BIBLIOMETRIC ANALYSIS OF THE RELATIONSHIP BETWEEN BIODIVERSITY AND ECOSYSTEM FUNCTIONING

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Abstract. The relationship between biodiversity and ecosystem functioning (BEF) and its intrinsic mechanisms has always been a hot research topic among ecologists. However, there are few recent reviews and syntheses on BEF research. We analyze the annual publication volume, research strength, and research hotspots of the literature about BEF in Web of Science from 2001 to 2021 to explore the current status and future trends. The results showed that the number of publications on BEF research increased steadily from 2001 to 2021, with the initial development stage occurring before 2007 and a steady growth stage from 2008 to 2012, as well as a steady growth trend can be observed in the number of publications. After 2013, it entered a phase of rapid development, with the highest number of publications in 2021, with 596 publications. The studies were mainly conducted in developed countries, such as the USA, England, and France, which outstood in terms of the quantity and quality of literature published. China has the 5th highest number of publications in the world and the strongest growth in the last 5 years. The Centre National De La Recherche Scientifique (CNRS) was the institution with the most publications, while the German Center for Integrative Biodiversity Research (iDIV), the Helmholtz Center for Environmental Research (UFZ), and the Helmholtz Association all accounted for more than 60% of their respective publication volumes in the last 5 years, demonstrating the trend of rapid development in Germany in recent five years. The author with the most publications was Schmid B, while Verheyen K had been more active with 69.23% of the total number of papers published over the previous five years. *Ecology* was the journal with the most publications among the top 15 journals, but *Global Change Biology* and *PNAS* had the highest impact factors and the highest average citation frequency. The BEF hotspots primarily concentrate on biodiversity and its productivity, but with the extinction of species around the world, the effects of climate change, and the loss of biodiversity, it is important to investigate the relationship between biodiversity and ecosystem services. There is a disparity in the number of publications and average citations per article between scholars in China and in European and American countries. However, the number of Chinese publications increased rapidly in the last five years. Furthermore, BEF relationships are anticipated to differ across multiple trophic levels, but this subject has received less attention in terms of animal diversity, belowground biodiversity, and ecosystem multifunctionality within and across ecosystems, which needs to be thoroughly investigated to provide a strong base for the conservation of biodiversity.
Keywords: *biodiversity and ecosystem functioning, Web of Science, bibliometrics, analysis, development*

Introduction

Climate change and human interventions have put immense pressure on ecosystems, resulting in a decline in biodiversity (Cardinale et al., 2011; Zheng and Ouyang, 2014). This trend is expected to continue in the future. Biodiversity conservation has become a significant concern for scientists worldwide due to its negative influence on ecosystem functioning and services (Allan et al., 2015; Cardinale et al., 2012).

It has been suggested that diverse ecosystems may be more productive (Guyot et al., 2016; Liang et al., 2016; Schnabel et al., 2019) or more resistant to disease by herbivores (Guyot et al., 2016; Castagneyrol et al., 2014). For example, plant diversity

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has been demonstrated to provide higher primary production, nutrient cycling, carbon store and herbivores control than monocultures (Cardinale et al., 2012; Setiawan et al., 2014). Scientists have been investigating biodiversity and ecosystem functioning since 1991 (Schulze and Mooney, 1994). The early studies on grassland research immediately provided the first evidence that biodiversity can increase primary productivity above what would be expected based on monoculture yield (Naeem et al., 1994; Tilman et al., 1996; Tilman and Downing, 1994). Primary productivity was the primary focus of this early BEF study since it is a crucial ecosystem function that incorporates the effect of biodiversity on other functions, such as pest and disease resistance (Cardinale et al., 2012). As a consequence, productivity as an indicator of ecosystem functioning has become the most extensively studied subject. Experimental results in grassland ecosystems show that biodiversity is closely related to ecosystem functioning. Explanation of the mechanisms underlying these results has been a completely different viewpoint, including the experimental design and analytical methodology (Huston, 1997; Loreau et al., 2001), which are widely debated. Some scholars have called 2002 the year of debate on the relationship between biodiversity and ecosystem functioning (Cameron, 2002). Nonetheless, additional studies on other ecosystem functions in grasslands proliferated swiftly, solidifying the current agreement that biodiversity promotes ecosystem functioning and multifunctionality (Hector and Bagchi, 2007). Previous BEF research has also raised new questions about the generality of mechanisms behind BEF relationships (Tilman et al., 2014; Weisser et al., 2017), specifically how different aspects of biodiversity (e.g., species, functional, and phylogenetic diversity) influence ecosystem functioning (Flynn et al., 2011) and the role of abiotic factors (e.g., drought, etc.) (Craven et al., 2016). BEF researchers have made an effort to demonstrate that the findings from controlled diversity experiments apply to real-world ecosystems and are generalizable across different types of ecosystems in response to criticism (Aarssen, 1997; Huston, 1997). BEF research has expanded into habitats other than grasslands during the last two decades, including farm fields, woods, lakes, streams, and marine environments. Though BEF dynamics vary across systems, the overall findings show that biodiversity influences ecosystem functioning (Cardinale et al., 2011; Lefcheck et al., 2015).

A better understanding of the relationship between biodiversity and ecosystem functioning will allow for more accurate forecasts of the effects of climate change on ecosystems and assist in the optimization of strategies for tackling climate change and conserving biodiversity. Currently, there are few recent reviews and syntheses on BEF research based on various approaches and perspectives (Ali, 2023; Mori et al., 2018; Scherer-Lorenzen et al., 2022; van der Plas, 2019). In this article, we used bibliometric approaches to analyze the annual publication volume, research strength, research hotspots, and future trends of the literature about BEF published in the Web of Science from 2001 to 2021. The main objective of this research is to provide significant insights into BEF's development history, current situation, and potential directions for future research, as well as to provide references for future BEF research.

Materials and methods

Data sources

The Web of Science (WoS) is the world's authoritative, comprehensive, multidisciplinary core journal database. It is worldwide famous and contains over

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13,000 authoritative and high-impact academic publications from a wide range of subjects in academia. It is regarded as one of the most important and widely utilized scientific research databases in the world. We conducted a bibliometric analysis of literature on the relationship between biodiversity and ecosystem functioning from 2001 to 2021 through the WoS Core Collection's Science Citation Index Expanded (SCI-E) scientific citation database.

We adopted the Science Citation Index Expanded (SCI-E) science citation database in the Web of Science Core Collection to conduct a bibliometric analysis of papers on BEF research from 2001 to 2021 by conducting an exact search in the SCI-E database for "TS = biodiversity and ecosystem functioning OR bio-diversity and ecosystem functioning OR bio-diversity ecosystem functioning OR biodiversity ecosystem functioning OR biodiversity-ecosystem functioning" and setting the type of document to the article. After excluding literature unrelated to the search topic, we obtained 4508 publications on BEF research. Subsequently, we downloaded and exported the retrieved literature—at least 500 articles in Txt format each time—and saved them as "download" files, which were then used as data samples for categorization and data analysis.

Data analyses

To investigate the progression of BEF in the last 20 years, we used the WoS database's literature analysis function to explore the annual number of publications, authors, institutions, countries of publication, journal distribution, and hotspots of the 4508 valid publications. The visual analysis was carried out with the VOSviewer software, and the figures were created with the software R version 4.3.0 (https://www.r-project.org).

Results

Annual number of publications

The number of publications reflects the level of attention and progress in a given topic or discipline (Chuan et al., 2016). The annual publication volume on the BEF relationship increased steadily from 2001 to 2021 (*Fig. 1*). Specifically, before 2007, BEF was in its early stages of development. The annual number of publications was less than 100, the growth trend was obscure, and the number of publications was minimal. From 2008 to 2012, the number of publications progressively grew. Following 2013, the number of articles increased rapidly. The number of publications reached a peak of 596 in 2021, which is 27.1 times more than in 2001. Particularly, the cumulative number of publications from 2015 to 2021 was 2,925, accounting for 64.88% of the total number of publications. Similarly, despite swings in publishing growth, there has been a general increasing tendency from 2001 to 2021, with an average annual growth rate of 18.5%. Overall, this demonstrates that the BEF's research intensity has dramatically increased and received significantly more attention in recent years.

Distribution of research strength

Main issuing countries

The number of publications from various countries can reflect their degree of activity and research (Zhou et al., 2019). 138 countries and regions have participated in BEF

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research over the last 20 years. The majority of the top 15 countries with the most published papers were developed countries in Europe and North America, such as the USA, Germany, England, and France (*Table 1*). Additionally, the USA had the most publications, with a total of 1,064 publications, accounting for 23.60% of all publications. Germany, England, and France were next, with 874, 630, and 627 publications, respectively. The number of publications published in the USA in the last five years is 455, accounting for 42.76% of all publications in the country and indicating a consistent growth trend. The number of publications in Germany, France, Switzerland, Portugal, and Brazil accounted for more than half of the total number of articles published in the previous five years, demonstrating that these countries have been more active in BEF research in recent years. Correspondingly, China had published 530 papers, ranking fifth in the world, while the proportion of papers published in the last five years was as high as 70.94%, ranking first among all countries with the top 15 publications. This demonstrates that, while China's BEF research lags behind Europe and the United States, it has recently become more active, showing a trend toward faster growth.

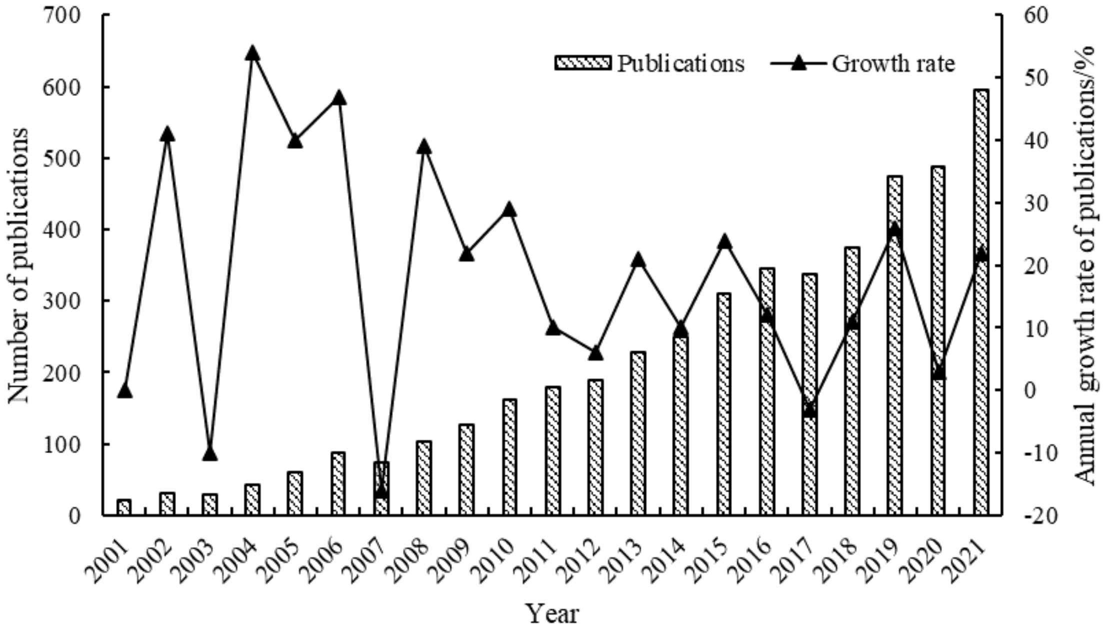

Figure 1. *Annual number of publications on the relationship between biodiversity and ecosystem functioning*

Institutions distribution

Among the top 15 institutions (*Table 2*), the Centre National De La Recherche Scientifique (CNRS) had the highest number of publications (425), followed by the French Research Universities (Udice) and the Chinese Academy of Sciences (CAS). The German Center for Integrative Biodiversity Research (iDIV), the Helmholtz Center for Environmental Research (UFZ), and the Helmholtz Association all accounted for more than 60% of their respective publication volumes in the last 5 years, demonstrating the trend of rapid development in Germany in recent years. In the last 20 years, the Chinese Academy of Sciences (CAS) has published 255 research articles

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in BEF research, ranking third internationally. The number of publications published by CAS in the last five years accounted for 66.27% of its total literature, making it second among the top 15 countries in terms of article publication. These findings indicate that CAS makes an important contribution to the field of BEF research.

Table 1. *Top 15 countries in the number of publications*

No.	Country	Number of publications	Proportion of all publications (%)	Proportion of publications in recent five years (%)
1	USA	1064	23.60	42.76
2	Germany	874	19.39	52.75
3	England	630	13.98	46.51
4	France	627	13.91	50.72
5	China	530	11.76	70.94
6	Switzerland	450	9.98	52.22
7	Spain	416	9.23	56.25
8	Canada	375	8.32	52.53
9	Australia	345	7.65	49.57
11	Netherlands	337	7.48	48.96
10	Italy	289	6.41	54.67
12	Brazil	289	6.41	69.55
13	Sweden	269	5.97	42.01
14	Belgium	189	4.19	56.61
15	Portugal	172	3.82	62.21

Table 2. *Top 15 institutions in the number of publications*

No.	Institutions	Number of publications	Proportion of all publications (%)	Proportion of publications in recent five years (%)
1	Centre National De La recherche Scientifique CNRS	425	9.43	52.00
2	Udice French Research Universities	304	6.74	50.00
3	Chinese Academy of Sciences CAS	255	5.66	66.27
4	Helmholtz Association	243	5.39	60.91
5	Swiss Federal Institutes of Technology Domain	220	4.88	52.73
6	INRAE	213	4.72	58.22
7	N8 Research Partnership	212	4.70	42.45
8	Institut de Recherche pour le Development IRD	207	4.59	57.49
9	German Ctr Integrat Biodivers Res iDIV	194	4.30	74.74
10	Conse jo Superior De Investigaciones Cientificas CSIC	180	3.99	48.89
11	Université de Montpellier	174	3.86	54.60
12	University of California System	174	3.86	37.93
13	University of Zurich	168	3.73	52.98
14	Helmholtz Center for Environmental Research UFZ	159	3.53	62.26
15	CNRS Institute of Ecology Environment INEE	157	3.48	42.68

Authors distribution

Scholars from different countries were among the top 15 authors in terms of total publications (*Table 3*), with Schmid B from the University of Zurich having the most

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publications (93 in total). Eisenhauer N from Germany's Center for Integrative Research on Biodiversity and Bruelheide H from Martin Luther University followed.

Table 3. *Top 15 authors in the number of publications*

No.	Author	Country	Number of publications	Proportion of all publications (%)	Proportion of publications in recent five years (%)
1	Schmid B	Switzerland	93	2.06	48.39
2	Eisenhauer N	Germany	90	2.00	58.89
3	Bruelheide H	Germany	71	1.57	69.01
4	Scherer-Lorenzen M	Germany	61	1.35	37.70
5	Scheu S	Germany	52	1.15	36.54
6	Weisser WW	Germany	50	1.11	32.00
7	Reich PB	Australia	46	1.02	43.48
8	Roscher C	Germany	45	1.00	42.22
9	Loreau M	France	40	0.89	57.50
10	Fischer M	Switzerland	39	0.87	46.15
11	Verheyen K	Belgium	39	0.87	69.23
12	Weigelt A	Germany	39	0.87	46.15
13	Isbell F	USA	37	0.82	51.35
14	Hillebrand H	Germany	37	0.82	32.43
15	Hector A	England	35	0.78	25.71

Furthermore, in the previous five years, the top three writers accounted for more than 45% of their total publications, demonstrating a consistent growth tendency. However, Verheyen K from Ghent University in the Netherlands had published 69.23% of the total number of publications in the last 5 years, and Loreau M and Isbell F had published more than 50%, indicating that these three scholars have recently become more involved in BEF research. Chinese scholars, such as Han Xingguo and Ma Keping from the Institute of Botany, Chinese Academy of Sciences, had also contributed to the BEF research, but there was still a gap compared to scholars from developed countries.

Journals distribution

By analyzing the top 15 journals based on the number of articles published (as shown in *Table 4*), it was discovered that the majority of these journals were focused on environmental sciences, ecology, agroforestry sciences, and biology. *Ecology*, *PLoS One*, *Oikos*, *Ecology Letters*, and the *Journal of Ecology* were the top five journals in terms of article count, with 170, 158, 122, 113, and 107 articles, respectively. Inversely, the remaining journals have fewer than 100 articles. Among the top 15 journals, *Global Change Biology* has the highest impact factor (12.3) and is ranked fourth in terms of average citation frequency (69.12 times). Additionally, *PNAS* has the highest average citation frequency (221.89 times) and was ranked second in terms of impact factor (12.0). This indicates that papers published in these two journals have a significant impact on BEF research and get more attention from peers.

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Table 4. *Top 15 journals in the number of publications*

No.	Journal	Number of publications	Proportion of all publications (%)	Five-year impact factor	Average citations per item
1	Ecology	170	3.77	5.3	95.25
2	PLoS One	158	3.50	3.8	42.13
3	Oikos	122	2.71	3.6	40.49
4	Ecology Letters	113	2.51	9.8	138.03
5	Journal of Ecology	107	2.37	6.3	58.95
6	Ecological Indicators	98	2.17	6.6	30.99
7	Science of the Total Environment	98	2.17	9.6	21.54
8	Oecologia	92	2.04	3.0	47.82
9	Global Change Biology	82	1.82	12.3	69.12
10	Functional Ecology	79	1.75	6.0	55.41
11	Journal of Applied Ecology	77	1.71	6.5	53.51
12	Marine Ecology Progress Series	77	1.71	2.6	37.55
13	Ecology and Evolution	76	1.69	3.0	20.42
14	Scientific Reports	75	1.66	4.9	32.37
15	PNAS	71	1.57	12.0	221.89

Highly cited papers

Publication citation frequency serves as a direct measure of a paper's quality, reflecting scholars' academic proficiency and global significance (Chuan et al., 2016). In this study, we created a list of the top 15 cited papers in BEF research (*Table A1*). We found that the most cited paper, authored by Mouillot D and published in *Ecology* in 2008, had accumulated remarkable 1989 citations. This paper examines the multifaceted framework of functional ecology through the lens of a novel multidimensional functional diversity index. Following closely behind, Loreau M's publication in *Nature* in 2001 on zonal selection and complementarity in biodiversity experiments has garnered 1972 citations. Ranking third is Tilman D's work in *Science* in 2001, which delves into the relationship between diversity and productivity in a long-term grassland experiment with an impressive citation count of 1549. Five of the top fifteen most cited papers were from the USA, four were from France, and the other publications were from developed countries in Europe and the United States. However, no Chinese scholars were included in this list, demonstrating Europe's and the USA's prominence and influence in BEF research.

Comparison of research strength

The number of research articles and the average citation frequency were often used to assess the scientific research strength of research subjects such as countries, institutions, journals, and authors. The number of publications might indicate the level of interest in a given topic, whereas the frequency of citations represents the influence of the publications (Zhou et al., 2019).

When considering national strength in BEF research (*Fig. 2*), countries like the USA, England, and France stand out among nations with a higher number of publications and an average frequency of citations in BEF research. Switzerland, Canada, Australia, Sweden, and the Netherlands had a relatively high average citation frequency despite having fewer publications. On the contrary, Germany and China had more articles but a lower average citation frequency. Particularly, China's average citation frequency was

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the second lowest among the 15 countries, indicating the need to enhance the quality of research outcomes. Furthermore, Spain, Italy, Brazil, Belgium, and Portugal had both below-average numbers of publications and average citation frequency, suggesting that both the quantity and quality of their research findings may be improved.

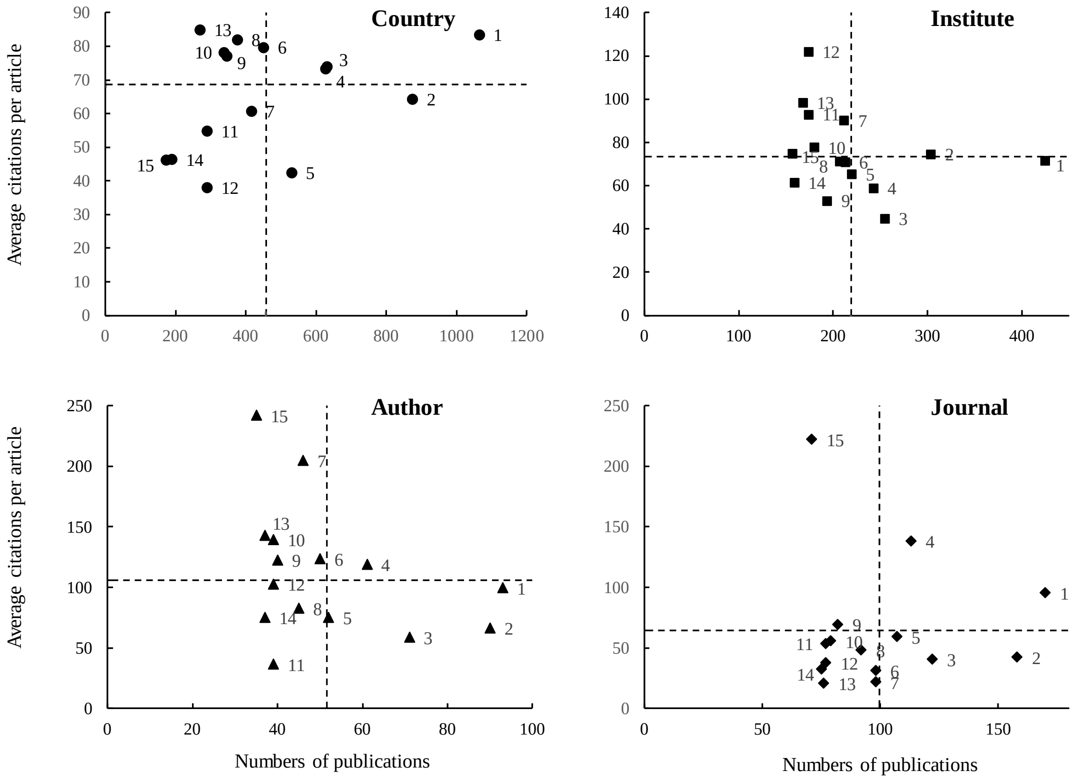

***Figure 2.** Comparison in research strength. All numbers in Figure 2 correspond to the serial numbers in Tables 1-4, respectively. The intersection point of the two dotted lines is the average value of the number of publications and the average citation frequency*

Based on the strength of institutions (*Fig. 2*), the French Research Universities (Udice) had a higher number of publications and a higher average citation frequency. Conversely, the University of California System (UCS), the University of Zurich, and the University of Montpellier had below-average publication volumes but higher citation frequencies. In particular, the UCS had an average citation frequency of 121.83 citations per article. In comparison, the Centre National De La recherche Scientifique (CNRS), the Chinese Academy of Sciences (CAS), and the Helmholtz Association had above-average publication volumes but lower citation frequencies. The Institut de Recherche pour le Development (IRD), the German Center for Integrative Biodiversity Research (iDIV), and the Helmholtz Center for Environmental Research (UFZ) had fewer publications and citations than the average. Furthermore, although ranking third in terms of the number of articles published, the Chinese Academy of Sciences (CAS) had the lowest average citation frequency, indicating space for improvement in terms of literature quality.

In terms of the research strengths of the authors (*Fig. 2*), Scherer-Lorenzen M from the University of Freiburg, Germany, had an above-average number of publications and average citation frequency in BEF research; Hector A from the

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University of Oxford, UK, had the highest average citation frequency (241.66 citations) despite having the fewest number of publications (35). Additionally, Schmid B, Eisenhauer N, and Bruelheide H had the most papers yet a lower-than-average citation frequency.

Ecology and *Ecology Letters* had a higher-than-average number of articles and an average citation frequency in terms of the research strengths of journals (*Fig. 2*). This shows that these two more influential journals were the primary disseminators of BEF research. However, *PLoS One*, *Oikos*, and the *Journal of Ecology* had more articles but a lower-than-average citation frequency. Although *PNAS* and *Global Change Biology* had fewer articles, they had a higher average citation frequency and the highest impact factor.

Analysis of research hotspots and themes

Subject areas

According to our findings (*Table 5*), the key study areas in BEF were environmental science and ecology, biodiversity conservation, and marine freshwater biology. Environmental science and ecology alone accounted for 2973 publications, accounting for 65.95% of all articles. This implies that the most important and popular research direction in the study of the relationships between biodiversity and ecosystem functioning was researched by combining the ecological environment. This subject direction was also supported by allied disciplines such as biodiversity conservation and plant sciences. Furthermore, the area includes the study of organism-organism relationships within the ecological environment, which includes disciplines such as agriculture, forestry, microbiology, and zoology, among others. Overall, previous experiments on biodiversity and ecosystem functioning have focused on grassland ecosystems, with fewer studies on other ecosystems, especially aquatic ecosystems.

Table 5. *Top 15 research directions in the number of publications*

No.	Research direction	Number of publications	Proportion of all publications/%
1	Environmental Sciences Ecology	2973	65.95
2	Biodiversity Conservation	558	12.38
3	Marine Freshwater Biology	514	11.40
4	Science Technology Other Topics	469	10.40
5	Plant Science	371	8.23
6	Agriculture	281	6.23
7	Forestry	236	5.24
8	Evolutionary Biology	218	4.84
9	Oceanography	201	4.46
10	Life Science Biomedicine Other Topics	172	3.82
11	Microbiology	122	2.71
12	Geology	100	2.22
13	Water Resources	97	2.15
14	Zoology	97	2.15
15	Physical Geography	94	2.09

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Analysis of research hotspots

The keywords in the BEF research were visualized using the information visualization software VOSviewer (*Fig. A1*). This software allowed us to identify the correlation between the keywords and represent them as circles with labels. The size of the circles indicated the frequency of each keyword's occurrence. After analyzing the visualization, we discovered that several keywords were frequently mentioned in BEF research from 2001 to 2021. These hotspots included productivity, experiment, grassland, plot, ecosystem service, management, soil, etc. These high-frequency keywords indicate the current research directions and hot topics in the field of BEF.

We conducted a comprehensive analysis of BEF research keywords from 2001 to 2021 and identified the research trends in this field during different periods (*Table A2*). Specifically, the important keywords in BEF from 2001 to 2007 were biodiversity, productivity, ecosystem function, species diversity, complementarity, ecology, stability, grassland, etc. The research during this period focused mainly on biodiversity and its productivity. From 2008 to 2012, the main keywords still revolved around biodiversity and its productivity, while new ones arose, such as conservation. These studies explored the BEF relationship and yielded significant research findings. In the years 2013–2017, the research direction continued to emphasize biodiversity and its ecosystem-functional relationship. However, new hot keywords such as ecosystem service, functional diversity, biodiversity loss, and climate change emerged. The focus of research shifted towards investigating the connection between climate change, biodiversity loss, and ecosystem functions and services. In the most recent period, 2018–2021, the hot keywords remained largely consistent with previous years, and the main research still centered around the relationship between biodiversity and ecosystem functions. However, there was an increased frequency of keywords relating to functional diversity and climate change.

In conclusion, studies in the field of BEF research have primarily focused on biodiversity and productivity, but with global species extinction, climate change, and biodiversity loss, there is a need to further define the relationship between biodiversity and ecosystem services.

Discussion and conclusions

The development of BEF in the world over 20 years

The number of publications in BEF has increased steadily from 2001 to 2021, with three distinct stages of development: initial development, stable growth, and rapid development. In the initial development stage, which lasted until 2007, the number of articles published annually was less than 100. From 2008 to 2012, the field entered a steady growth stage, with a gradual increase in the number of articles and growing attention from the academic community. Since 2013, the BEF has entered a phase of rapid development, with a significant increase in the number of publications. In 2021, the number of articles reached a peak of 596. Notably, during the period from 2015 to 2021, a total of 2,925 articles were published, accounting for 64.88% of the total number of articles. This indicates a significant increase in interest and attention towards BEF research in recent years and suggests that BEF research will continue to receive continuous attention from scholars in the future.

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In terms of research strength distribution, developed countries in Europe and the United States dominate in the field of BEF research. Countries such as the USA, England, and France had a large international influence in terms of both the quantity and quality of published literature. With 530 articles, China ranks fifth in the world. However, 70.94% of these articles were published during the last five years, putting China among the top 15 countries in terms of recent publication output. This indicates that China has the strongest development momentum in the field of BEF research. The Centre National De La Recherche Scientifique (CNRS) stands out as the research institution with the highest number of publications, with 425 articles accounting for 9.43% of the total. The French Universities Research (Udice) also ranks highly in terms of publications and average citation frequency. German research institutions have shown rapid development in this field, accounting for more than 60% of all publications over the last five years. Among the top 15 authors, Schmid B from the University of Zurich, Switzerland, has the most publications. More than half of these publications were attributed to German scholars, while the remaining contributions come from scholars in Europe and the United States. This highlights the influence of German scholars in the field of BEF research. *Ecology* was the journal that published the most academic articles in BEF research, but *Global Change Biology* and *PNAS* had the highest impact factors and the highest average citation frequency. This suggests that these two journals possessed strong influence and were able to attract significant attention from fellow scholars.

The development of BEF in China over 20 years

Research in China on the relationship between biodiversity and ecosystem functioning started later than in developed countries in Europe and the United States. While the number of publications in China was among the highest in the world, indicating a certain level of strength, there is still a significant gap compared to Europe and the United States. Currently, China is ranked 5th in the world in terms of the number of publications, with 530. The Chinese Academy of Sciences (CAS) plays a prominent role in this field and has experienced rapid development in recent years. However, Chinese scholars have not been able to enter the top 15 in terms of the number of publications. The scholars with the most publications in China were Han Xingguo and Ma Keping from the Institute of Botany, CAS, with 28 and 26 publications, respectively. Especially, Ma Keping has demonstrated a significant impact on BEF research with 20 articles published in recent years. Overall, China has shown some strength in the field of BEF research, with a more active performance in the past five years, indicating a stage of rapid growth. However, there is still a substantial disparity between the average number of citations for Chinese scholars compared to those from Europe and the United States. There is ample room for improvement in both the quality and quantity of research results compared to developed countries in Europe and the United States. With China’s continuous investment in scientific research in recent years, it is expected that BEF research will progress more quickly in the future.

Analysis of subject areas

According to our findings, previous experiments in BEF have focused on grassland ecosystems, with fewer studies on other ecosystems, especially aquatic ecosystems and forest ecosystems. Forest BEF experiments offer several advantages, such as the

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capacity to conduct experimental studies at the individual level, control density, and homogeneity, and observe changes in inter-species relationships and their interactions with the environment over time. They also allow us to conduct experimental studies at the individual level, control density and homogeneity, and observe changes in inter-species relationships and their interactions with the environment over time (Ma, 2013; Mori et al., 2017; van der Plas, 2019). Furthermore, BEF relationships are anticipated to differ across multiple trophic levels, but this subject has received less attention in terms of animal diversity, belowground biodiversity, and ecosystem multifunctionality within and across ecosystems, which needs to be thoroughly investigated to provide a strong case for the conservation of biodiversity (van der Plas, 2019).

Perspectives

Currently, biodiversity as a major determinant of ecosystem functioning and dynamics has been demonstrated in many studies (Tilman et al., 2014), however, most of these studies have focused on a single ecosystem function while neglecting the trade-offs between different functions. For instance, enhancing soil nutrient turnover can lead to the release of carbon dioxide, which can benefit crop production but may also reduce carbon storage (Wood et al., 2015). Ecosystem functions are inherently multidimensional, and biodiversity can influence multiple functions simultaneously. For example, an increase in the diversity of tree species within forests can enhance productivity, soil and water conservation, and reduction of greenhouse gas emissions. By only considering a single ecosystem function, we underestimate the significance of biodiversity (Garland et al., 2021). Consequently, some scholars have gradually realized that multiple ecosystem functions should be considered at the same time, and the concept of ecosystem multifunctionality (EMF) has been proposed accordingly.

The concept of multifunctionality was first introduced by Sanderson et al. (2004). However, Hector and Bagchi (2007) quantified the effects of plant species diversity on multiple ecosystem processes simultaneously and found that maintaining EMF requires more species than maintaining individual ecosystem functions. Therefore, Hector and Bagchi’s study can be considered pioneering research in biodiversity and ecosystem multifunctionality (BEMF). Subsequently, some studies have conducted BEMF research from the perspectives of the microscopic level and different spatial and temporal scales (He et al., 2009; Isbell et al., 2011; Zavaleta et al., 2010). At present, BEMF has become a new hot research direction in the BEF (Duffy et al., 2017; Manning et al., 2018; van der Plas, 2019). However, there are still shortcomings in the current BEMF research. For example, there is a lack of consistent criteria for selecting and measuring ecosystem functions. This makes it challenging to compare findings from different studies. Additionally, the methods used to quantify these functions have a weak mathematical basis, making it difficult to differentiate between biological and statistical factors. Furthermore, long-term studies are lacking, which makes it difficult to accurately predict the long-term response of biome structure and ecosystem multifunctionality to global changes. For instance, early studies on BEMF in grassland ecosystems had accumulated a significant amount of research results, but there have been relatively few studies conducted in forest ecosystems.

Therefore, future studies should combine field observations and controlled experiments to accumulate long-term research data. For example, two global networks, ForestGEO (https://forestgeo.si.edu, Anderson-Teixeira et al., 2015; De Cáceres et al.,

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2012; Piponiot et al., 2022; Reu et al., 2022) and TreeDivNet (https://treedivnet.ugent.be, Grossman et al., 2018; Paquette et al., 2018; Verheyen et al., 2016), contribute significantly to our understanding of BEMF mechanisms. These networks investigate BEMF at various dimensions of biodiversity, different abiotic drivers, and different spatial and temporal scales. Additionally, there are several recommendations for further research in this area. Firstly, it is important to integrate BEMF into theoretical studies such as community building, assemblage communities, and genealogical evolution. Secondly, there is a need to develop new methods for quantifying ecosystem multifunctionality, taking into account the strengths and weaknesses of existing methods and their mathematical foundations. Finally, new concepts should be applied to expand research directions, such as using biodiversity for the assessment of biodiversity conservation. In conclusion, global long-term diversity experiments can enhance our understanding of BEMF mechanisms, and a globally distributed experimental network with a common methodology is the future direction of BEMF research.

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APPENDIX

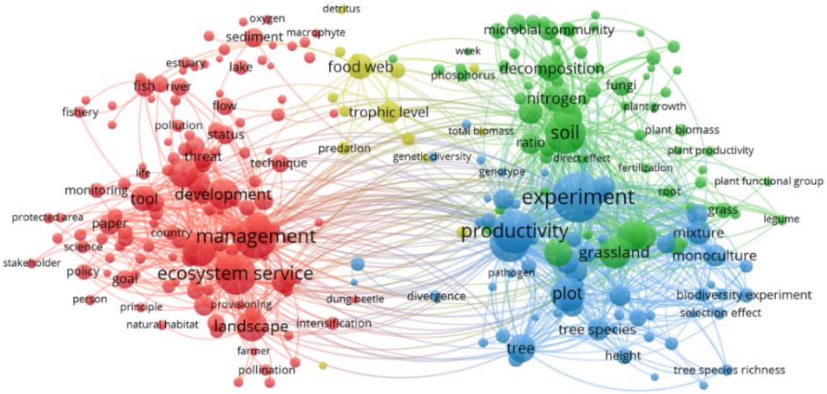

Figure A1. *Analysis of research hotspots in the field of the relationship between biodiversity and ecosystem functioning*

Table A1. *The influence of top 15 cited papers in the field of the relationship between biodiversity and ecosystem functioning during 2001-2021*

No.	Article title	Corresponding author	Country	Journal	Year	Citations
1	New multidimensional functional diversity indices for a multifaceted framework in functional ecology	Mouillot D	France	Ecology	2008	1989
2	Partitioning selection and complementarity in biodiversity experiments	Loreau M	France	Nature	2001	1972
3	Diversity and productivity in a long-term grassland experiment	Tilman D	USA	Science	2001	1549
4	Plant functional markers capture ecosystem properties during secondary succession	Garnier E	France	Ecology	2004	1462
5	Biodiversity and ecosystem stability in a decade-long grassland experiment	Tilman D	USA	Nature	2006	1317
6	Effects of biodiversity on the functioning of trophic groups and ecosystems	Cardinale BJ	USA	Nature	2006	1264
7	Novel ecosystems: theoretical and management aspects of the new ecological world order	Hobbs RJ	Australia	Global Ecology and Biogeography	2006	1255
8	Functional diversity (FD), species richness and community composition	Petchey OL	England	Ecology Letters	2002	1183
9	Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines	Ceballos G Ehrlich PR	Mexico	PNAS	2017	1157
10	Soil biodiversity and soil community composition determine ecosystem multifunctionality	van der Heijden MGA	Switzerland	PNAS	2014	1118
11	The economic value of ecological services provided by insects	Losey JE	USA	BioScience	2006	1080
12	Global human footprint on the linkage between biodiversity and ecosystem functioning in reef fishes	Mora C	Canada	PLoS Biology	2011	1078
13	Freshwater biodiversity conservation: recent progress and future challenges	Strayer DL	USA	Journal of the North American Benthological Society	2010	1049
14	Functional diversity measures: an overview of their redundancy and their ability to discriminate community assembly rules	Mouchet MA	France	Functional Ecology	2010	975
15	High plant diversity is needed to maintain ecosystem services	Isbell F	Canada	Nature	2011	968

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Table A2. *High-frequency keywords at different publication years*

Keywords (2001-2007)	**Keywords (2008-2012)**	**Keywords (2013-2017)**	**Keywords (2018-2021)**
Biodiversity	Biodiversity	Biodiversity	Biodiversity
Productivity	Diversity	Diversity	Diversity
Diversity	Ecosystem functioning	Productivity	Productivity
Ecosystem functioning	Productivity	Species richness	Ecosystem functioning
Ecosystem function	Species richness	Ecosystem functioning	Species richness
Species-diversity	Ecosystem function	Communities	Functional diversity
Richness	Communities	Ecosystem services	Communities
Communities	Species-diversity	Functional diversity	Plant diversity
Stability	Plant diversity	Ecosystem function	Patterns
Biomass	Richness	Conservation	Ecosystem services
Complementarity	Ecology	Plant diversity	Conservation
Patterns	Consequences	Biodiversity loss	Climate-change
Grassland	Complementarity	Patterns	Ecosystem function
Community	Patterns	Richness	Impacts
Species richness	Conservation	Climate-change	Responses

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