

Original Paper

Research Progress on Moss Traits in the Last Decade: A Bibliometric Analysis Based on CiteSpace

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Fund Project

This work was supported by the National Natural Science Foundation of China; Responses of rock-dwelling bryophyte diversity and functional traits to rocky desertification succession in Guizhou Province; (Project Number: 31960262)

Received: October 23, 2024 Accepted: November 11, 2024 Online Published: November 25, 2024
doi:10.22158/se.v9n4p87 URL: <http://dx.doi.org/10.22158/se.v9n4p87>

Abstract

Mosses are small, higher plants with a wide variety of species and are an important component of various ecosystems. The study of moss traits helps in understanding their physiological and ecological processes, as well as enhancing our overall knowledge of the plant kingdom. To clarify the research context and development trends of moss traits, this paper conducts a bibliometric analysis of 471 existing articles using the Web of Science database and CiteSpace (6.4.R1) software. The results show that research on moss traits experienced a rapid increase from 2015 to 2021 before leveling off. The main disciplines publishing articles on moss traits are Plant Sciences, Ecology, and Environmental Sciences. The primary publishing countries are the USA, People's Republic of China, and Germany. Major journals include Plants-Basel (Q1), American Journal of Botany (Q2), and New Phytologist (Q1). Among all journals, New Phytologist (255), Journal of Ecology (233), and Ecology (211) are the most frequently cited. Research hotspots in moss traits mainly focus on functional traits, growth, and community, and comparative studies with other groups (such as lichens) are expected to be a future research trend.

Keywords

moss plants, bibliometrics, Web of Science

1. Introduction

The term "trait" is used to characterize organismal performance and is widely applied in studies ranging from the individual level to the ecosystem level. Violle et al. (2007) define traits as any measurable morphological, physiological, or phenological features at the cellular to individual level. Therefore, the scope of moss traits can be considered broad, as any measurable characteristic falls within the category of a trait. Mosses are an ancient and unique group of plants that are found in various parts of the world, from polar to tropical regions and from tundra to deserts (Slate, Antoninka, Bailey et al., 2024; Kulshrestha, Jibran, Van Klink et al., 2022). They are pioneer species in harsh environments (Cheng, Gao, Zhang et al., 2021; Cheng, Li, Long et al., 2020; Deng, Zhang, Wang et al., 2020) and are an important component of many ecosystems (Bjerke, Bokhorst, Callaghan et al., 2017). Research on moss traits helps to understand their ecological roles in the environment. In recent years, the ecological significance of moss plants to ecosystems has gradually been recognized and explored. Trait-based studies have shown that mosses play important ecological roles in ecosystem processes, such as soil and water conservation (Hu, Gao, Li et al., 2023), nutrient accumulation (Bao et al., 2019), promoting ecological succession (Li et al., 2024), increasing species diversity (Fontúrbel et al., 2021), and facilitating carbon and nitrogen cycles (Alvarenga & Rousk, 2022; Slate, Sullivan, & Callaway, 2019). Moss traits not only reflect their own adaptive evolution but also provide ecological benefits to the structure and function of ecosystems. Research on moss traits has become one of the key topics in plant biology and ecology.

In recent years, research on moss plants has grown rapidly, making it necessary to review and analyze the related literature. Bibliometrics, as an effective analytical method, can quantify a large number of publications and reveal issues such as research trends, hot topics, and the distribution of researchers and institutions within a specific field. It has been widely used in the visualized analysis of literature across various disciplines (Lyu, Liu, & Yao, 2023). CiteSpace, a scientific mapping and knowledge visualization software developed by Dr. Chaomei Chen, a professor at the College of Information Science and Technology, Drexel University, uses spectral clustering to analyze co-citation networks in scientific literature. It can display the development trends or directions of a discipline or knowledge field over a certain period and show the evolutionary trajectory of several research frontier areas. Due to its efficiency and accuracy in visualizing literature, it is often used in bibliometric analyses. Bibliometric studies have been widely conducted in environmental science, ecology, and plant science, such as research on water stress in economic forests (Yin et al., 2024), advances in Brassicaceae plant research (Zhou et al., 2024), and global trends in the usage of chlorophyll fluorescence (Zavafer & Labeeuw, 2020). However, bibliometric research on moss plants is rarely reported. Therefore, this paper conducts a bibliometric and visual analysis of the literature related to moss traits, aiming to reveal the current research status of moss traits, analyze research hotspots, and clarify the research dynamics of moss plants. This will help researchers stay abreast of the forefront of moss plant research and provide valuable insights and references for future studies on moss traits.

2. Study Method

On October 28, 2024, a search was conducted in the Core Database using Web of Science with the topic "moss trait." After exporting the results and performing deduplication, a total of 471 valid documents published between 2015 and 2024 were identified. The documents were analyzed and visualized using both the citation analysis feature in Web of Science and CiteSpace (6.4.R1) software. The analysis included authors, keywords, publication titles, disciplinary categories, countries/regions, references, cited authors, and cited journals.

3. Results

3.1 Trends, Distribution and Main Sources of Publications

The search results show that the number of publications has rapidly increased over the past decade, from 18 papers in 2015 to 55 papers in 2019. After a slight decrease in 2020, the number of publications rose again to 60 in 2021 and then stabilized around 55 papers (Figure 1). These papers span across various disciplines, including ecology, environmental science, animal and plant studies, among others. The largest number of publications comes from Plant Sciences, with a total of 210 papers, accounting for 44.492% of all publications. This is followed by Ecology, with 129 papers, representing 27.331%, and Environmental Sciences, with 73 papers, accounting for 15.466%. The top three disciplines together represent 87.289% of all papers, while the remaining papers are scattered across fields such as Forestry (8.475%), Biodiversity Conservation (5.72%), and Soil Science (5.297%). The USA is the leading contributor, with a total of 106 papers, followed by the People's Republic of China, Germany, and Spain, with 67, 57, and 53 papers, respectively. The top four countries have over 50 publications each, while in the top 10 countries/regions, the lowest number of papers is 25 (Brazil) (Table 1).

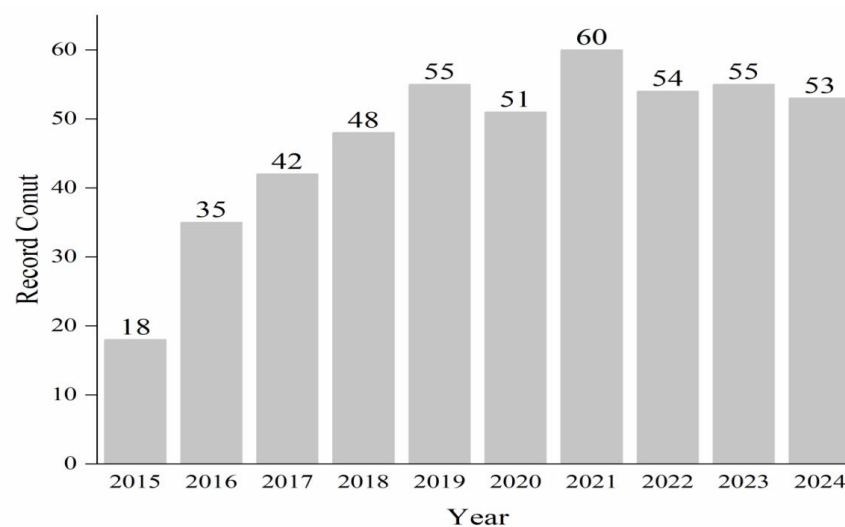


Figure 1. Annual Published Paper Number of moss Trait Research

Table 1. Ranking the top 10 of Disciplinary Categories and Countries/regions

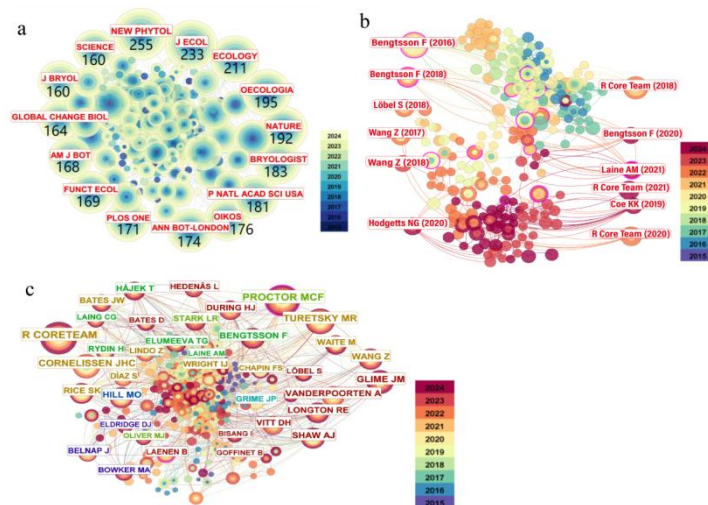
Ra nk	Disciplinary Categories	Record Count	Percentage of 471 (%)	Ra nk	Countries/regi ons	Record Count	Percentage of 471 (%)
1	Plant Sciences	210	44.492	1	USA	106	22.458
2	Ecology	129	27.331	2	PEOPLES R CHINA	67	14.407
3	Environmental Sciences	73	15.466	3	GERMANY	57	12.076
4	Forestry	40	8.475	4	SPAIN	53	11.229
5	Biodiversity Conservation	27	5.72	5	CANADA	44	9.322
6	Soil Science	25	5.297	6	SWEDEN	44	9.322
7	Evolutionary Biology	23	4.873	7	POLAND	34	7.203
8	Agronomy	19	4.025	8	ENGLAND	31	6.568
9	Multidisciplinary Sciences	18	3.814	9	FRANCE	26	5.508
10	Zoology	17	3.602	10	BRAZIL	25	5.297

3.2 Publication Source, Highly Cited Author, Paper Analysis

The 417 papers were published in 207 different journals, indicating a relatively dispersed distribution, with a decreasing trend. As shown in Table 2, the top 10 journals mainly focus on plant and ecology-related topics. The journal with the highest number of publications is *Plants-Basel*, with 17 articles, accounting for 3.602%. This is followed by *American Journal of Botany*, *New Phytologist*, and *Journal of Ecology*, most of which are classified as Q1 journals. Among these, *New Phytologist* (255) has the highest citation count, followed by *Journal of Ecology* (233), *Ecology* (211), and *Oecologia* (195) (Figure 2a). These are all mainstream ecological journals, with each node containing multiple layers, indicating that these journals are continuously being cited. The most co-cited paper is by Bengtsson (2016), followed by Bengtsson (2018) and R Core Team (2018). Among the highly cited papers, the first authors is Bengtsson F, R Core Team, and Wang Z appearing more than twice in highly cited papers. The co-citations of more recent papers (with purple node layers) are still at a relatively low level (Figure 2b). In Figure 2c, the largest nodes, R Core Team and Proctor MCF, are the two scholars with the highest co-citation counts. Other scholars with relatively high co-citation counts include Cornelissen JHC, Bengtsson F, and Wang Z. The complex network connections illustrate the close relationships between these scholars, with many authors being jointly cited.

Table 2. Ranking the top 10 of Publications Titles

Rank	Publication Titles	Record Count	Percentage of 471 (%)
1	Plants-Basel (Q1)	17	3.602
2	AMERICAN JOURNAL OF BOTANY(Q2)	16	3.39
3	NEW PHYTOLOGIST(Q1)	15	3.178
4	JOURNAL OF ECOLOGY(Q1)	13	2.754
5	SCIENCE OF THE TOTAL ENVIRONMENT(Q1)	13	2.754
6	ANNALS OF BOTANY(Q1)	11	2.331
7	Ecology and Evolution(Q2)	11	2.331
8	Ecological Indicators(Q1)	10	2.119
9	JOURNAL OF VEGETATION SCIENCE(Q2)	9	1.907
10	PLANT AND SOIL(Q1)	9	1.907

**Figure 2. Network Co-occurrence Map. Co-citation network map of cited journals (abbreviations)**

Node size represents the co-citation frequency, and the numbers indicate the citation frequency of the journals. Different node colors represent the citation years, with corresponding years shown in the legend on the right (same applies below). NEW PHYTOLOGIST: *NEW PHYTOLOGIST*; J ECOL: *JOURNAL OF ECOLOGY*; ECOLOGY: *ECOLOGY*; OECOLOGIA: *OECOLOGIA*; NATURE: *NATURE*; BRYOLOGIST: *BRYOLOGIST*; P NATL ACAD SCI USA: *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*; OIKOS: *OIKOS*; ANN BOT-LONDON: *ANNALS OF BOTANY*; PLOS ONE: *PLoS One*; FUNCT ECOL: *FUNCTIONAL ECOLOGY*; AM J BOT: *AMERICAN JOURNAL OF BOTANY*; GLOBAL CHANGE BIOL: *GLOBAL*

CHANGE BIOLOGY; J BRYOL: *JOURNAL OF BRYOLOGY*; SCIENCE: *SCIENCE* (a). Journal co-citation network co-occurrence map (b). Author co-citation network co-occurrence map. To make the diagram concise and easier to read, only nodes with larger co-citation frequencies are shown (c).

3.3 Main Research Content

From the keyword co-occurrence network map (Figure 3a), it can be observed that the nodes for functional traits, growth, and diversity are the largest, representing the main topics in moss trait-related research and the areas of greatest interest among scholars. Multiple literature analyses show that, to date, research on moss traits covers various aspects of moss biology, including community-level studies, the relationship between traits and climate change, trait responses to climate change, moss plant decomposition, evolution, and their connections to carbon, among others. Furthermore, the primary research focus has shifted over different time periods. Since 2015, water and vegetation became research hotspots, continuing for two years. Research interest then shifted to climate and plant functional traits in 2017, with these topics remaining popular for two and three years, respectively. By 2018, the focus shifted to plants and litter decomposition. In 2019, there was widespread research on deposition, land plants, *Physcomitrella patens*, and biological soil crusts, which were all key research areas for 1-3 years. The study of lichen and sexual reproduction has been ongoing since 2021. Strength is an indicator that measures the intensity of changes in keyword frequencies over a specific time period. The top three keywords by strength are water (3.35), climate (3.09), and deposition (2.98), showing substantial changes in their frequency over the corresponding time periods. The strength of all other keywords is above 2.

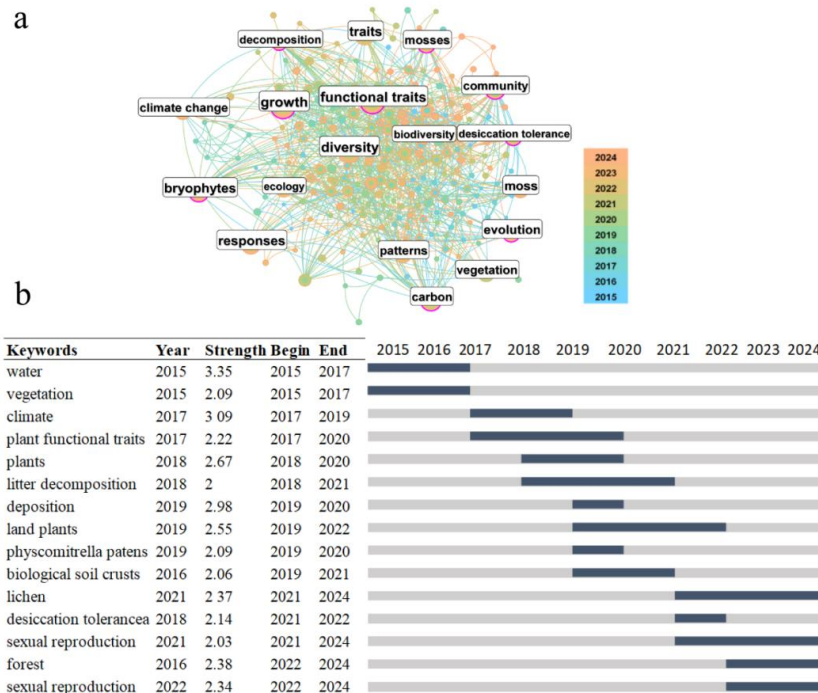


Figure 3. Keyword Co-occurrence Network Map

Co-occurrence network of keywords (a). Temporal trend of keyword emergence. Year: The year in which research on the keyword first appeared. Strength: A measure of the change in frequency of research on the keyword over a specific time period; the higher the value, the more significant the change. Begin: The start year of the keyword's emergence. End: The end year of the keyword's emergence (b).

4. Discussion

4.1 Research Development of Moss Trait in the Last 10 Years

Research on plant traits has traditionally focused on various vascular plants. However, in recent years, there has been an increasing application of research on vascular plant traits to mosses, marking the beginning of exploration into moss traits. Over the past decade, research on moss traits has yielded substantial results. From 2015 to 2021, the volume of research on moss traits steadily increased, but there was a significant decline in 2020, likely due to the global spread of COVID-19. Looking at the publication trends, more and more scholars showed interest in moss traits from 2015 to 2021, but the enthusiasm began to level off in subsequent years. As of the search date, there are 471 records in total, distributed across various disciplines, with plant sciences being the most prominent field, accounting for 44.49% of moss trait research. Additionally, the distribution across other disciplines indicates that research on mosses has made progress in various fields. For example, studies in environmental sciences mostly focus on the ecological functions of mosses (van Zuijlen, 2024) and research related to their environmental adaptability (Martins et al., 2024). The USA, People's Republic of China, and Germany are the leading countries in moss trait research, occupying core positions in this field and driving global research on moss traits in the past decade. Notably, within the study of moss traits, Sphagnum has been the most extensively researched species, with over 70 records related to Sphagnum out of the 471 total records. Sphagnum mosses play a significant role in peat formation and carbon sequestration in mire ecosystems (Shtang, Ponomareva, & Skryabina, 2024), which is why many researchers have chosen Sphagnum as a model species for a series of studies. Significant progress has already been made in areas such as Sphagnum morphology, chemical composition, and carbon sequestration potential, and it is expected that there will be further research on Sphagnum in the future.

4.2 High-Impact Papers and Authors

R CORETEAM is the most cited author in the study of moss traits, indicating that the application of R language is particularly important for the research of moss traits. R language has become a necessary tool for academic research due to its powerful computational and analytical functions, such as using R to calculate Community Weighted Mean (CWM) and conducting Structural Equation Models (SEM) analysis in moss research (Laine et al., 2021). Another major figure is Proctor MCF. A closer look at his work reveals that Proctor has been researching various aspects of mosses, including desiccation tolerance (Proctor, 2001), morphology (Proctor, 1979), and physiology (Proctor, 1977), since the last century and continues to do so today. His articles and books have fully elaborated on moss, and there is

no doubt that he is a senior expert in moss research. Another key figure is Turetsky MR, who focuses primarily on the ecological functions of mosses and the impact of environmental changes. His important findings have been published in leading ecological journals (Turetsky et al., 2012; Turetsky et al., 2008), making them highly valuable references. The most-cited paper is a 2016 study by Bengtsson F, published in *Ecology and Evolution*, titled "Photosynthesis, growth, and decay traits in Sphagnum - a multispecies comparison" (Bengtsson, Granath, & Rydin, 2010). This study examines the relationship between growth and decomposition in 15 species of peat mosses. Using photosynthesis and decomposition rates as indicators of moss growth and decay, the results support a trade-off between moss growth and decomposition traits. Another highly cited paper by Turetsky, published in *Plant and Soil* in 2018, is titled "Biochemical determinants of litter quality in 15 species of Sphagnum" (Bengtsson, Rydin, & Hájek, 2018). The study found that the corrosion resistance of peat moss is positively correlated with the polysaccharide Sphagnan and soluble phenolics, with these metabolites' effects on decomposition influenced by habitat nutrient availability. The high citation rates of these two papers indicate that both the research methods and results have been widely recognized.

4.3 Analysis of Research Hotpot in Moss Traits

The most researched topics in moss trait studies today are functional traits, growth, diversity, community, climate change, bryophytes, and responses (Figure 3). However, the research focus that emerged first in the past decade was the keyword "water." As mosses are poikilohydric plants, their water retention capacity can vary significantly between species, ranging from 50% of their dry weight to up to 20 times that amount (Wu, 1998). This remarkable water retention ability has sparked the interest of researchers. After two years of research focused on "water," climate and plant functional traits became the new hot topics starting in 2017. Research on plant functional traits in vascular plants has already matured, and applying the functional traits framework to moss studies represents a new direction. It offers an effective method for gaining deeper insights into the ecological functions (Slate et al., 2024), environmental adaptability (Mohanasundaram & Pandey, 2022), and biodiversity (Wang et al., 2022) of mosses. As a result, the study of functional traits in moss research has remained a hot topic. In 2021, comparative studies between lichens and mosses gained momentum. For example, Wang et al. (2022) compared the concentrations of C, N, P and photosynthetic rates in lichens, mosses, and vascular plants, showing a shift in how scholars view mosses—from isolated studies of mosses to the exploration of interactions among different plant groups. Research on moss desiccation tolerance has been a continuing hot topic since 2021. Drought is a common environmental stress that mosses face, affecting their survival, reproduction, and ecological niches (Greenwood, Stark, & Chiquoine, 2019). As a result, the impact of drought stress on moss physiology and ecology has been widely studied. Desiccation-rehydration experiments are commonly used methods to measure plant desiccation tolerance (Morales-Sánchez et al., 2022), providing valuable insights into the physiological responses of mosses under different drying conditions. Another key research focus is on moss reproductive traits. Mosses can reproduce both sexually and asexually. Sexual reproduction typically has higher survival

rates, while asexual reproduction offers greater dispersal capabilities. Environmental and geographic limitations can lead to different reproductive strategies, which in turn influence the ecological niches of mosses (Maruo & Imura, 2020). The habitat preferences and geographic distribution of mosses will help explain their reproductive strategies (Calleja et al., 2022). However, due to the wide distribution of moss species, their reproductive strategies are not yet fully understood. Thus, since 2021, there has been an increasing amount of research on moss reproductive traits. Based on the above results, it is concluded that desiccation tolerance, reproductive characteristics and comparison with other types of plants such as lichen and vascular plants will continue to be a hot topic.

5. Conclusion

The research on Moss traits, after experiencing a rapid development phase from 2015 to 2021, has begun to stabilize, with the number of publications remaining steady at around 55 articles. Overall, the USA, People's Republic of China, and Germany are the main research forces, accounting for 48.9% of the total publication output. The primary disciplinary categories are plant sciences and ecology. A total of 471 related papers have been published in 207 different journals, with the distribution being relatively dispersed. *New Phytologist* is the journal with the highest citation frequency. The most commonly researched topics are moss functional traits and growth. *Sphagnum* is the most extensively studied species, and future research may focus more on *Sphagnum*. Additionally, comparative studies of moss plants with other groups (such as lichens) may continue to be a hot topic in the future.

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