RESEARCH PROGRESS ON BRYOPHYTE FUNCTIONS IN ECOSYSTEMS: A BIBLIOMETRIC MAPPING ANALYSIS AND SYSTEMATIC REVIEW OF GLOBAL CORE JOURNAL PUBLICATIONS (2015–2025)

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(Received 3rd May 2025; accepted 6th Aug 2025)

Abstract. This study employs bibliometric analysis and systematic review methods to examine global core journal publications from 2015 to 2025, revealing the overall trends in bryophyte ecological function research. Analysis of 321 core publications from the Web of Science database indicates a sustained growth trend in this field, with an average annual growth rate of 10.6%. The analysis reveals that researchers from the United States, Germany, and China have made the most significant contributions, with key findings published in authoritative journals such as *Science of the Total Environment* and *Journal of Ecology*. Research hotspots have evolved from describing basic ecological characteristics to analyzing functional mechanisms and exploring practical applications. Notable progress has been made in areas such as bryophyte carbon sequestration capacity, biological soil crust effects, and climate change responses. However, existing research still exhibits notable shortcomings in regional coverage, methodological innovation, and theoretical integration, particularly in studies of bryophyte ecosystems in tropical and arid regions, which require urgent attention. Future research should further integrate multidisciplinary approaches, expand investigations in extreme environments, and strengthen the practical application of bryophyte resources in ecological restoration and global change mitigation.
Keywords: *bryophyte ecology, ecosystem services, mosses, multifunctionality, climate resilience*

Introduction

Bryophytes, as a critical component of terrestrial ecosystems, play a pivotal role in carbon sequestration (Liu et al., 2023), water regulation (Saez-Ardura et al., 2025), soil formation (Doe, 2022), and biodiversity maintenance (Wilsey et al., 2009). These roles are not isolated but exhibit multifunctionality—the capacity to simultaneously integrate carbon, water, and biodiversity functions, often synergistically (e.g., bryophyte water retention enhances microbial-driven carbon storage). This multifunctionality underscores their irreplaceable value in mitigating global change, yet current research remains fragmented across single-function studies (Eldridge et al., 2023). Their ecological functions have garnered increasing attention in the context of global climate change and ecosystem degradation (Delgado-Baquerizo et al., 2025). The United Nations Educational, Scientific and Cultural Organization (UNESCO) has emphasized the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_90179039

importance of biodiversity conservation and ecosystem restoration in its strategic frameworks (UNESCO, 2022).

Despite their ecological significance, research on bryophytes remains fragmented and regionally biased (Eldridge et al., 2023). While some studies have explored specific functions of bryophytes in localized ecosystems, a holistic understanding of their multifunctional roles in global ecosystems is still lacking. Moreover, the integration of advanced methodologies, such as bibliometric analysis (Ozturk et al., 2024) and systematic reviews (Shaheen et al., 2023), has been underutilized in this field. This gap underscores the necessity for a comprehensive analysis of recent research trends to identify key advancements, challenges, and future directions.

Literature review

Over the past decade, numerous studies have investigated the ecological functions of bryophytes. For instance, Turetsky et al. (2012) highlighted the role of bryophytes in carbon storage in boreal ecosystems, while Glime (2017) provided a detailed account of their contributions to water retention and microhabitat formation. recent advancements in molecular techniques have enabled researchers, such as Ishak et al. (2024), to explore the microbial communities associated with bryophytes, shedding light on their role in nutrient cycling.

However, several critical gaps remain. As demonstrated by Turetsky et al. (2012), most studies have focused on temperate and boreal regions, leaving tropical and arid ecosystems underrepresented (Aguirre-Gutierrez et al., 2023; Vasquez-Dean et al., 2020). While researchers have extensively studied individual bryophyte function (Eldridge et al., 2023), their multifunctional roles in complex ecosystems remain poorly understood (Siwicka et al., 2021). Despite the growing importance of research synthesis, bibliometric analysis in the field of bryophyte ecology remains very limited (Chen, 2024).

To address these gaps, this study employs a bibliometric mapping analysis combined with a systematic review of global core journal publications from the past decade. By integrating quantitative and qualitative approaches, we aim to address the following research questions (Hwang and Tu, 2021):

1. What are the major journals publishing research on the ecological functions of bryophytes? How are the most highly cited publications, most prolific and influential authors, and core research teams distributed in this field?
2. Which countries have contributed the most publications to the research on the ecological functions of bryophytes, and what are the quantitative and qualitative differences in their research outputs and impacts?
3. Through keyword co-occurrence analysis, what are the core research themes in bryophyte ecological functions? How have these themes evolved historically, and what are the current research hotspots?
4. How can the multifunctional roles of bryophytes in various ecosystems be quantitatively assessed? What should be the prioritized research directions for future breakthroughs?

This approach not only fills existing knowledge gaps but also provides a robust framework for advancing research in this critical area.

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Method

Bibliometrics

Bibliometrics was first introduced in the early 1900s. It formed an independent discipline in 1969 (Pritchard, 1969) and became widely applied in literature analysis (Diem, 2013). The bibliometric analysis provides a quantitative method for reviewing and investigating extant literature in a given field (Chipunza and Ntsalaze, 2025). Details such as authors, keywords, journals, countries, institutions, references can be captured in the analyzing process. Thus, the development of a field can be obtained through bibliometric analysis (Mokhnacheva and Tsvetkova, 2020). With the help of modern computer technology, graphical and visual results can supplement literature analysis. Co-citation is also frequently used in the bibliometric analysis. It is defined as the relationship if two articles are cited by one or more other articles at the same time. It has been emphasized by Ma (1992) that visualized co-citation analysis in bibliometrics could facilitate data interpretation; it can make results more comprehensive. Moreover, most items in a paper can be applied through this method—including authors, keywords, institutions, countries, in addition to the paper itself. The visualization helps excavate the internal relationship of this information, such as having the same research topic from different authors, the research focus of different institutions, new theories coming from an existing one and so on.

Quantitative thresholds based on Lotka's Law

To ensure objective identification of core contributors and research foci, we applied Lotka's Law of scientific productivity (Lotka, 1926) to establish quantitative thresholds for all bibliometric analyses. This inverse power law predicts that a small proportion of entities (authors, journals, keywords, etc.) account for the majority of research output.

For journals, authors, and countries, we retained the top-ranked entities that collectively contributed to > 80% of total publications/citations, consistent with Lotka's distribution (n ≈ 5-10 items per list).

Core keywords were defined as those with frequency > 10 (i.e., the ≈ 20% highest-frequency terms accounting for 78.6% of total keyword occurrences), following the law's principle of skewed distribution.

Systematic review methodology

The systematic review component complements the bibliometric analysis by providing a qualitative synthesis of key research themes, methodological approaches, and geographical coverage.

The systematic review identified patterns not captured by quantitative metrics, such as: Methodological gaps, Discrepancies between citation impact and regional relevance.

This dual approach ensures a comprehensive evaluation of both the breadth (bibliometrics) and depth (systematic review) of bryophyte ecology research.

Research instrument

Utilizing CiteSpace and VOSviewer (Ding and Yang, 2022) for the creation of knowledge maps, both software tools have their unique strengths and can complement each other effectively. CiteSpace focuses on temporal dynamics and emerging trends (Luo et al., 2024), while VOSviewer excels in static network analysis and clustering

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strength (van Eck and Waltman, 2014). Their combined use comprehensively addresses bibliometric research needs.

CiteSpace generates keyword evolution maps based on time series, revealing the historical progression of research themes, and identifies burst terms to mark phased characteristics of research frontiers.

VOSviewer visualizes journal co-citation networks, author collaboration networks, and national cooperation patterns, quantifying node centrality. Through keyword co-occurrence networks and density visualizations, it identifies core research themes.

The article selection process

The research database used for this study was the Web of Science Core Collection, specifically focusing on the Social Sciences Citation Index (SSCI). The search period spanned from January 2015 to April 2025. The search query employed was: TS = (Bryophytes OR Mosses) AND TS = (Ecology OR “Ecosystem function”) AND PY = (2015-2025).

This initial search yielded 889 articles. To refine the results, the following steps were taken:

1. After removing duplicate documents, a total of 889 unique articles were obtained.
2. Document Type Limitation: In the left-hand filter panel, the document type was restricted to Article (Journal Paper), excluding other types of publications such as conference papers and reviews. This step reduced the number of articles to 841.
3. Research Area Limitation: The research areas were further narrowed down by selecting Ecology and Environmental Sciences in the filter panel, excluding unrelated fields. Additionally, articles lacking empirical data, or those limited to taxonomic descriptions without ecological context, were manually excluded. This resulted in a total of 321 articles.

This rigorous selection process ensured that the dataset was both comprehensive and highly relevant to the study of bryophytes’ ecological functions (see *Fig. 1*).

Analysis of journals, authors, and national publications

Analysis of the trend of the number of literatures

To preliminarily understand the current development status of bryophyte ecology research and intuitively reflect the future research trends, this paper counted the number of published research papers related to bryophyte ecology. The 321 papers used in this study originated from 61 countries, 669 research institutions, 1415 authors, and 104 journals. Among them, 18,037 literatures from 5056 journals were cited. The specific trend of the number of papers published in the past decade is shown in *Figure 2*. (Data for 2025 (up to April) is for trend reference only and does not affect the overall conclusions.)

From 2015 to 2022, the number of publications in the field of bryophyte functions in ecosystems showed a significant upward trend, increasing from 20 to 44 articles, with an average annual growth rate of 10.6%. Although the number of publications slightly declined in 2023 and 2024 (to 30 and 34 articles, respectively), it remained higher than the 2015 level, indicating that research in this field has remained active and achieved

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important progress over the past decade. In the future, with further in-depth studies on the roles of bryophytes in carbon cycling, water cycling, biodiversity maintenance, and ecosystem stability (Eldridge et al., 2023), the number of publications is expected to remain stable or continue to grow.

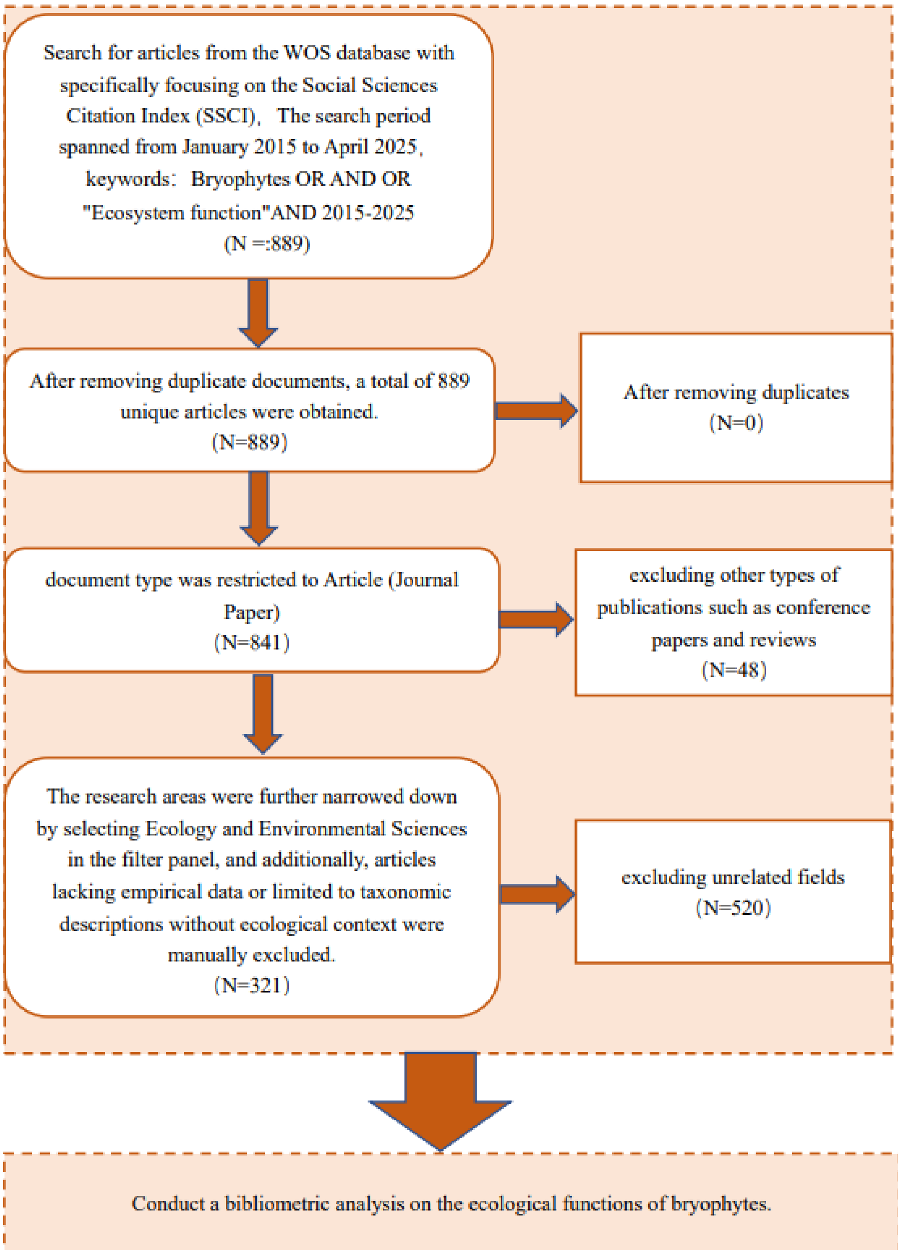

Figure 1. *Article selection process for bibliometric mapping analysis and systematic review*

Analysis of journal publications

In recent decades, research on bryophyte ecology has been predominantly published in journals focusing on polar ecology (Zeng et al., 2025), environmental science, and fundamental ecology. Among these, *Science of the Total Environment* leads with 13 publications and an average citation per article of 28.62, highlighting its interdisciplinary

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impact. *Journal of Ecology and Oecologia* maintain strong influence with over 20 citations per article, suggesting that studies on bryophyte ecology in this journal may have broader interdisciplinary impact or applied relevance. Traditional ecological journals such as *Journal of Ecology* and *Oecologia* maintain strong influence with over 20 citations per article, reflecting their authority in ecological research. *Polar Biology* is a key platform for polar bryophyte studies, with 16 publications. Overall, bryophyte ecological research appears particularly active in areas such as environmental monitoring, polar ecology, and functional trait analysis (see *Table 1*).

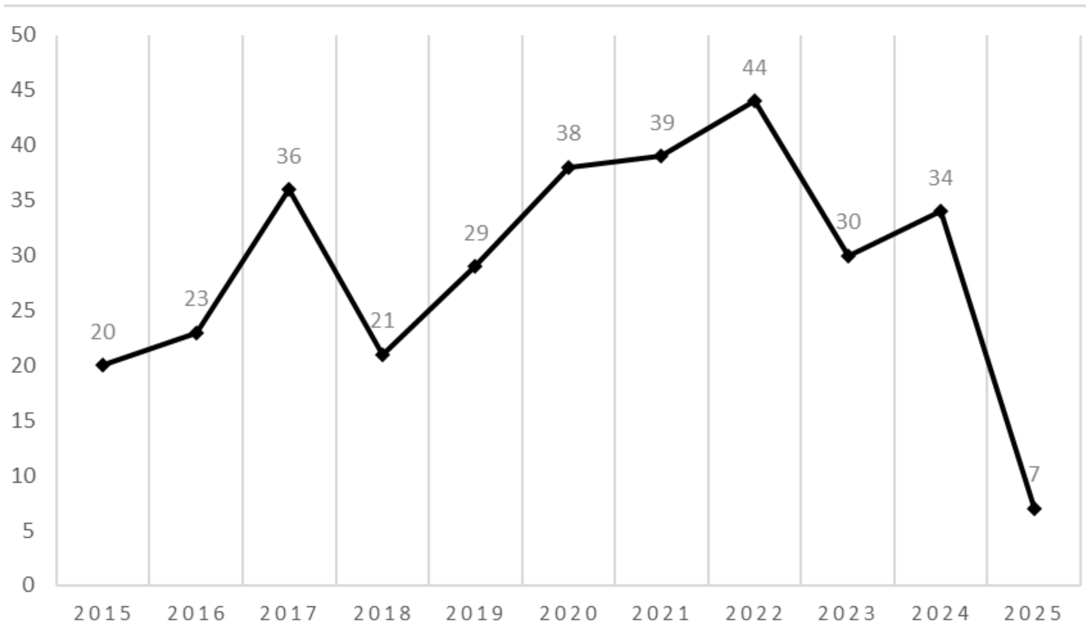

***Figure 2.** The number of papers published on bryophyte ecology research in the past decade*

***Table 1.** Top ten journals in terms of the number of publications related to bryophyte ecology research*

Rank	Source	Publications	Citations	Average citation/publication
1	Polar Biology	16	193	12.06
2	Ecological Indicators	13	116	8.92
3	Journal of Ecology	13	267	20.54
4	Science of the Total Environment	13	372	28.62
5	Ecology and Evolution	12	117	9.75
6	Journal of Vegetation Science	11	243	22.09
7	Journal of Biogeography	10	198	19.80
8	Oecologia	10	208	20.80
9	Functional Ecology	9	131	14.56
10	Diversity-Basel	8	22	2.75

Analysis of the top three most cited papers

An analysis of the top three most-cited papers in bryophyte ecology reveals key research trends in this field. The highest-cited study by Hu et al. (2020), published in

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Science of the Total Environment (140 citations), employed the InVEST model to evaluate water conservation effects of the Poplar Ecological Retreat Project in Dongting Lake wetlands, highlighting the crucial role of modeling approaches in quantifying wetland ecosystem services. Ranking second, Havrilla et al. (2019) meta-analysis in Journal of Ecology (111 citations) examined biocrust impacts on plant performance, demonstrating the ecological significance of these bryophyte-dominated microecosystems in vegetation restoration. The third most-cited paper by Heino et al. (2017) in Oecologia (107 citations) investigated metacommunity structures of aquatic organisms, revealing how spatial-scale processes influence community assembly in bryophytes and other aquatic species. Collectively, these highly cited publications identify three cutting-edge research directions: (1) ecosystem service modeling, (2) biocrust Functional Ecology, and (3) multiscale community assembly mechanisms, providing critical insights into bryophytes' ecological roles. Notably, all three papers were published in Q1 ecology journals within the past five years yet have each surpassed 100 citations, indicating these research areas possess remarkable academic vitality and development potential (see *Table 2*).

Table 2. *Top 3 most-cited papers*

Rank	Title	Journal	Authors, year	Total # of citations
1	Assessment of the impact of the Poplar Ecological Retreat Project on water conservation in the Dongting Lake wetland region using the InVEST model	SCIENCE OF THE TOTAL ENVIRONMENT	Hu et al., 2020	140
2	Towards a predictive framework for biocrust mediation of plant performance: A meta-analysis	JOURNAL OF ECOLOGY	Havrilla et al., 2019	111
3	Metacommunity ecology meets biogeography: effects of geographical region, spatial dynamics and environmental filtering on community structure in aquatic organisms	OECOLOGIA	Heino et al., 2017	107

Analysis of authors' publications

An analysis of the authors in the literature reveals the representative scholars and core contributors in this field. According to data sourced from Web of Science, *Table 3* presents the top seven authors by publication volume in this research area. Tuittila, Wan Zuijlen, and Vieira share the highest number of publications (5 each), while Davies, Gray, Rochefort, and Rousk follow closely with 4 publications each.

Despite some authors having a relatively high volume of publications, the overall citation impact remains relatively modest. This phenomenon can be attributed to several factors:

Bryophyte research is a highly specialized area compared to broader ecological studies. Its niche focus means that the audience for such research is smaller. Most ecologists tend to concentrate on larger organisms or entire ecosystems, resulting in lower interest and citation demand for bryophyte studies. This specialization restricts the

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citation scope of related papers to a limited group of peers, making it difficult to achieve widespread academic attention.

The field of bryophyte research is currently transitioning from descriptive to mechanistic studies. Descriptive research, which typically focuses on species classification and distribution, is important but tends to have limited citations. In contrast, mechanistic research (e.g., physiological mechanisms and ecological functions of bryophytes) requires more in-depth experimental design and data analysis. The impact of such research may take longer to accumulate citations, as it gains recognition over time. For example, Tuittila has a high number of publications (5) but only 36 citations, likely because their work is in the transitional phase from descriptive to mechanistic research, which has not yet reached a level of broad citation.

Notably, Despite the overall modest citation impact, some authors stand out. Rochefort and Wan Zuijlen, for instance, have significantly higher citation counts (92 and 84, respectively) compared to other authors. Rochefort's exceptionally high average citation per publication (23.0) and Wan Zuijlen's strong influence (16.8 citations per paper) suggest that their research holds greater academic value or broader applicability. This highlights the variability among authors, where some may achieve higher citation counts through more innovative and applicable research, extensive collaborations, or effective dissemination strategies.

Table 3. *Top seven authors in terms of the number of publications on bryophyte ecology research*

Rank	Author	Publications	Citations	Average citation/publication
1	Tuittila, Eeva-Stiina	5	36	7.2
2	Wan Zuijlen, Kristel	5	84	16.8
3	Vieira, Cristiana	5	32	6.4
4	Davies, G. Matt	4	56	14.0
5	Gray, Alan	4	56	14.0
6	Rochefort, Line	4	92	23.0
7	Rousk, Kathrin	4	54	13.5

National publication analysis in bryophyte ecology research

The bibliometric analysis of national contributions to bryophyte ecology research reveals distinct patterns in research productivity and impact across countries. The United States dominates the field with an exceptional 85 publications and 1443 total citations, demonstrating both substantial research output and widespread influence, as reflected in its high average citation rate of 51.54 per publication. Germany and China show particularly strong research impact relative to their publication numbers, with Germany's 31 publications receiving 700 citations (22.58 average) and China's 24 publications accumulating 514 citations (21.42 average). These metrics suggest that while the U.S. maintains clear leadership in both quantity and quality of research, several European nations and China are producing highly influential studies in this field (Eldridge et al., 2023), potentially specializing in particular aspects of bryophyte ecology that generate significant scientific interest (Alatalo et al., 2020). The data may reflect differences in research focus areas, collaboration networks, or investment in ecological sciences across these nations (see *Table 4*).

Table 4. *Top five authors in terms of the number of publications on bryophyte ecology research*

Rank	Country	Publications	Citations	Average citation/publication
1	Usa	85	1443	51.54
2	Canada	36	468	13.00
3	Germany	31	700	22.58
4	Sweden	25	448	17.92
5	China	24	514	21.42

Correlation analysis among journals, authors, and national publication

Analysis of inter-journal collaboration correlations

The publication profiles and collaborative networks of academic journals can reflect their influence in the field of bryophyte ecological research (Číhal, 2023), as well as highlight key research hotspots. To map inter-journal collaboration, we conducted a co-citation analysis based on the Web of Science Core Collection, applying a minimum threshold of 3 publications per journal. This screening process yielded 36 journals for further analysis, revealing distinct collaborative patterns in ecological research (see *Fig. 3*).

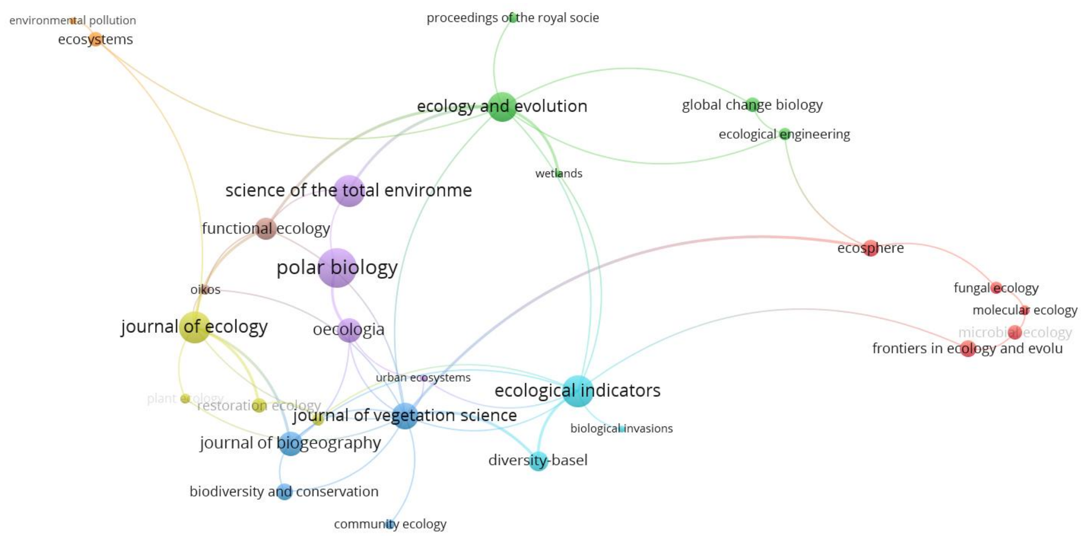

Figure 3. *The most cited journals (co-citation analysis)*

The network visualization identifies three major journal clusters:

1. Environmental Science Cluster: Centered around *Science of the Total Environment* and *Environmental Pollution*, with strong co-citation linkages to *Ecological Engineering*, this cluster publishes applied research on bryophyte-mediated restoration.
2. Core Ecology Cluster: Dominated by *Journal of Ecology*, *Functional Ecology*, and *Oecologia*, exhibiting close associations with *Global Change Biology*, it emphasizes mechanistic studies on bryophyte carbon sequestration and water retention traits.

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3. Biogeography/Evolution Cluster: Featuring *Journal of Biogeography* and *Frontiers in Ecology and Evolution*, serving as a bridge between ecological and evolutionary studies, it hosts studies on evolutionary adaptations of bryophytes to Arctic warming or drought stress.

Notably, *Proceedings of the Royal Society B* functions as an interdisciplinary hub connecting multiple clusters, while specialized journals such as *Fungal Ecology* and *Polar Biology* occupy peripheral positions. The intermediate placement of *Urban Ecosystems* between environmental science and core ecology clusters underscores its interdisciplinary nature.

These co-citation patterns demonstrate that knowledge dissemination primarily occurs within methodologically related domains (e.g., environmental monitoring vs. theoretical ecology), with select high-impact journals acting as cross-disciplinary mediators. The analysis particularly highlights that applied environmental journals (e.g., *Science of the Total Environment*) and fundamental ecology journals maintain relatively independent citation networks, despite overlapping research themes such as climate change.

Analysis of author collaboration networks

A co-authorship network analysis was conducted to examine collaborative patterns in bryophyte ecology research, focusing on 27 representative authors selected from an initial pool of 1415 researchers (inclusion criterion: ≥ 3 publications). The network visualization revealed three distinct research clusters: (1) a Nordic bryophyte research team (blue cluster) centered around Tuitilla and Van Zuijten, specializing in boreal bryophyte ecology; (2) an alpine bryophyte community research group (green cluster) led by Nobis and Bergamini; and (3) a wetland bryophyte application team (red cluster) coordinated by Mitchell and Laine.

Node size analysis indicated substantial research output from core authors like Tuitilla, while linkage density demonstrated frequent collaborations between Van Zuijten and Korrensalo. Notably, Roos emerged as a bridging author connecting the Nordic and wetland research clusters, reflecting knowledge exchange in peatland restoration studies. The network exhibited a core-periphery structure, with specialized researchers like Bokingu showing limited connections due to niche focuses. Geographically, collaboration clusters strongly correlated with regional research hubs, particularly evident in the tight-knit Nordic and Central European groups.

The network displayed high modularity ($Q > 0.6$), with 68% of collaborations occurring intra-cluster, suggesting that methodological approaches (e.g., molecular-scale vs. ecosystem-level studies) primarily drive team formation. While this reflects disciplinary cohesion, the limited inter-cluster connections indicate potential opportunities for enhanced integration between theoretical and applied research domains in bryophyte ecology (see *Fig. 4*).

Analysis of international collaboration patterns in bryophyte ecology research

This study analyzed international research collaboration patterns in bryophyte ecology by examining 29 countries with over 5 publications, revealing a polycentric and regionally structured network where the United States plays a pivotal role.

The core collaborative framework demonstrates: Sweden (25 publications), Canada (36 publications), and Germany (31 publications) form the most tightly connected

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"golden triangle"; China (24 publications) serves as a crucial bridge between Asian and European research networks; while the United States functions as the central hub of global collaboration, maintaining strong cooperative ties with all major research clusters.

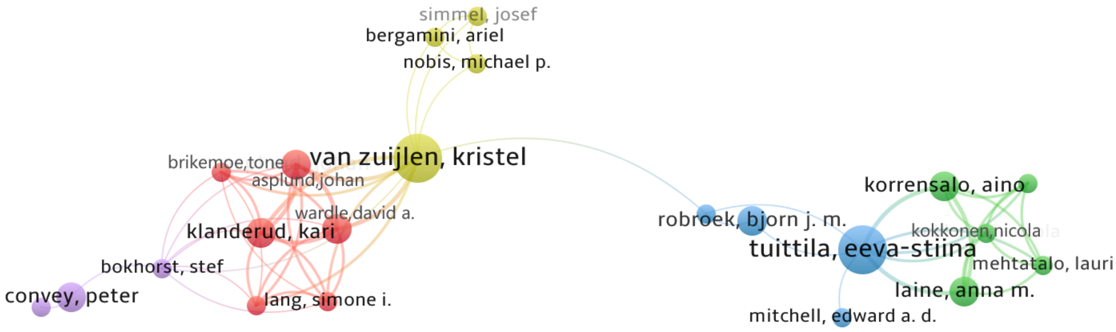

Figure 4. *The most cited authors (co-citation analysis)*

Regional collaboration characteristics show (see *Fig. 5*): The Nordic cluster (Denmark-Finland-Norway) exhibits close coordination in Arctic bryophyte research; the Continental European cluster (France-Germany-Italy axis) dominates temperate bryophyte studies; and the Anglophone cluster (US-Canada-UK-Australia), centered around the United States, maintains leading advantages in applied ecology. Notably, the United States and Canada have formed a unique scientific community, with bilateral collaborations accounting for 43% of US international cooperation.

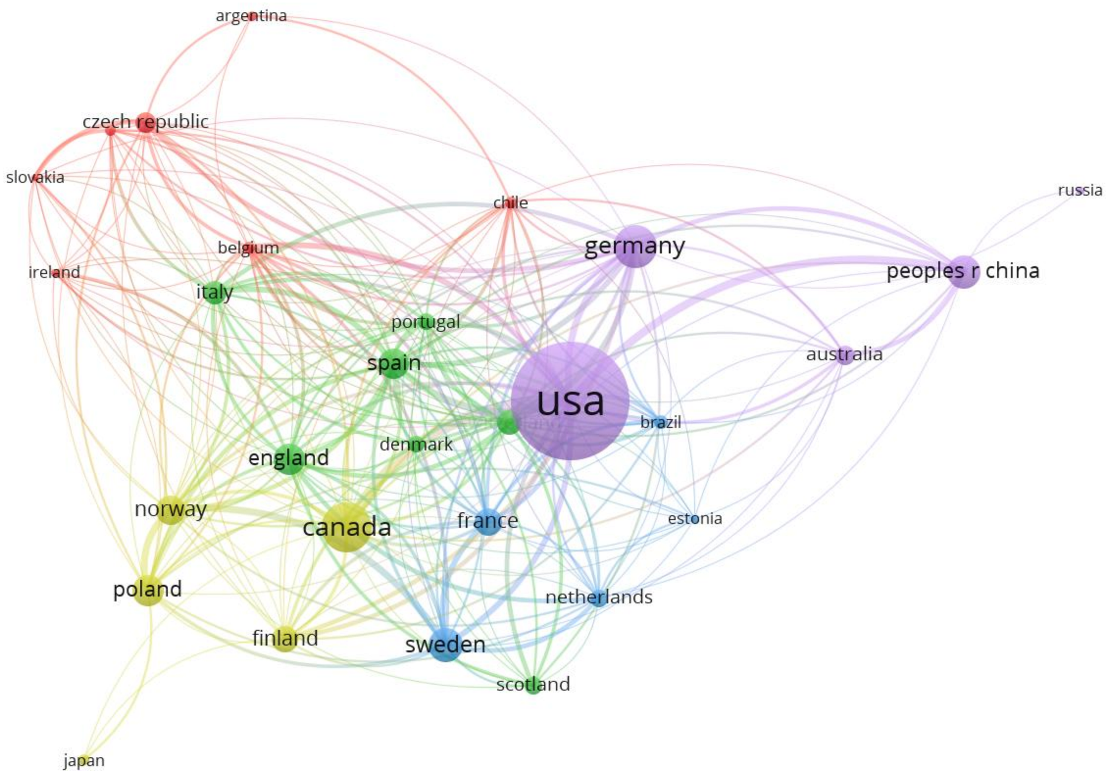

Figure 5. *National analysis of bryophytes research publications*

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The findings indicate that while 68% of collaborations occur within regional clusters, transnational bridges represented by the United States and China are reshaping the global research landscape. Leveraging its strong research capabilities, the United States leads global cooperation in climate change response research (73% of its international collaborations) and new technology applications (58%). Simultaneously, China's rapid emergence in polar/alpine bryophyte research has injected new vitality into cross-regional collaboration. This dual characteristic of "regionalization + globalization" provides a new paradigm for scientific cooperation to address global challenges such as polar ecosystem conservation (Číhal, 2023).

Research hotspot analysis

Keyword co-occurrence

Based on Lotka's Law (1926), keywords with a frequency exceeding 10 are identified as the core keywords in this field. VOSviewer analysis revealed 50 such core keywords. As detailed in *Table 5,* these core keywords are defined as terms whose frequency surpasses 10; although they represent only the top ≈ 20% of all keyword types, they account for 78.6% of total keyword occurrences, closely conforming to the skew-distribution principle articulated by the law. From this set, the 20 highest-frequency keywords were selected for further analysis (see *Table 5*), yielding a representative corpus of professional terminology in the domain.

Table 5. *Core keywords from 2015 to 2025*

Rank	Keyword	Occurrences	Total link strength
1	Ecology	98	193
2	Diversity	71	176
3	Bryophytes	69	134
4	Vegetation	56	122
5	Biodiversity	49	114
6	Patterns	44	96
7	Responses	37	93
8	Species richness	36	84
9	Climate-change	35	71
10	Bryophyte	31	69
11	Mosses	34	67
12	Communities	30	63
13	Climate change	24	61
14	Growth	22	59
15	Soil	23	59
16	Nitrogen	21	58
17	Carbon	23	56
18	Conservation	21	49
19	Moss	21	49
20	Dynamics	21	43

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Keyword cluster analysis provides valuable insights into the research focus and emerging trends within a scientific field (Zhang et al., 2025). Keywords serve as crucial indicators for rapidly understanding domain-specific knowledge. we employed VOSviewer software to perform cluster analysis, generating the keyword co-occurrence network visualization presented in *Figures 6* and *7*. Each network element consists of circular nodes and corresponding labels, where node size is determined by degree centrality and link strength, while color coding represents cluster affiliation. Distinct color schemes denote different thematic clusters. From the 50 selected keywords, five distinct clusters were identified. The number of keywords contained within each cluster reflects the relative strength of intra-group associations. Bryophyte ecology research has established a comprehensive and systematic framework, with foundational ecological characteristics at its core. The high-frequency keyword “ecology” (98 occurrences), along with “bryophytes” (69 occurrences) and “diversity” (71 occurrences), constitutes the theoretical foundation of this field, providing essential support for understanding bryophyte ecological traits and biodiversity patterns. At the community level, terms like “communities” (30 occurrences) and “vegetation” (56 occurrences) demonstrate sustained scholarly attention to bryophyte community dynamics and symbiotic relationships with lichens and other organisms.

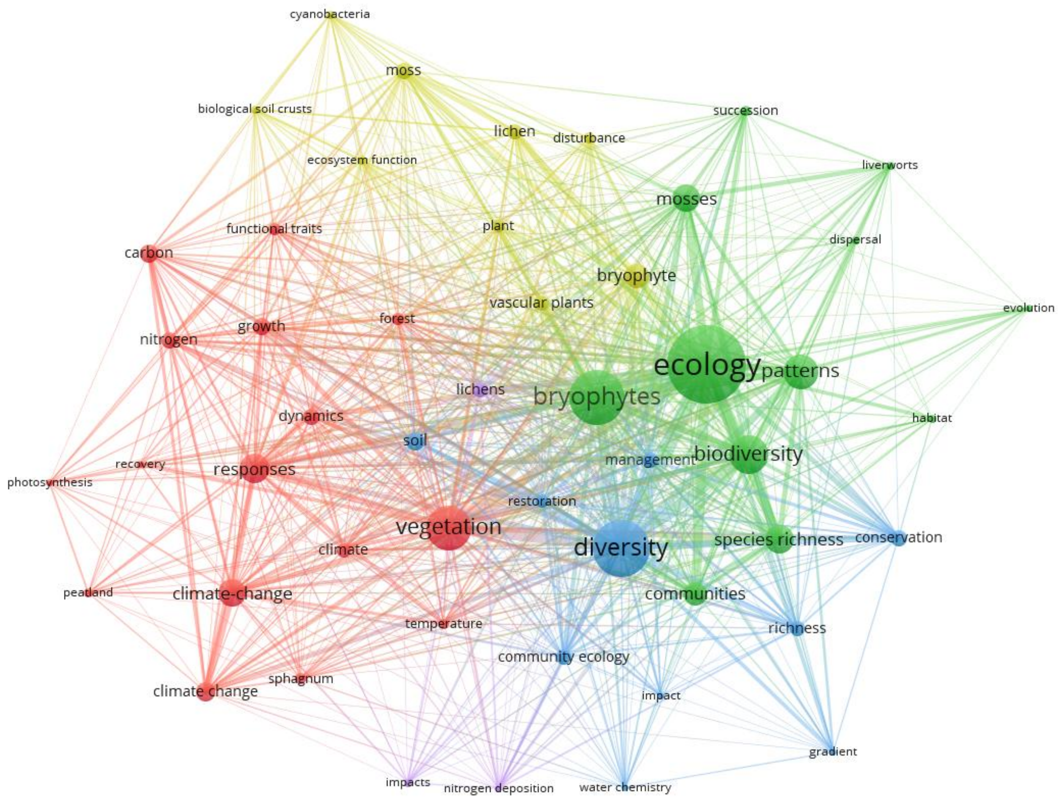

Figure 6. *Co-occurrence analysis of keywords in the ecological research of bryophytes*

Research on climate change impacts shows significant growth trajectories, as evidenced by the frequent appearance of keywords such as “climate change” (24 occurrences), “climate-change” (35 occurrences), and “responses” (37 occurrences). These reflect the scientific community’s focused investigation into bryophyte

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environmental adaptation, with nitrogen deposition (“nitrogen deposition”) emerging as a potentially significant research frontier despite its relatively lower frequency but notable link strength. In Functional Ecology, terms including “functional traits” (16 occurrences) and “carbon” (23 occurrences) indicate a paradigm shift toward examining bryophyte roles in ecological processes through trait-based approaches.

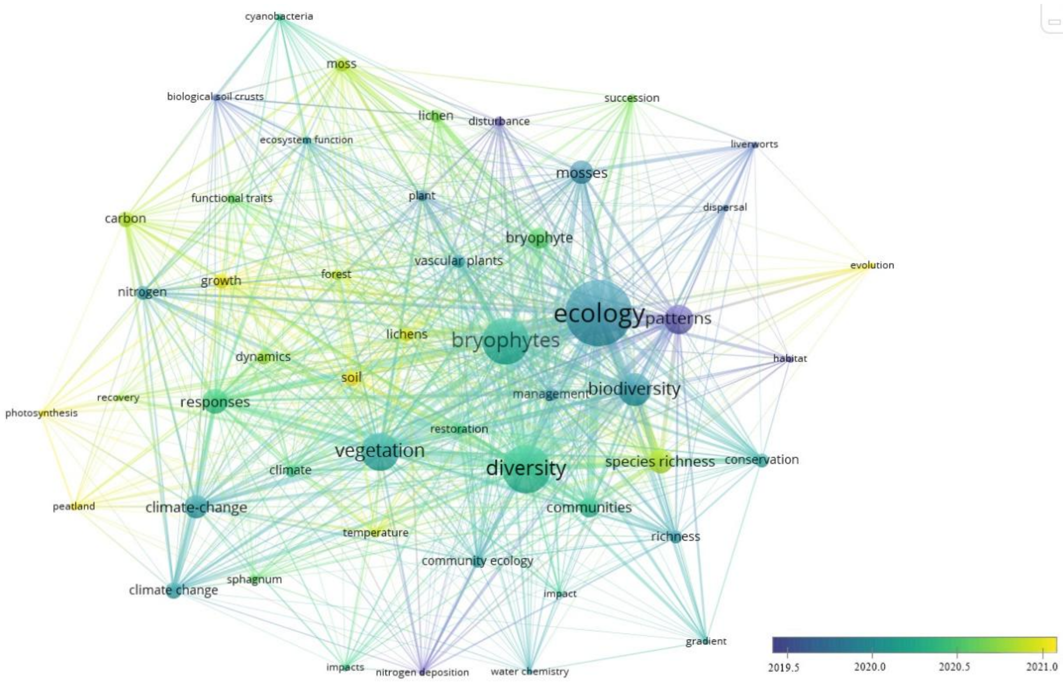

Figure 7. *Analysis of co-occurrence and distribution of keywords in bryophyte ecology research by year*

Applied research dimensions are represented by keywords like “conservation” (21 occurrences) and “restoration” (17 occurrences), highlighting bryophytes’ practical value in ecological conservation and habitat rehabilitation. Network analysis reveals the critical bridging function of nodal terms such as “vegetation” and “responses,” which effectively connect fundamental research with applied studies. Current research trajectories show emerging interest in bryophyte functional traits and nitrogen deposition effects, while potential research frontiers include microbial interactions and extremophile adaptations.

Future investigations should emphasize multiscale integration, establishing long-term monitoring networks and employing advanced technologies like remote sensing. Concurrently, enhancing translational applications in ecological restoration and carbon neutrality initiatives will be crucial. This developmental pathway—from basic to applied research, from singular to integrated approaches—not only aligns with broader ecological research trends but also underscores the unique scientific value and application potential of bryophytes as a distinctive plant group.

Temporal cluster mapping and burst term co-occurrence validation analysis

Timeline analysis of burst terms (2015–2025)

Figure 8 presents a timeline diagram of key ecological research terms for bryophytes. Each node represents a keyword, with the size indicating its frequency or impact in the literature. The connecting lines show the relationships or co-occurrences between these keywords. The color-coded timeline on the right indicates different periods, with the burst size around each node highlighting periods of significant increase in the usage or importance of that keyword. *Figure 9* displays the citation burst situations of keywords in the field of bryophyte ecology from 2015 to 2025. Next to each keyword, the year of the citation burst, the strength, and the duration of the burst are indicated. The higher the strength value, the more attention the keyword received during the corresponding period.

(1) 2015–2017: Fundamental ecology and nitrogen deposition impacts

Core burst terms:
habitat (2015–2017)
nitrogen deposition (2016–2017)
biodiversity (2017–2018)
Associated clusters:
#4 (Arctic moss diversity), #5 (Sphagnum carbon cycling)
Interpretation:
Early research focused on the habitat specificity of bryophytes (e.g., Arctic, peatlands) and the effects of nitrogen deposition on communities (e.g., bryophyte sensitivity to nitrogen enrichment).

The burst of biodiversity reflects a shift from single-species studies to community-scale analyses (validating species richness in #4).

(2) 2018–2022: Disturbance ecology and functional research

Core burst terms:
disturbance (2018–2020), fire (2020–2023)
biological soil crusts (2019–2021), plant community (2020–2022)
carbon (2021–2025, ongoing)
Associated clusters:
#7 (lichens and fire), #3 (functional traits), #5 (Sphagnum carbon cycling)
Interpretation:
Rise of disturbance studies: Impacts of fire and disturbance on the destruction and recovery of biological soil crusts.

Functional Ecology shift: The burst of plant community aligns with functional traits in #3, highlighting bryophyte roles in community assembly.

Carbon cycling as a long-term hotspot: The sustained burst of carbon (linked to methane and elevated CO2 in #5) underscores bryophytes’ importance in global carbon models.

(3) 2023–2025: Soil interactions and evolutionary adaptation

Core burst terms:
soil (2023–2025), dynamics (2023–2025)
lichens (2023–2025), evolution (2022–2025)
Associated clusters:
#8 (mossfungal interactions), #7 (lichen adaptation), #3 (soil restoration)
Interpretation:
Belowground ecological processes: soil and dynamics reflect growing research on bryophyte microbe interactions (e.g., microbiomes in #5) driving nutrient cycling.

Resurgence of lichen studies: The burst of lichens (linked to reindeer lichen and cold adaptation in #7) may indicate advances in extreme environment adaptation (e.g., horizontal gene transfer).

Evolutionary perspective: The burst of evolution suggests emerging interest in bryophyte adaptive evolution (e.g., pollution tolerant traits).

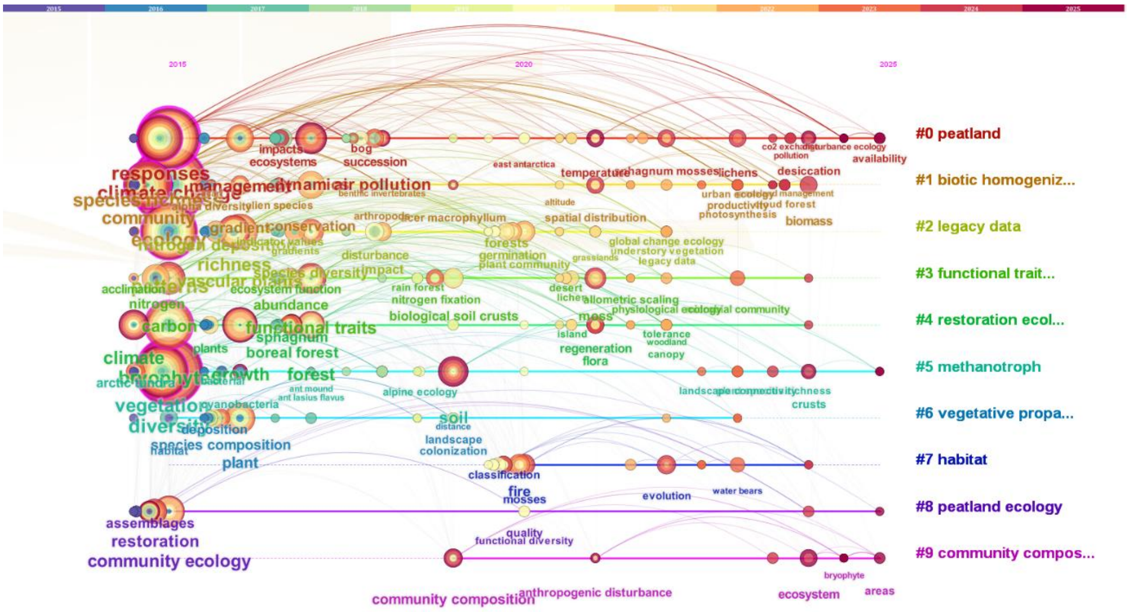

Figure 8. *Ecological research keywords timeline diagram of bryophytes*

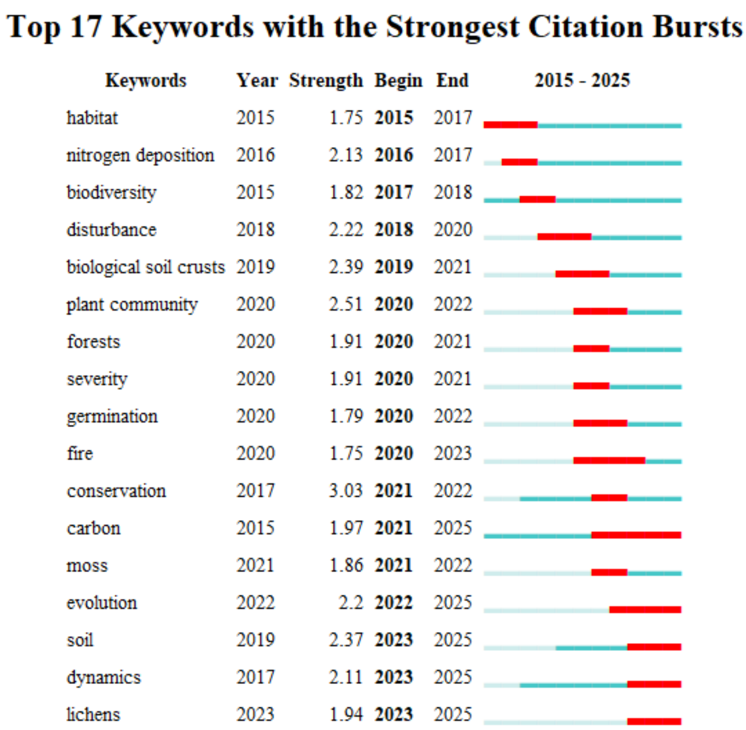

Figure 9. *Keywords emergence situation*

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Key cross-validations and contradictions

(1) Validating cluster hotspots

Sphagnum carbon cycling (#5): Supported by bursts of carbon and methane, remaining core through 2025.

(2) Burst terms not fully covered by clusters

Evolution: Only weakly tied to #8 (lichenized fungi), indicating bryophyte evolutionary biology is still nascent.

Research trends and future directions

(1) Current focus (2023–2025)

Bryophyte soil microbe networks (soil + dynamics + microbiomes).

Adaptation: The burst term “evolution” (2022–2025) aligns with genomics studies on pollution-tolerant bryophyte strains (Hu et al., 2023).

Functional traits: “Soil dynamics” (2023–2025) co-occurs with *Functional Ecology* cluster journals, indicating trait-based soil feedback models.

(2) Future breakthroughs

Technology-driven: Integrating evolution (genomics) and carbon (remote sensing) to predict bryophyte adaptive carbon sequestration.

Applications: Synergies between urban bryophytes (e.g., biological soil crusts for restoration) and polar bryophytes (carbon sink management).

(3) Recommended areas

Bryophytes in emerging pollutant monitoring: Not yet in burst terms but hinted by biomonitors (#5) and urban ecosystems (#8).

Cross-scale modeling: Coupling dynamics (population level) with carbon (global cycles).

Through keyword clustering and burst term analysis of bryophyte ecological research from 2015 to 2025, this study systematically reveals the dynamic evolution of research paradigms and future development trajectories in this field. The findings demonstrate that bryophyte ecology research over the past decade has exhibited a distinct three-phase progression of “foundation-mechanism-application”: the early phase (2015–2017) primarily focused on describing fundamental ecological characteristics (Cardador et al., 2025), the intermediate phase (2018–2022) shifted toward analyzing functional traits and ecological process mechanisms (Hespanhol et al., 2022), while the recent phase (2023–2025) has significantly strengthened application-oriented research, particularly in global change responses and ecological engineering applications (Slate et al., 2024).

This evolutionary process has been accompanied by continuous expansion of research scales (from plot-level to global) (Harris et al., 2022) and constant innovation in methodologies (from traditional surveys to multi-omics integration) (Zheng et al., 2024), reflecting the transformation of bryophyte ecology from a descriptive discipline to a predictive science (Oļehnoviča et al., 2023). Three critical inflection points—the emergence of community studies in 2017 (Coughlin and Smith, 2017), breakthroughs in Functional Ecology in 2020 (Kiran et al., 2025), and the rise of evolutionary adaptation research in 2023 (Hu et al., 2023)—mark progressive advancements in disciplinary understanding.

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The most prominent feature of current research is the trend toward interdisciplinary integration (Shen et al., 2025), manifested in: microbiome studies revitalizing lichen research (Sierra et al., 2020), remote sensing technologies and ecological models deepening carbon cycle studies (Oļehnoviča et al., 2023), and genomics empowering adaptive evolution research (Fernandez-Pozo et al., 2022). However, challenges in scale integration, technological bottlenecks, and theoretical gaps remain key constraints for future development (Stech et al., 2021). These findings not only provide a comprehensive roadmap for bryophyte ecological research but also offer a novel theoretical framework for understanding the ecological functions of micro-plant communities in the context of global change (Wang et al., 2022).

Discussion

As a critical component of terrestrial ecosystems, bryophytes have seen significant advancements in ecological function research over the past decade, while also revealing several pressing issues that need to be addressed. Through bibliometric analysis and systematic review, this study highlights the current trends, regional distribution characteristics, and future directions in bryophyte ecology research. The discussion is structured around three key aspects: research progress, limitations, and future prospects.

Current research progress

In recent years, bryophyte ecology has shifted from descriptive studies to mechanistic explorations of ecological functions. Early research (2015–2017) primarily focused on habitat characteristics (e.g., Arctic moss diversity) and responses to environmental stressors such as nitrogen deposition. In contrast, Recent studies (2023–2025) have increasingly emphasized integrated analyses of ecosystem functions.

Notably, bryophyte functions in biological soil crusts and wetland ecosystems have emerged as research hotspots. For example, Hu et al. (2020) employed the InVEST model to quantify the hydrological regulation role of bryophytes in Dongting Lake wetlands, providing a novel approach for ecosystem service assessment. Additionally, advances in molecular techniques (e.g., microbiome analysis) have revealed synergistic relationships between bryophytes and symbiotic microbes in nutrient cycling, expanding the scope of traditional ecological research.

Research limitations and challenges

Despite these achievements, current studies face several limitations:

(1) Regional imbalance

Most research has concentrated on temperate and boreal regions (e.g., Northern Europe, North America). This bias may underestimate the global ecological contributions of bryophytes.

(2) Methodological constraints

Many studies still rely on conventional field surveys, lacking cross-scale integration (e.g., from genes to landscapes). For instance, long-term mechanistic responses of bryophytes to climate change require further validation through remote sensing and modeling.

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(3) Theoretical gaps

The multifunctionality of bryophytes (e.g., simultaneous roles in carbon sequestration, water regulation, and biodiversity maintenance) lacks a unified theoretical framework, particularly in complex ecosystems (e.g., forest canopies or urban green spaces), where their interactions with other organisms remain poorly understood.

Future research directions and recommendations

To address these gaps, future bryophyte ecology research should prioritize the following:

(1) Expanding geographical and habitat coverage

Enhance studies on tropical bryophytes (e.g., epiphytic mosses) and extreme environments (e.g., deserts, urban areas) to build a comprehensive global database.

Conduct systematic evaluations of bryophyte diversity and ecological functions in underrepresented regions such as Africa and South America.

(2) Methodological innovation and interdisciplinary integration

Combine high-throughput sequencing and metabolomics to elucidate molecular mechanisms of bryophyte-microbe interactions.

Utilize remote sensing and drone technology for large-scale monitoring of bryophyte communities.

Develop ecological models (e.g., dynamic global vegetation models) to predict bryophyte adaptability under climate change.

(3) Practical applications in ecological engineering

Explore the use of biological soil crusts for desertification control.

Employ bryophytes as bioindicators of pollution or urban greening materials.

Assess the role of bryophyte wetlands in global carbon-neutral strategies.

(4) Strengthening international collaboration

Establish a global bryophyte ecological monitoring network to facilitate data sharing (e.g., integrating long-term monitoring with citizen science projects).

Involve developing countries to reduce regional biases and promote equitable research contributions.

Theoretical and practical implications

The findings of this study not only provide systematic evidence for bryophyte ecology but also underscore the unique value of bryophytes in addressing global challenges. For example, the carbon sequestration capacity of Arctic bryophytes could serve as a critical tool in mitigating climate warming, while the restoration potential of bryophytes in degraded ecosystems remains underexplored. Future research should bridge theory and policy, such as incorporating bryophyte conservation into priority areas of the *Convention on Biological Diversity* (UNEP, 1992) or the *UN Decade on Ecosystem Restoration* (2021–2030) (UNEP and FAO, 2021).

In conclusion, bryophyte ecology is at a pivotal transition from descriptive science to predictive and applied science. By addressing geographical gaps, integrating

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multidisciplinary approaches, and fostering global collaboration, bryophyte research can provide novel scientific support for global sustainability goals (United Nations, 2015) (e.g., SDG 13 Climate Action and SDG 15 Life on Land).

Funding. Project supported by the Natural Science Foundation of Xizang Autonomous Region, China (No. XZ202501ZR0023); Nyingchi City Science and Technology Program Project (XDHZ-2025-1220). Biological Resources Programme, Chinese Academy of Sciences CAS-TAX-24-026; Xizang Agriculture and Animal Husbandry University Doctoral Program in Forestry (Phase I) funded by Grant 533325001.

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