, improved grazing-ban regulations, controlled grazing intensity, and mowing control—into explanations of carbon processes, and coupled these with microbial processes through pathways linking vegetation

inputs to transformations in the soil environment. For example, enclosure and fencing management can significantly affect ecosystem multifunctionality by increasing soil nutrients such as soil organic carbon, ammonium nitrogen, nitrate nitrogen, and available phosphorus, while also altering moisture conditions. At the same time, dominant drivers differ across management scenarios: enclosure and mowing are driven more by soil moisture, whereas grazing scenarios are driven more by plant and bacterial diversity.⁴¹ Meanwhile, this research line began to show a refined demand for vegetation structure/allocation parameters: diversity–productivity relationships exhibit nonlinearity and spatial heterogeneity under grazing disturbance and climatic fluctuations, which has pushed research from “describing relationships” toward “explaining mechanisms and parameterization.”⁴²

After 2025, research on carbon processes began to introduce new perspectives and stronger interdisciplinary integration. For example, across different grassland types in China's three major plateaus (the Loess Plateau, Qinghai-Tibetan Plateau, and Inner Mongolian Plateau), some studies examined the distance-decay pattern of β -diversity in soil methane-oxidizing bacterial communities and emphasized differences in the relative importance of assembly processes—such as dispersal limitation, drift, and environmental filtering—across scales and grassland types.⁴³ Within this research line, studies on microbial community assembly mechanisms may be regarded as a new frontier, while research on carbon processes is increasingly moving toward explainable mechanisms supported by multi-source evidence.

3.4.3. Research Line C: Ecosystem service assessment and spatial governance

As shown in Figure 8 and Table 1, the hotspots of this research line are concentrated mainly in #1 InVEST, #6 ecological security, and #2 ecological restoration. It can be observed that the core of Research Line C is not simply the “calculation of ecosystem service value”; rather, it forms three tightly coupled hotspot modules organized around governance-goal orientation, service quantification as decision support, and land use and spatial patterns as operational levers. Research hotspots centered on InVEST focus primarily on two indicators that can be directly incorporated into governance targets—carbon storage and habitat quality—and are often coupled with land-use simulation modules such as PLUS for scenario prediction and comparison over periods such as 2000–2030 and beyond. Meanwhile, #2 ecological restoration takes engineering measures and policies as exogenous shocks and emphasizes long-term trajectories and driver interactions. Accordingly, restoration-related hotspots

have shifted from asking whether restoration is effective to examining how restoration alters system trajectories over long time spans and how underlying drivers interact. In addition, #6 ecological security shows a transition from a focus on ecological security patterns and ecological red lines toward spatial optimization under constraints, with hotspot topics increasingly emphasizing how to configure land-use structures under the tension between ecosystem conservation and economic development.

From 2015 to 2020, this research line was characterized by a paradigm that emphasized governance goals, while balancing the relationship between ecological security and constrained/optimized spatial allocation. Spatial configurations were solved through suitability assessment and optimization algorithms, highlighting “optimal allocation under constraints.” During 2021–2023, a prominent shift was that assessment objects moved from static patterns to comparable scenarios (e.g., nitrogen deposition [ND] vs. ecological protection/ecosystem carbon density [ECD]), and service indicators such as carbon storage and habitat quality were used as direct evidence for evaluating scenario performance. During 2024–2025, research trends further evolved from prediction and comparison toward three directions: intervention-effect evaluation, explanation of driver interactions, and multi-objective governance coordination.

Overall, future trends in Research Line C may develop along three major directions. First, research may shift from scenario simulation toward verifiable evaluation of policies and engineering interventions. As workflows such as PLUS-InVEST become more widely applied at watershed and urban-agglomeration scales, studies are likely to place greater emphasis on translating policy instruments—such as ecosystem conservation, restoration projects, and urban expansion—into verifiable counterfactual scenarios, and on conducting comparative assessments using indicators such as habitat quality and carbon storage.^{44,45} Second, research may shift from “single-indicator services” toward multi-objective coordination and trade-off management. Although carbon storage and habitat quality will likely remain core indicators, they are increasingly likely to be integrated with ecological security constraints, development-intensity control, and the protection of ecological red lines/ecologically sensitive areas into multi-objective optimization frameworks.⁴⁶ Third, research may move from “result maps” toward mechanistic explanations of driver interactions and spatial heterogeneity. High-quality future studies are likely to treat the relative importance and interaction effects of driving factors as essential analytical components. For example, studies in the Yanhe River Basin have already

demonstrated path effects and interaction amplification/attenuation mechanisms through which natural and socioeconomic drivers operate via variables such as NDVI; this kind of mechanistic explanation is likely to become a key threshold for translating ecosystem service assessment into governance decision-making.⁴⁷

4. Discussion

4.1. Formation and evolutionary logic of research hotspots

The formation of research hotspots in China's grassland ecosystem studies has long been shaped mainly by practical ecological problems and national policy demands, while the gradual advancement of research methods has also played an important driving role. Grassland degradation, global warming, drought, grazing pressure in grassland regions, and changes in land use have made keywords such as "climate change," "human activities," "NDVI," "grazing," and "drought" remain at the core of this field for a long time. Early studies mainly focused on the identification of and monitoring ecological changes in grasslands, but later gradually shifted toward the attribution of drivers related to human activities and climate change. Since 2020, amid China's "dual-carbon" goals and the growing demand for ecological restoration and spatial governance, research hotspots in China's grassland ecosystems have further shifted toward topics such as carbon storage and ecosystem services. Overall, this reflects an evolutionary logic from ecological change monitoring, to driver-mechanism explanation, and then to governance-oriented application.

4.2. Interpretive synthesis from clusters to three research lines

Based on the five keyword clusters, this study identified three interrelated research trajectories. Clusters centered on "NDVI," "remote sensing," "climate change," and "human activities" support the trajectory of driver attribution and remote sensing diagnosis, reflecting sustained attention to the spatiotemporal patterns of grassland change and their driving factors. Clusters centered on "eddy covariance," "carbon storage," "plant diversity," "bacterial community," and "soil properties" support the trajectory of carbon-cycle processes and vegetation–soil–microbial mechanisms, indicating a deepening shift toward process-based explanations. Clusters centered on "InVEST," "PLUS," "ecosystem services," "scenario simulation," "ecological security," and "restoration" support the trajectory of ecosystem service assessment and spatial governance, showing that research is increasingly oriented toward governance and decision-making.

4.3. Challenges and improvements in China's grassland ecosystems in the 21st century

The thematic evolution of research on China's grassland ecosystems since the beginning of the 21st century shows that keywords centered on "climate change," "human activities," "NDVI," "drought," and "grazing" have consistently remained at the core of the research network, indicating the continued deepening of this field in terms of driver identification and response diagnosis. At the same time, the increasing importance of process- and evidence-chain-related keywords—such as "eddy covariance," "carbon storage/sequestration," "bacterial community," and "plant diversity"—suggests that research is shifting from phenomenological description toward mechanistic explanation and multi-source validation.^{43,48,49} In parallel, governance-oriented themes such as "InVEST," "PLUS," "scenario simulation," "ecological restoration/security," and "trade-offs" are increasingly clustered, indicating that research outputs are being embedded more frequently into policy and spatial-planning contexts.⁴⁵ However, this parallel expansion structure of "drivers–processes–governance" also reveals persistent constraints in both research and practice within the field, including insufficient cross-scale interpretability, inadequate methodological consistency and uncertainty expression, and an incomplete feedback chain linking model-based assessment to policy implementation.⁴⁸

To address these limitations and enhance the capacity of grassland research to support governance decision-making, this study—drawing on the thematic structure revealed by the knowledge maps—summarizes several key challenge modules faced by research on China's grassland ecosystems in the 21st century.

4.3.1. Data foundations and observational representativeness

High-quality and traceable data constitute the foundation of grassland ecosystem research. The representativeness, temporal continuity, and spatial coverage of flux observations, remote-sensing products, ground plots, and management records directly determine the robustness of assessments of carbon exchange, productivity, and ecosystem services. Although "eddy covariance" and carbon-related themes form key clusters in the knowledge maps, the representativeness of site-based observations in spatially heterogeneous landscapes remains limited, and coarse-resolution products are unable to resolve carbon dynamics and land-use change impacts. As a result, upscaling to high-resolution representations remains a long-term challenge in itself.⁴⁸

At the same time, although microbial, nutrient, and soil processes appear as hotspots in the maps, data integration between these processes and the flux–carbon pool–service assessment chain remains insufficient, making it difficult to fully close the evidence chain from “input–process–output” and thereby weakening the reliability of cross-regional comparisons and model parameterization.^{49,50}

Consequently, datagaps are expressed not only as missing observations but also as cross-scale interface uncertainty—i.e., the inability to consistently connect national-scale attribution signals to site-scale process evidence—thereby amplifying uncertainty in parameterization and cross-region comparability.

4.3.2. Consistency of methodological systems and cross-scale coupling

Existing research shows methodological diversification in driver attribution, process simulation, and spatial upscaling. Remote-sensing indicators, such as NDVI, and trend–driver decomposition frameworks have been widely used to distinguish climatic and anthropogenic contributions.³⁴ Stability research has further introduced multidimensional structures and dimensional-correlation characterization based on resistance, resilience, and temporal stability.²⁴ Meanwhile, service assessment and scenario simulation studies increasingly adopt workflows such as InVEST/PLUS to compare carbon storage, habitat quality, and land-use scenarios.^{44,45}

However, the strong cross-linkages among clusters in the knowledge maps also suggest that climatic fluctuations, grazing management, and land-use change are highly collinear, making causal identification prone to correlation-based explanation. This reduces comparability across studies in terms of system boundaries, scale transformation, threshold setting, and variable selection. In particular, when research is extrapolated from sites to watersheds, regions, and the national scale, ensuring parameter transferability and process consistency becomes difficult.⁴⁸

In addition, the relationships among grazing-related climate impacts, stability and diversity, and ecological productivity may follow different mechanisms across spatial scales, further increasing the difficulty of cross-scale coupling and unified representation.²³

Greater attention should be paid to coupling across temporal, regional, and spatial scales to better portray the state and condition of the ecological environment in a more multidimensional way. It is important to focus on the mutual influence and interaction among these three dimensions and to avoid treating them in isolation.

4.3.3. Mechanistic deepening and uncertainty representation

Research hotspots have shifted from asking “whether change has occurred” to “why it occurs” and “how it occurs,” as reflected in the emergence of mechanistic themes such as diversity, microbial communities, soil moisture, and nutrient limitation. However, mechanistic explanations still face two major difficulties.

First, multi-process coupling creates interpretability challenges. Taking management measures as an example, enclosure can enhance ecosystem multifunctionality and is closely related to soil nutrient and moisture conditions, yet dominant drivers differ across management scenarios. Meanwhile, enclosure duration may alter the trade-off between diversity and productivity, as well as the prioritization of restoration goals, indicating that the same “intervention” may affect functional outputs through different mechanistic pathways.⁵¹ It is further shown that restoration may be constrained by key limiting factors, such as soil nitrogen supply, leading to nonlinear patterns across stages.⁵¹

Second, the uncertainty expression remains insufficient. Results from driver attribution, model simulation, and scenario prediction often present the “most likely picture,” but data errors, structural uncertainty, and sensitivity to scenario assumptions are not adequately disclosed, leaving the “credibility boundary” of the results unclear in policy contexts.⁴⁸ Cross-regional mechanistic differences are also an important source of uncertainty. For example, across the three major plateaus and different grassland types, the β -diversity of methane-oxidizing bacterial communities shows distance decay, while the relative importance of assembly processes such as dispersal limitation, drift, and environmental filtering differs significantly across scales and grassland types. This suggests that “microbial mechanisms” cannot be treated as homogeneous.⁴²

In summary, future research may pay greater attention to mechanisms such as biodiversity, microbial communities, soil moisture, and nutrient limitations. Although mechanistic studies are relatively challenging, they may represent highly valuable and innovative directions if combined with new monitoring techniques and advanced modeling approaches.

4.3.4. Governance implementation and feedback closure

At the level of practical governance, the clustering of “InVEST/PLUS–scenario simulation–ecological restoration/security” in the knowledge maps shows that research is actively aligning with policy demands. However,

a critical gap remains between “computable assessment” and “implementable governance.”

First, ecological security constraints, multi-objective coordination, and stakeholder constraints are difficult to fully incorporate into models. Thus, although trade-offs are frequently discussed, they are often hard to translate into operational zoning control and implementation rules.^{44,45}

Second, restoration projects and management measures often lack verifiable long-term controls and feedback mechanisms, making it difficult to determine where interventions are effective, when they work, and how costs are converted into benefits. This constrains policy iteration and optimized resource allocation. In contrast, some watershed- and city-scale studies have begun to provide quantifiable comparisons of habitat quality and degradation under different scenarios, suggesting that verifiable scenarios and indicator-based comparisons can serve as an important interface for closing governance feedback loops.⁴⁴

In other words, the current difficulty in governance practice is not the absence of assessment tools, but the lack of an institutionalized closed-loop mechanism that can translate assessment results into action and continuously recalibrate them.

Future research may further address this weakness through in-depth investigation, with particular attention to the relationship between assessment results and institutionalization, and by exploring a more integrated pathway.

5. Conclusion

Since the beginning of the 21st century, WoSCC-indexed English-language publications on China's grassland ecosystems have increased steadily, with slow growth before 2020 and rapid expansion thereafter. This study analyzed 1,077 publications from 30 countries/regions. China contributed the largest share (1,051 papers), followed by the USA (89), Australia (28), the UK (25), and Germany (24). These results show that China is the primary contributor within the WoSCC English-language corpus, while international collaboration has become increasingly active.

The knowledge map results identify three coupled thematic mainlines. The first is driver attribution and remote-sensing diagnosis, centered on climate change, human activities, and indicators such as NDVI, reflecting sustained attention to spatiotemporal dynamics and climatic versus anthropogenic drivers. The second is carbon-cycle processes and the vegetation–soil–

microbe line, involving eddy covariance, carbon storage/sequestration, plant diversity, and soil microbial communities, indicating a shift toward process-oriented explanations of carbon-related outcomes. The third is ecosystem service assessment and spatial governance, featuring ecosystem services, InVEST/PLUS, scenario simulation, ecological security, and restoration, reflecting the growing use of service indicators and scenario-based evaluation for planning and management.

The main contribution of this study is to demonstrate that the development of research on China's grassland ecosystems is not merely reflected in increased publication output, but also in a structural transition from ecological change monitoring and driver attribution to mechanism analysis, and further to governance evaluation. This finding helps clarify the developmental trajectory of Chinese grassland ecology research and provides knowledge-map-based evidence for identifying future research directions. Future studies should further strengthen the integration of multilingual datasets, cross-scale validation, uncertainty assessment, and the linkage between ecological model outputs and policy practice.

This study is limited to WoSCC English-language publications and excludes Chinese-language journals, policy-oriented gray literature, many domestic technical reports, and some preprints. Thus, it may under-represent domestically driven research and policy debates, particularly in grassland conservation and restoration. The findings should therefore be understood as a map of research represented in international databases, not a complete picture of all domestic research and policy discourse.

Future research should integrate multilingual databases, especially major Chinese literature platforms, and policy/gray literature; link remote-sensing attribution with site observations and process understanding; improve consistency in preprocessing, model settings, and uncertainty reporting; and develop policy-auditable frameworks that combine scenario assessment, long-term monitoring, and feedback mechanisms.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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