

Review

Review of the Current Status and Development Trend of Global Forest Carbon Storage Research Based on Bibliometrics

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Abstract: Forests are one of the largest terrestrial ecosystems on Earth, absorbing carbon dioxide from the atmosphere through photosynthesis and storing it as organic carbon, thereby mitigating global warming. Conducting bibliometric analysis of forest carbon storage can identify current research trends and hot issues in this field, providing data support for researchers and policy makers. This review article provides a comprehensive bibliometric analysis of global forest carbon storage research, using databases from the Web of Science Core Collection. CiteSpace software (6.2.6 version) was employed to visualize and analyze the data, focusing on key researchers, institutions, and countries, as well as major research themes and emerging trends. The main findings are as follows: (1) Since the 21st century, the publication volume in this field has been increasing, with the United States and China being the top contributors. (2) There is active collaboration among key authors, institutions, and countries, with a notable close-knit network centered around French author Philippe Ciais. This group includes nearly half of the field's authors and many of them are crucial for advancing research in this field. (3) Cluster and citation burst analyses suggest that future research will focus more on the impact of forest management policies on carbon stocks, with particular attention to the roles of northern temperate forests and mangroves in global carbon storage. These findings provide valuable insights into the current state and future directions of forest carbon storage research. This article is instrumental in elucidating the role of forest ecosystems within the global carbon cycle, evaluating the impacts of anthropogenic activities on forest carbon stocks, and informing the development of effective climate change mitigation strategies.

Keywords: forest carbon storage; forest carbon dynamics; global climate change; carbon stocks; carbon sequestration; bibliometrics; CiteSpace; research trends



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1. Introduction

With the extensive use of fossil fuels, industrial production, deforestation, and land-clearing activities by humans, a significant amount of carbon dioxide is being emitted into the atmosphere [1]. Reducing carbon dioxide emissions to mitigate regional and global climate change has become one of the most challenging issues faced by humanity [1]. In addressing the problem of global climate change, forest ecosystems have received widespread attention due to their crucial role in the global carbon cycle. Increasingly, scientists are conducting various studies to estimate the carbon storage capacity of forests [2,3]. Globally, forests cover more than 4.1 billion hectares of the Earth's land surface [4]. Through biomass, litter, organic residues, and soil organic matter, forest ecosystems store a substantial amount of carbon [2], accounting for approximately 46% of the total terrestrial carbon storage, making them the most important and irreplaceable carbon sink in terrestrial ecosystems [3]. However, the forest carbon pool is fragile; once the forest ecosystem is damaged or disturbed by human activities such as logging, a large amount of stored carbon can be rapidly released

into the atmosphere. The process of reforestation to restore this carbon is much slower compared to the release process [5,6]. Given the significant role of forest ecosystems in the carbon cycle, understanding the mechanisms by which forest ecosystems store carbon, estimating changes in forest carbon storage, studying factors affecting forest carbon storage, and examining the impact of human activities and forest management policies on carbon storage are all critical for predicting future increases in atmospheric carbon dioxide and formulating reasonable climate change mitigation policies.

The scientific literature is the objective record of knowledge, the primary form of existence and expression of science and technology, and an essential component of the scientific communication system. Studying and analyzing the scientific literature in a specific field is an important means to understand the development of that discipline [7]. Bibliometrics is a discipline that “studies the distribution structure, quantitative relationships, change patterns, and quantitative management of bibliographic information using mathematical, statistical, and other measurement methods, thereby exploring certain structures, characteristics, and laws of science and technology” [7]. Applying bibliometric methods to analyze the literature in the field of global forest carbon storage can comprehensively, systematically, objectively, and quantitatively understand the development status, overall layout, research hotspots, and predict future development trends in this field. In today’s field of bibliometrics, CiteSpace is widely used as a major visualization tool. Its powerful text mining and visualization capabilities help researchers understand collaboration networks, co-citation network structures, clustering situations, and citation bursts [8].

Building on the information outlined above, this research addresses a critical gap in the existing literature on forest carbon stocks. Despite the expanding volume of re-search in this area, there is a noticeable absence of a recent, comprehensive bibliometric analysis that captures the global research landscape. Such an analysis is essential for understanding the development history, identifying key trends, uncovering research gaps, and tracing the evolution of scientific collaboration in forest carbon stock studies.

This study is dedicated to conducting a thorough bibliometric analysis of global research on forest carbon stocks, utilizing CiteSpace. It seeks to explore the following key questions:

- (1) What are the main trends and patterns in the global research on forest carbon stocks?
- (2) Which authors, institutions, and countries are the key contributors and what are the major collaborative networks in this field?
- (3) What are the major research themes or sub-topics in forest carbon stock studies and how have they been evolved over time?
- (4) What are the current research hotspots and future research directions identified from the current literature?

2. Materials and Methods

The research procedures undertaken in this study are systematically summarized and depicted in the flowchart presented in Figure 1. To provide further specificity, we detail the process of acquiring input data from the Web of Science (WOS) Core Collection, describe the utilization of CiteSpace, and offer an explanation of the analytical methods employed in this study. This study utilizes the Science Citation Index Expanded (SCI) and Social Science Citation Index (SSCI) databases within the WOS as the data source. These databases include relevant journal articles published from the 1980s to the present (up to November 2023, the time of writing). The searching strategy employs the following Boolean query based on the WOS’s SCI expanded database operators: TS = Topic; TI = Title; AND = Conjunction keyword; OR = Keyword group connection; * = Wildcard (for singular and plural suffixes). The specific search string used is as follows: TS = Forest* AND TI = (“Carbon storag*” OR “carbon stock*” OR “carbon sink*” OR “carbon sequestration*” OR “carbon content*” OR “carbon densit*”).

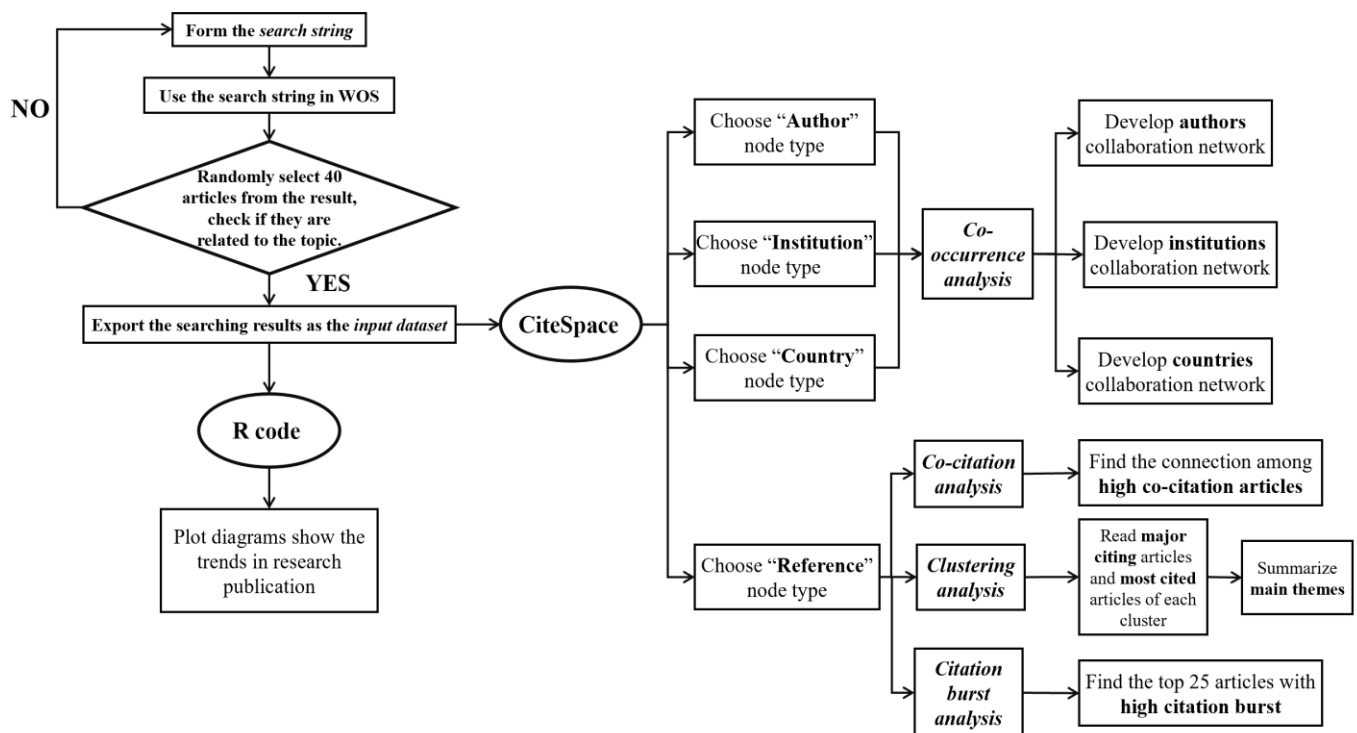


Figure 1. The overall workflow.

For the obtained searching results, we refined the selection by checking the “document type” categories of articles, review articles, conference papers, early access, and data papers, resulting in a total of 5403 documents. The content was downloaded as a “full record” plain text file. This means that there are 5403 records in this text file, each of which represents an article that meets the search string. Each record contains the title of the article, the name, institution, and country of the authors, sources, times cited count, accession numbers, keywords, hot paper, highly cited, and other article-related information. Those records were used as the input data when we used R (4.4.0 version) and CiteSpace (6.2.6 version) software.

The computer programming language R was only used to study the trends in research publications. Meanwhile, the main visualization tool used in this study is the CiteSpace software. Compared to other bibliometric analysis tools, CiteSpace has some unique advantages. Its integration of temporal analysis, citation burst detection, and sophisticated network metrics with advanced visualization capabilities make it particularly effective for identifying emerging trends and mapping the evolution of scientific fields [9,10]. These strengths enable CiteSpace to provide a more comprehensive and integrated bibliometric analysis than other visualization tools like VOSviewer, CoPalRed, Sci2, and so on [10–12]. In this study, we mainly used the functions provided by CiteSpace software to conduct the following analysis:

Firstly, we identified key researchers, institutions, countries, and their relational networks through co-citation analysis. The co-citation analysis is also known as the co-occurrence analysis. In CiteSpace, the main idea of co-citation analysis is calculated as the co-citation frequency using Equation (1) to figure out if the frequently co-cited documents are likely to be related in content. If $C(A, B)$ represents the co-citation frequency of documents A and B , then:

$$C(A, B) = \sum_{i=1}^N \delta_i(A, B), \quad (1)$$

where $\delta_i(A, B) = 1$ if both A and B are cited in the same documents i , $\delta_i(A, B) = 0$ otherwise.

Secondly, we summarized major research themes and tracked the evolution of specific topics over time through co-citation and clustering analysis. In CiteSpace, modularity Q and silhouette score are calculated to group related items into clusters. Modularity Q as

defined by Equation (2) evaluates the strength of the division of a network into clusters. For the network with m number of edges, A_{ij} is the weight of the edge between nodes i and j , k_i and k_j are the degrees of nodes i and j , c_i and c_j are the clusters to which nodes i and j are assigned, and Q is defined as follows:

$$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j), \quad (2)$$

where $\delta(c_i, c_j) = 1$ if nodes i and j are in the same cluster, 0 otherwise [10]. The silhouette score $S(i)$ for each node i is used in CiteSpace to measure the consistency of clusters, and it is defined as follows:

$$S(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}, \quad (3)$$

where $a(i)$ is the average distance between i and all other nodes in the same cluster and $b(i)$ is the minimum average distance from i to all nodes in any other cluster [10].

Thirdly, we identified research frontiers through citation burst analysis. CiteSpace uses Kleinberg's burst detection algorithm to identify sudden increases in citations [10]. The strength of a burst $B(i)$ for a citation or keyword i is defined as follows:

$$B(i) = \frac{C(i) - \mu_i}{\sigma_i}, \quad (4)$$

where $C(i)$ is the actual citation count during the burst period. μ_i and σ_i are the mean and standard deviation of citations over the entire timeline [13].

3. Results

The results presented in this section provide a comprehensive analysis of global research trends in forest carbon storage. Section 3.1 tracks the evolution of research publications in this field from 1993 to 2023, based on the data downloaded from the WOS database. In addition to the overall global publication trends, it also highlights the changes in the publication volume among the most contributing countries in this field. Secondly, the results in Section 3.2 show the collaborative networks among authors, institutions, and countries engaged in this research, identifying the key authors, influential institutions, and leading countries. Thirdly, Section 3.3 employs co-citation analysis, clustering analysis, and burst detection analysis to illustrate the research foundations, themes, and emerging frontiers in forest carbon storage research. This section also reveals the interconnection between highly cited and highly central articles, providing insights into developing research themes over time in this field.

Figures 2–4 were generated using R (4.4.0 version), while Figures 5–9 were generated using CiteSpace (version 6.2.6). It is worth noting that in the top right corner of Figures 5–9, there is a line of text indicating the storage location of the data used for the visualisations, which includes some non-English characters. However, this does not affect the information conveyed by the images. The information following “WoS” can be translated as “D:\BaiduSyncdisk\GeoHASM\PhDstudy\Year1\Bibliometrics\usingcitespace\data”.

3.1. Trends in Research Publications

The first study on forest carbon storage was published in the early 1980s. However, during the entire 1980s, the global average annual publication in this field was less than one paper. It was not until the 21st century, with increasing global attention on climate change, that research on forest carbon storage began to develop gradually. Figure 2 illustrates the global publication trends in this study field and research publications in general. The blue line shows the overall publication trends in this field from 1993 to November of 2023, as the data used for this research were downloaded in November of 2023. The red line represents the annual articles published in scientific and technical journals from 1996 to 2020, using data from Our World in Data [14]. It serves more like a reference, allowing us

to compare the trends of the blue line with the red one and determine whether the field we are interested in is gaining more attention relative to other fields. The blue line in this figure indicates a general upward trend in the number of publications, suggesting that the field of forest carbon storage has received increasing global attention. The changes in the publication volume in this field can be roughly divided into three stages. From 1993 to 1999, it was the initial development and germination stage, with few publications, accounting for less than 3% of the total. From 2000 to 2009, it was the slow growth stage, with an annual average of nearly 75 papers. Since 2010, it has entered a rapid growth stage, with a significant increase in publication volume, especially noticeable during 2012–2013 and 2020–2021. Especially when comparing the blue line in the time range from 2010 to 2017 with the red line, it can be seen that the growth in the number of publications in this study field is significantly faster and more pronounced than in the general field. In 2022, 519 related studies were published, the highest annual publication volume in this field. From January to November 2023, 473 related studies were published, and considering the monthly average, it is expected that the total publication volume in 2023 will not be lower than in 2022.

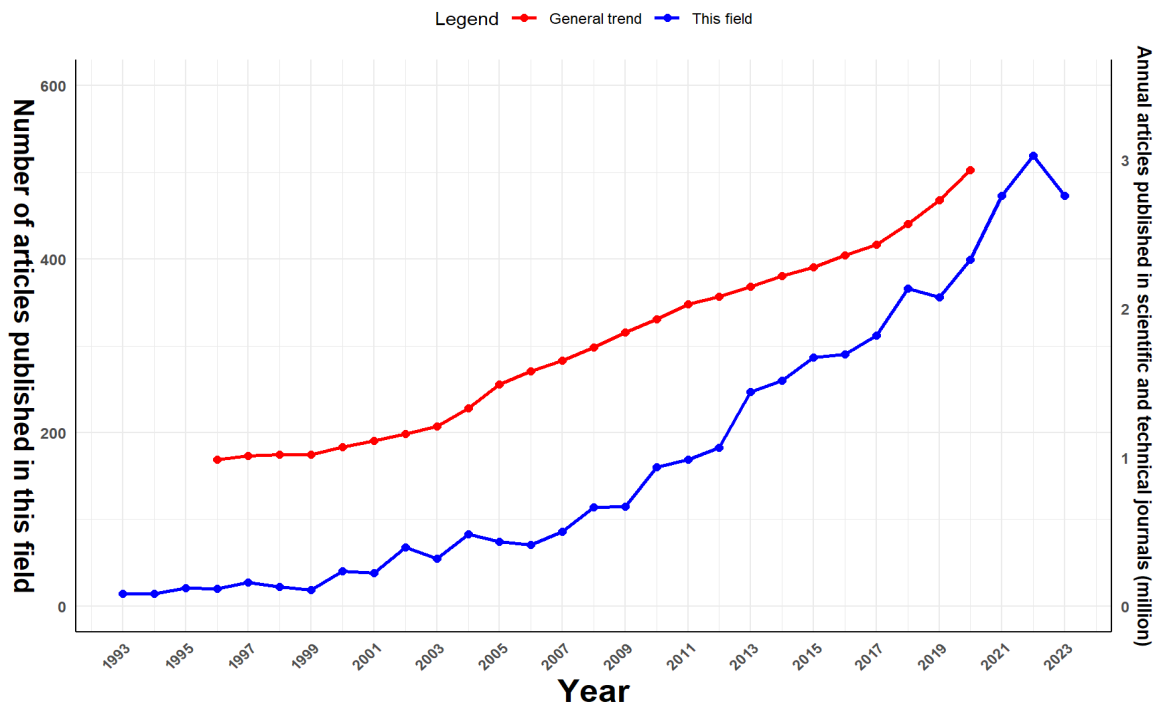


Figure 2. The global publication trends of the particular study field and all science study fields. The blue line is the annual articles published in the field of forest carbon storage research from 1993 to 2023. The red line is the reference line showing the annual articles published in scientific and technical journals worldwide. The scientific and technical journals include the journals in physics, biology, chemistry, mathematics, clinical medicine, biomedical research, engineering and technology, and earth and space sciences study fields.

Apart from illustrating the global publication trends, we also plotted Figures 3 and 4 to demonstrate the publication trends for different countries. In this part, the country for each publication is identified by the country of the first author of this publication. According to the analysis of the dataset exported from the WOS, the top five countries with the highest publication counts in the field are the United States, China, Canada, Germany, and India. Figure 3a illustrates the trend in the annual number of publications from 1993 to 2023 for these five countries in the field. To further illustrate whether the variation in the number of publications in different countries is due to the country attaching more importance to research in this field or simply because the country has more academic publications overall, Figure 3b was plotted as an additional reference. According to Figure 3a, the United States

(blue line) and China (red line) are the dominant contributors, with China's publication rate experiencing a dramatic increase, particularly after 2015, surpassing the United States in recent years. To be more specific, the United States always had the highest number of publications in this field until 2017. But the United States has shown a fluctuating downward trend in publication volume since 2014, which makes it the second in annual publications from 2018 to 2023. Considering the trend in Figure 3b, such a downward trend may be because the overall number of publications in the United States has been slowly decreasing since 2010, and may not necessarily indicate that the United States has no longer attached importance to research in forest carbon storage in the past decade. China contributed the second highest total publications in this field from 1993 to 2023. Comparing the publication curves of several other countries, it can be found that China did not have a clear advantage in the number of publications in this field before 2010. From 1993 to 2009, the growth rate of Chinese publications was relatively slow, and its average annual number of publications was similar to that of the other three countries, and significantly lower than that of the United States. However, since 2009, China's research in this field has developed rapidly, with a significant increase in publication volume, surpassing the United States in 2017. When comparing the red lines in Figure 3a,b, it can be found that before 2009, the increasing trend in the publication in this field is very similar with the trend of the general publication in China. From 2010 to 2023, the growth rate of Chinese publications in this field is more rapid than the general trend, indicating that Chinese researchers tend to pay more attention to forest carbon storage in the last decade. In contrast, the publication trends for Canada (green line), Germany (purple line), and India (orange line) are closely clustered, with the three lines frequently intersecting. These countries exhibit a more modest and steady increase in publication output compared to the United States and China, with no significant divergence between them throughout the time period analyzed. The close proximity of these three lines suggests that their contributions to this field are fairly similar in scale and have followed a comparable growth trajectory over the years.

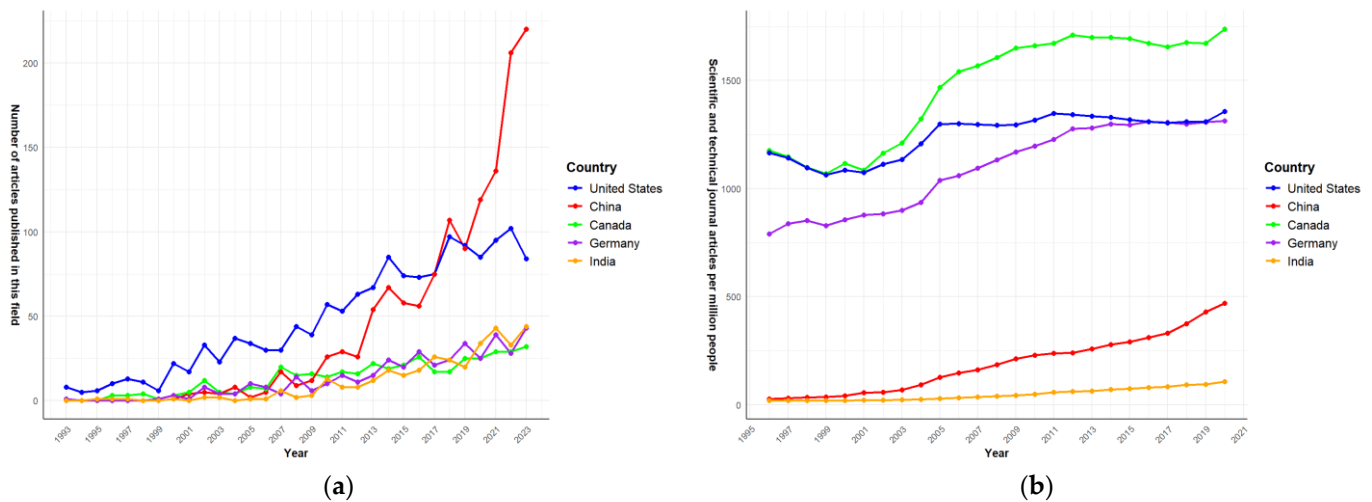


Figure 3. (a) The trend in the annual number of publications from 1993 to 2023 for the five countries with the highest publication counts in the field; (b) the trend of the number of scientific journal articles per million people in these five countries (using the data from “Our World in Data” [15]).

To analyze the relative contribution of each country in this field over the entire time period, a stack area plot was given. Figure 4 is the stacked area plot which illustrates the percentage share of the total publications in the field of forest carbon storage by the top five publishing countries over the period from 1993 to 2023. The United States (represented by the blue area) has consistently held the largest share of publications throughout the entire period, although its dominance shows some fluctuations, particularly with a noticeable decline in the mid-2000s and a gradual decrease in the recent years. China (red area)

has seen a significant and steady increase in its share of publications, especially after 2005. This increase is marked by a corresponding decrease in the relative contribution of the United States, indicating China's growing prominence in this research field. Canada (green area), Germany (purple area), and India (orange area) occupy smaller shares of the total publications. Their contributions are relatively stable, with slight increases over time, but they remain much smaller compared to the United States and China. The three countries maintain a consistent position relative to each other throughout the years, with Canada slightly ahead, followed by Germany and then India. Considering the relatively high amount of general publications Canada has, as shown in Figure 3b, this result is comparatively reasonable.

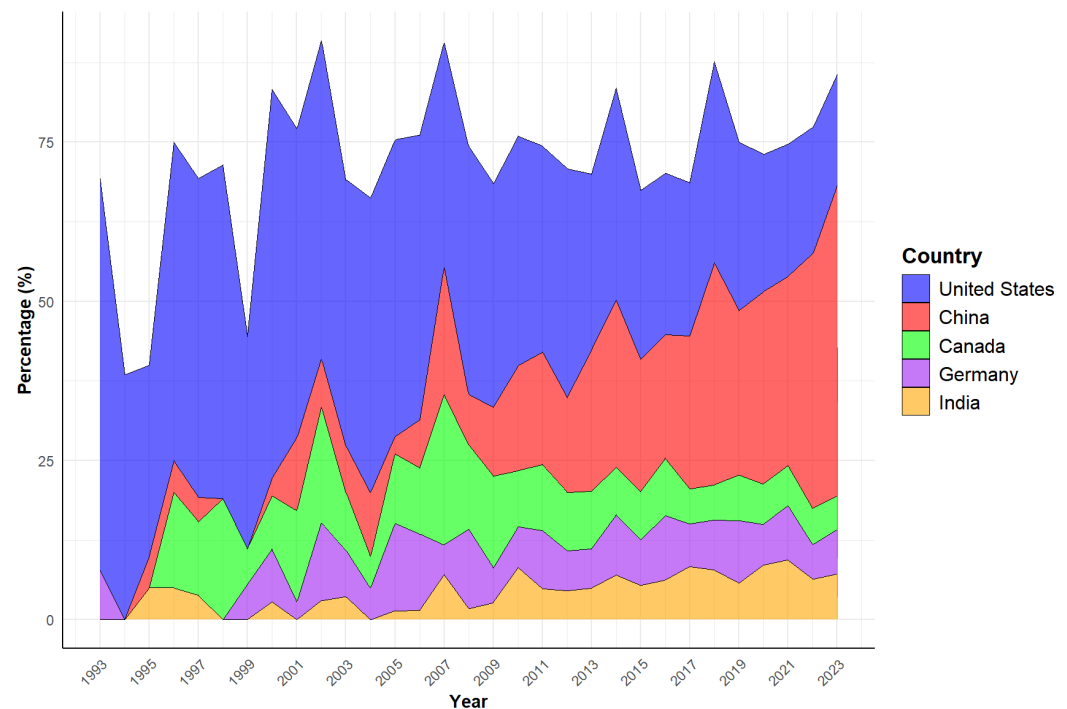


Figure 4. The percentage stacked area plot considering the five countries with the highest publication counts in the field.

3.2. Distribution of Research Forces

3.2.1. Author Collaboration Network

The bibliometric analysis of authors can reflect the trend of researchers globally participating in the field of forest carbon storage. By analyzing the distribution of author collaboration networks, co-citation frequency, citation burst strength, affiliated institutions, and countries, we can further understand the development history of this research field, identify influential core authors, and understand key research directions, significant research outcomes, and new breakthroughs.

To reflect the core authors and their relationships in the field of forest carbon storage, an author collaboration network analysis was conducted on 5403 papers. The resulting author collaboration network from CiteSpace is shown in Figure 5, where the nodes represent authors, and the size of the nodes represents the number of publications, with the larger nodes indicating more publications. The nodes are displayed in the form of annual rings, where the width of the ring for a given period represents the number of publications during that period. The links between the nodes represent collaboration between authors. According to Figure 5, it can be seen that before 2007, there were few researchers in this field, and collaboration among authors was not very active, forming only a few small author groups. However, starting from 2008, a large and closely collaborating author group formed around Philippe Ciais, with several smaller groups extending outward from Ciais as

the key node. This author group includes nearly half of the authors in this field, indicating that post-2008, the authors in this field have formed a broad collaboration network. To better illustrate the core authors in this field, the top ten authors by co-citation frequency are summarized in Table 1.

Table 1. Top 10 authors by co-citation frequency in the field.

Author	Institution	Country	Co-Citation Frequency	Number of Publications	H-Index
Philippe Ciais	Laboratoire des Sciences du Climat et de l'Environnement (LSCE)	France	25	31	22
Arun Jyoti Nath	Assam University	India	18	18	11
Lei Deng	Institute of Soil and Water Conservation, CAS; Northwest A&F University	China	16	21	13
Rattan Lal	Ohio State University	USA	16	34	25
Jingyun Fang	Institute of Botany, CAS; Peking University	China	15	25	19
Yadvinder Malhi	University of Oxford	UK	14		
Guomo Zhou	Zhejiang A&F University	China	14	25	17
Dongsheng Guan	Sun Yat-sen University	China	13	18	11
Amit Kumar	Nanjing University of Information Science and Technology; Indian Institute of Technology Roorkee	China, India	12	25	14
Gregory P Asner	Stanford University	USA	12	17	14

CiteSpace, v. 5.2.R5 (64-bit) Basic
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Timespan: 1993-2023 (Slice Length=1)
Selection Criteria: g-index (k=5), LRF=3.0, L/N=10, LBY=5, e=1.0
Network: N=253, E=269 (Density=0.0091)
Largest 5 CCs: 50 (23%)
Nodes Labeled: 1.0%
Pruning: None
Modularity Q=0.9255
Weighted Mean Silhouette S=0.991
Harmonic Mean(Q, S)=0.9571



Figure 5. Author collaboration network.

From the information in Figure 5 and Table 1, it can be observed that the author with the highest co-citation frequency is the French author Philippe Ciais, with 25 co-citations. The second is Indian author Nath Arun Jyoti, with 18 co-citations. Chinese author Lei Deng

and American author Rattan Lal are tied for third, each with 16 co-citations. Jingyun Fang is ranked fifth with 15 co-citations. Yadvinder Malhi, Guomo Zhou, Dongsheng Guan, Amit Kumar, and Gregory P Asner each have over 12 co-citations, ranking sixth to tenth. Philippe Ciais is also the author with the highest centrality, at 0.05, making him the key node in the collaboration network. From the information in Table 1 regarding authors' affiliations and countries, it is evident that 5 out of the top 10 authors are from China or affiliated with Chinese research institutions, indicating that Chinese scholars who are relatively active in this field may be more accustomed to completing research work in collaboration. In addition, considering Figure 5 and Table 1, it appears that since the 2010s, an increasing number of authors realized that forming stable and close-knit collaborative networks could positively impact their ability to publish influential articles in this field. This trend may also be driven by the rising quality standards of academic journals, which encourage authors to form larger research teams to produce high-quality articles, especially for studies on forest carbon storage at national or even global scales. Furthermore, as indicated by Figure 5 and Table 1, it is evident that relatively productive authors are more likely to develop close collaborative relationships. This pattern tends to be common across many other scientific research fields and can be attributed to various underlying factors.

Further analysis of the author collaboration network highlights several authors who deserve special attention. Firstly, French scholar Philippe Ciais is the most noteworthy, being the top author in both co-citation frequency (25) and centrality (0.05), and a key node in the collaboration network. Ciais is also one of the most important authors in this field, with the second highest number of publications (33) and the third highest H-index (18). His high productivity and reputation in this field may also be one of the reasons why he has so many collaborators. Ciais's primary collaborator and publication backbone is Changhu Peng, who has published 23 papers in this field, ranking tenth in author publication volume. Peng collaborates with other core authors Lei Deng and Guomo Zhou, connecting Ciais to their respective small collaboration networks. Ciais also collaborates with other top authors Jingyun Fang and Yadvinder Malhi, who have their small author groups. Thus, Ciais is the central figure in this field. Ciais's first paper in this field was published in 2001, focusing on long-term forest carbon storage and carbon sinks in global, European, African, and Chinese forests, and the temporal and spatial changes of terrestrial carbon sinks and their influencing factors. His paper "A large and persistent carbon sink in the world's forests" [3], cited 4489 times, is the most cited among the 5403 papers in this field. This paper, using forest inventory data and long-term field observation data, combined with statistical and process models, proposed a bottom-up estimation method for global forest carbon storage and flux, estimating the global forest carbon sink from 1990 to 2007 [3]. The article highlighted the potential of young forests to continue absorbing carbon, providing significant support for future carbon dioxide growth predictions and policy design and implementation for mitigation [3]. Ciais has been highly productive in this field over the past five years, with an average of over four papers annually, publishing eight papers in 2023 alone. Recently, Ciais has focused on changes in biomass carbon storage in northern young forests, noting that the growth of northern young forests has driven the increase in global biomass carbon storage over the past decade [16]. As a foreign academician of the Chinese Academy of Sciences and an important researcher at the Sino-French Institute for Earth System Science, Ciais collaborates closely with Chinese researchers, with eight papers over the past five years closely related to changes in China's forest carbon storage.

Secondly, Nath Arun Jyoti and Amit Kumar form a small author group, ranking second and ninth in co-citation frequency, respectively. Figure 5 shows that this group maintains internal collaboration but has almost no connections with other authors outside the group. Their work mainly focuses on estimating forest carbon stocks and their changes in India and the Himalayan region, with most collaborators also from India, aligning with the observation in Figure 5. Kumar, a relatively young author, earned his PhD in 2017 and began publishing extensively in this field in 2020, which might explain the lack of a broader collaborative network.

Thirdly, American scholar Rattan Lal ranks fifth in co-citation frequency. Lal's research primarily addresses soil organic carbon and soil carbon sequestration in agroforestry systems. Despite his high co-citation frequency and citation burst strength, Lal has not formed a collaborative network. This can be explained by analyzing his publications, which reveal that Lal typically collaborates with no more than three co-authors per paper, with no frequent collaborators. One-fifth of his works are solely authored.

Lastly, Chinese scholar Dongsheng Guan, ranking eighth in co-citation frequency, also lacks a clear collaborative network in Figure 5. Guan's first paper in 2008 used the continuous biomass expansion factor method to estimate forest carbon stocks and dynamics in the Pearl River Delta [17]. However, there was a period of low or no publications in this field until 2016, when he began consistently publishing again. Guan focuses on changes in carbon stocks in mangrove ecosystems, primarily in South China. Recent review articles have noted that research on mangrove ecosystems' carbon stocks has been relatively sparse and only recently gained attention [18]. Therefore, it is reasonable to infer that Guan, working in a relatively niche area and having only recently begun prolific output, has not yet formed a fixed collaborative team, and hence has no clear collaborative network.

3.2.2. Institution Collaboration Network

Analyzing the collaboration network among institutions can further reveal the distribution of research forces in the field of forest carbon storage. The institutional collaboration network is shown in Figure 6, where the nodes represent institutions, and the size of the nodes indicates the number of publications, with the larger nodes representing more publications. To make the figure easier to read, only nodes with a co-citation frequency greater than 30 were shown in the figure. Nodes with a purple ring indicate a centrality greater than 0.1, meaning these nodes are highly collaborative and serve as key points in the cooperation network. There are only three nodes with a purple ring in Figure 6, signifying centrality over 0.1: the Chinese Academy of Sciences (CAS), the French National Centre for Scientific Research (CNRS), and the United States Department of Agriculture (USDA). The links between the nodes represent collaborative relationships between institutions. The more collaborations an institution has, the higher its degree of cooperation with others. From Figure 6, it is evident that collaboration among research institutions in this field is highly active. Table 2 summarizes the top ten institutions in terms of publication volume and centrality.

Table 2. Top 10 institutions ranked by number of publications in the field.

Institution	Country	Number of Publications	Centrality
Chinese Academy of Sciences (CAS)	China	529	0.14
United States Department of Agriculture (USDA)	USA	291	0.12
United States Forest Service (USFS)	USA	241	0.1
University of the Chinese Academy of Sciences (UCAS)	China	175	0.01
University of California	USA	121	0.08
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	China	121	0.04
French National Centre for Scientific Research (CNRS)	France	92	0.14
Northwest A&F University	China	89	0.01
French National Institute for Agriculture, Food, and Environment (INRAE)	France	83	0.03
Natural Resources Canada	Canada	76	0.05

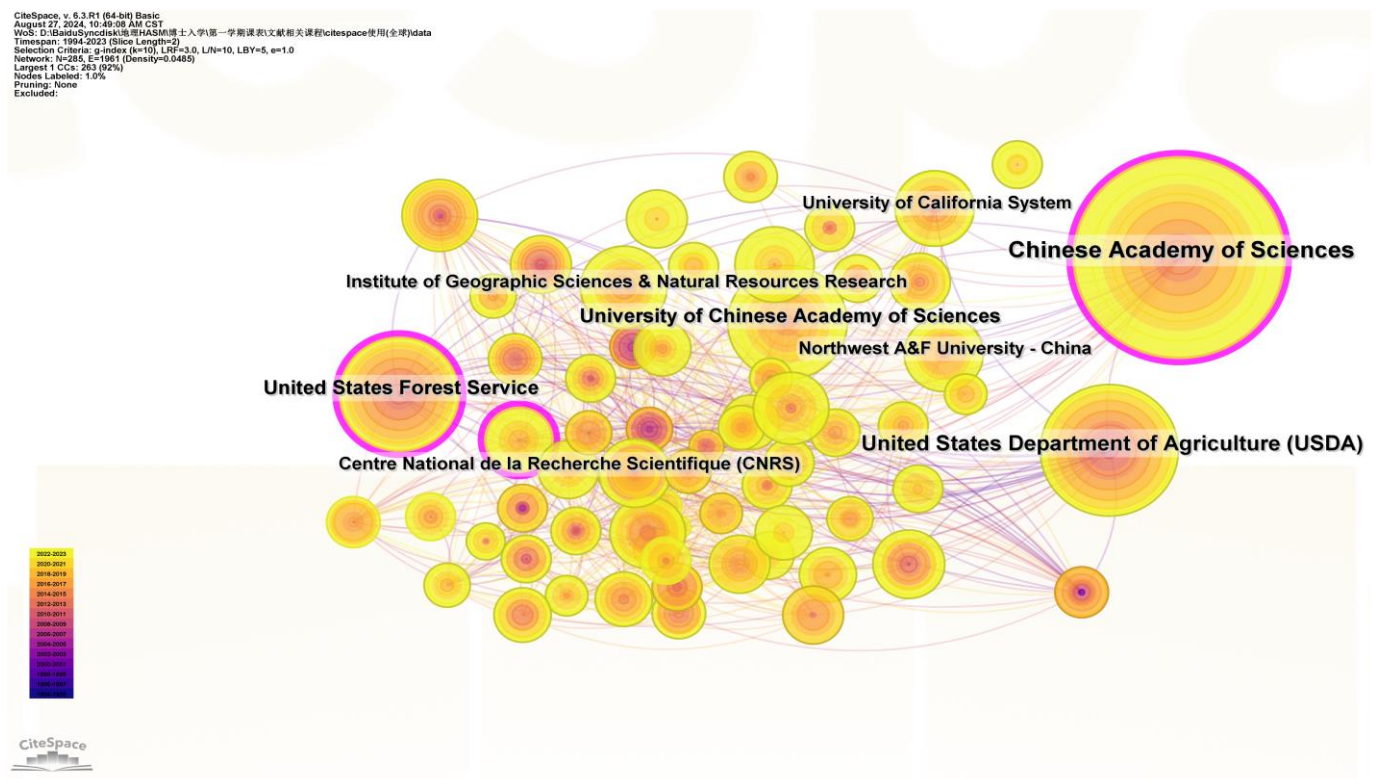


Figure 6. Institution collaboration network.

From Figure 6 and Table 2, it can be seen that the institutions with the highest publication volumes are the CAS, USDA, and USFS. The CAS is the leading institution, with the highest number of publications (529) and centrality (0.14), indicating its crucial role in the collaboration network. The CAS collaborates extensively with numerous other institutions, forming a dense network. The University of the Chinese Academy of Sciences (UCAS) and the Institute of Geographic Sciences and Natural Resources Research, both affiliated with the CAS, rank fourth and sixth, respectively, due to their close relationship with the CAS. Additionally, Northwest A&F University, which ranks seventh, is co-administered by the Institute of Soil and Water Conservation under the CAS and the Ministry of Water Resources, indicating a close relationship with the CAS. This implies that all top ten collaborating Chinese research institutions are closely linked with the CAS. Given the high co-citation frequency and centrality of the CAS, it can be concluded that this institution is highly active in collaborations with other research institutions in this field. It has produced a significant amount of research output, demonstrating its leadership in this research area within China and its important role globally. In addition, such a close connection between other Chinese institutions and CAS can also be found when we studied the collaboration among institutions for general scientific study. This also may indicate that CAS plays a very important role in scientific research in China.

3.2.3. International Collaboration Network

The international collaboration network for countries and regions involved in forest carbon storage research is illustrated in Figure 7. This network comprises 142 nodes and 1830 links. The top five countries and regions in terms of publication volume are the United States, China, Canada, Germany, and India. Among them, the United States leads with 1485 papers, accounting for 27.5% of the total, and shows active international interactions with a centrality of 0.18. Combining this finding and the finding shown in Section 3.1, it may be possible for us to conclude that American scholars maintain a leading position in this research area.

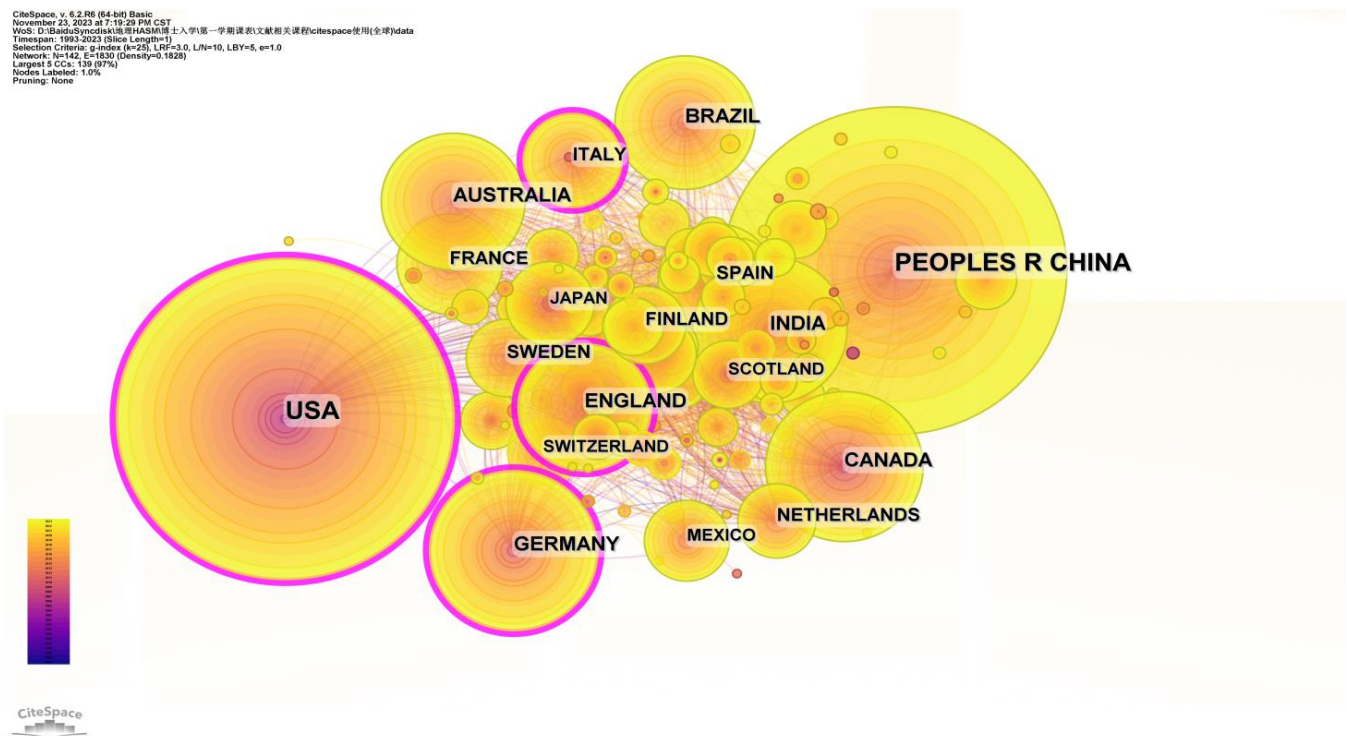


Figure 7. International collaboration network.

China ranks second with 1339 papers, representing 24.8% of the total, slightly behind the United States. However, China exhibits relatively low international cooperation compared to Western countries, with a centrality of less than 0.05. This suggests that while China has made significant contributions to this research field on an international level, there is still a need to enhance international collaboration.

Germany, the United Kingdom, and Italy also play significant roles in the collaboration network. Additionally, the color changes of nodes and links indicate that collaborative research on forest carbon storage among major countries started after 2010.

3.3. Research Foundation and Frontiers

3.3.1. Co-Citation Analysis

The development and research activities in science inherently involve the mutual citation of the scientific literature [19]. Citation analysis can uncover the structural dynamics within a scientific field, as well as interdisciplinary relationships, revealing the evolution of the field, its foundational research, and emerging hotspots [19]. When two or more documents are cited together by subsequent publications, they share a co-citation relationship. The process of exploring these relationships within a set of documents is known as co-citation analysis [8]. This method, proposed in 1937, has been widely used to elucidate the inherent connections and patterns among scientific documents and to map the dynamic structure of scientific development [19,20]. Using CiteSpace software, this study conducts a co-citation and clustering analysis on 5403 documents in the field of forest carbon storage, quantifying and analyzing their academic impact based on co-citation frequency and centrality.

Figure 8 illustrates the structural relationships among multiple documents. The upper part of the figure shows a cluster of document nodes connected by blue links, corresponding to the period from 1993 to 1998. The center-left part features nodes connected by deep purple links, linked to central red nodes, representing the period from 1999 to 2004. Light purple links indicate connections from 2005 to 2010. Most links are red, orange, and yellow, indicating that the majority of co-citation relationships occurred after 2011, especially after 2017, reflecting a significant increase in global publications on forest carbon storage. Five

documents have a co-citation frequency greater than 100, listed in descending order: R Core Team (2019) [21], Batjes (2014) [22], Pan (2011) [3], Pörtner (2022) [23], and Chave (2014) [24], with frequencies of 380, 203, 190, 158, and 101, respectively.

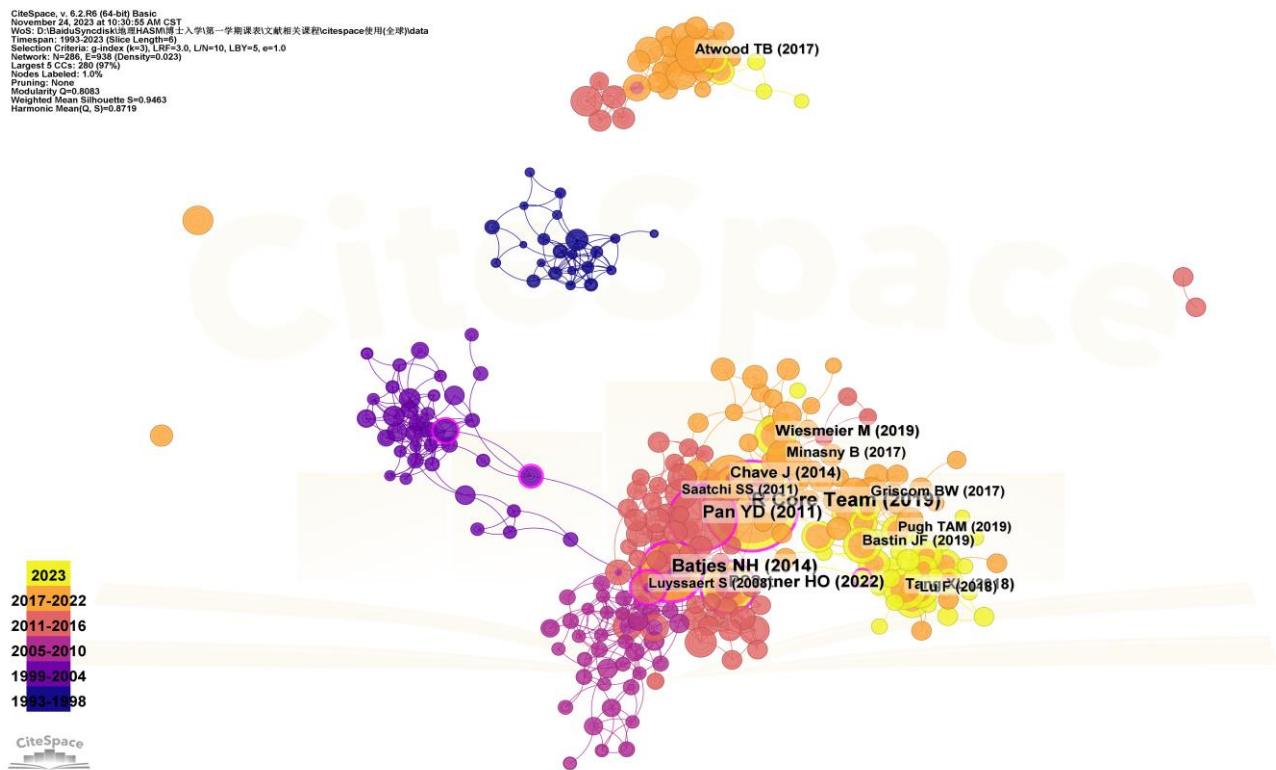


Figure 8. Co-citation and high centrality article hybrid network.

Table 3 lists eight documents with a centrality of 0.1 or higher. In order of centrality, their authors are Batjes (2014) [22], R Core Team (2019) [21], Post (2000) [25], Pörtner (2022) [23], Yao (2018) [26], Houghton (1999) [27], Pan (2011) [3], and Luyssaert (2008) [6]. Four of these documents also rank among the top five in co-citation frequency, indicating their pivotal role in the development of forest carbon storage research. Notably, R Core Team (2019) [21] is related to the use of the R language, highlighting the significant role of statistical methods and data analysis in recent forest carbon storage research. Additionally, the authors of Pan (2011) [3] and Luyssaert (2008) [6], both discussed in Section 3.2.1, include Philippe Ciais, demonstrating his substantial contributions to this field and the foundational nature of his work for subsequent studies.

Table 3. The information table for high-centrality articles.

Centrality	Article Information	DOI	Cluster Number
0.53	Batjes NH, 2014, EUR J SOIL SCI, V65, P10 [22]	10.1111/ejss.12114, 2	7
0.35	R Core Team, 2019, R LANG ENV STAT COMP, V0, P0 [21]	None	4
0.29	Post WM, 2000, GLOBAL CHANGE BIOL, V6, P317 [25]	10.1046/j.1365-2486.2000.00308.x	3
0.24	Pörtner HO, 2022, CLIMATE CHANGE 2022, V0, P0 [23]	10.1017/9781009325844	1
0.18	Yao YT, 2018, SCI BULL, V63, P1108 [26]	10.1016/j.scib.2018.07.015	0
0.17	Houghton RA, 1999, SCIENCE, V285, P574 [27]	10.1126/science.285.5427.574	3
0.15	Pan YD, 2011, SCIENCE, V333, P988 [3]	10.1126/science.1201609	2
0.11	Luyssaert S, 2008, NATURE, V455, P213 [6]	10.1038/nature07276	1

3.3.2. Research Field Clustering and Content Analysis

Using CiteSpace to perform co-citation clustering analysis on all the literature related to forest carbon stocks reveals the relationships and common themes among the documents in this field. The results of the clustering analysis are shown in Figure 9, which includes 266 nodes and 938 links in the co-citation network. After clustering analysis with CiteSpace, 11 clusters were identified. Figure 9 displays the eight largest clusters, labeled with log-likelihood ratio (LLR) tags. The effectiveness of clustering can be evaluated using the modularity and silhouette parameters located in the upper-left corner of the image [8]. Generally, a modularity (Q value) greater than 0.3 indicates a significant clustering structure, while a silhouette (S value) greater than 0.5 suggests that the clustering results are convincing [28]. In this case, the Q value is 0.8083, exceeding 0.3, and the average S value is 0.9463, surpassing 0.5, indicating that the clustering results shown in Figure 9 are both structurally significant and persuasive.

The following section will elaborate and analyze the research field by dividing it into four key themes based on the clustering structure displayed in Figure 9, the content of the key cited literature in each cluster, and their interconnections. More specifically, when identifying these four key themes, the clustering relationships and labels presented in Figure 9 were the primary considerations. Additionally, the main content of the highly cited and high-centrality literature within each cluster was also taken into account, along with the connections between these key works. The analysis will primarily focus on the highly cited or central literature, which provides the knowledge foundation for each theme. The recent highly cited literature will also be considered, as it reflects the current research hotspots in the field.

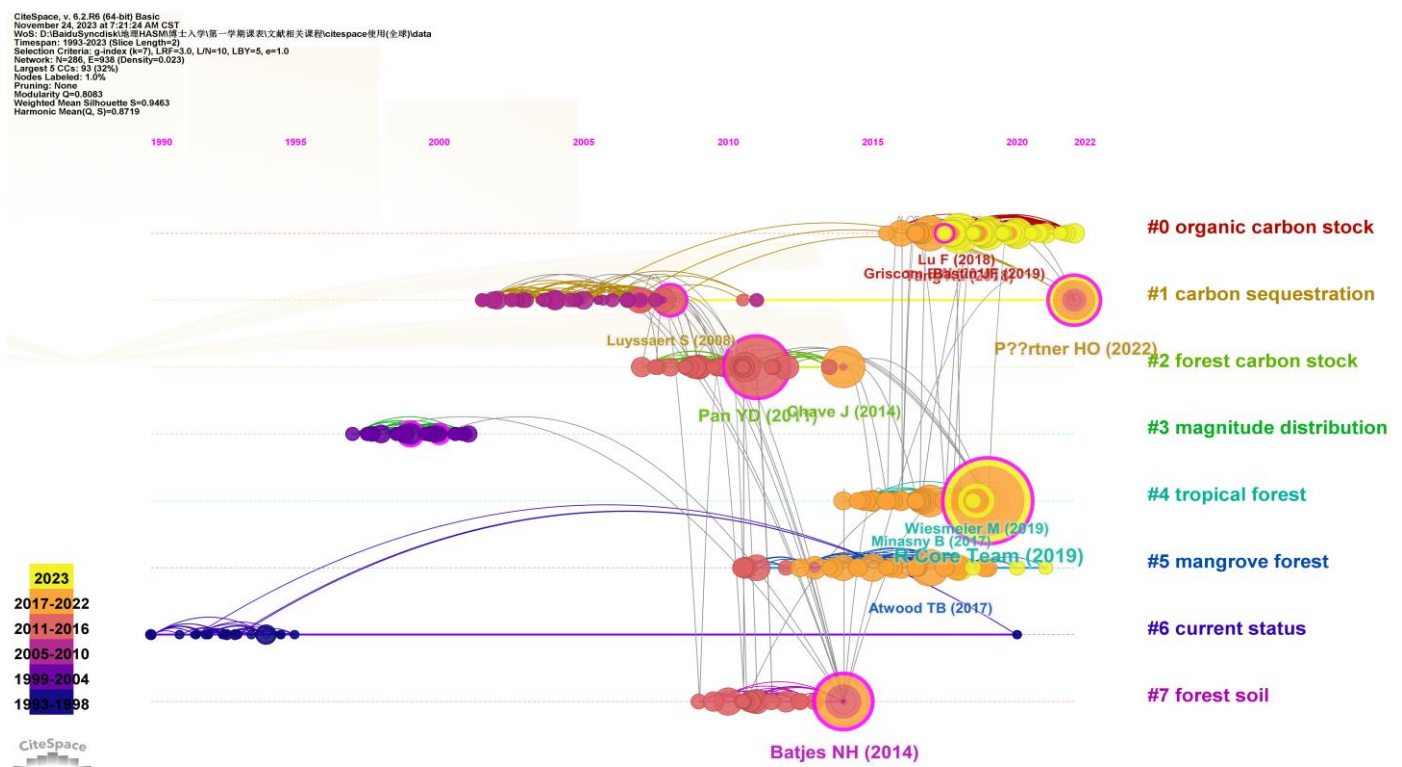


Figure 9. Timeline view of co-citation clusters in the literature on forest carbon storage. Note: Two question marks appear in the top left corner of the image, which is due to CiteSpace's inability to recognise the name of one of the authors. The corresponding content is Pörtner and the corresponding article is [23] of the reference list.

Theme 1: Estimation and Analysis of Forest Carbon Stocks and Influencing Factors. This theme includes clusters #0 (Organic Carbon Stock), #2 (Forest Carbon Stock), and #4

(Tropical Forest), encompassing a total of 124 nodes. The carbon stocks in forest ecosystems involve several components, with the two primary types being biomass carbon and soil carbon [2]. This theme addresses the estimation of forest carbon stocks from the perspectives of forest vegetation biomass carbon and forest soil carbon. Cluster #2 primarily corresponds to forest vegetation biomass, while Cluster #4 pertains to forest soil carbon. Cluster #0 represents a combination of both components, focusing on long-term and large-scale estimations and predictions of forest carbon stocks and total carbon sinks. In terms of temporal and relational aspects, the literature related to Cluster #2 appears earlier, and publications after 2010 are linked to those in Cluster #4. The literature in Cluster #0 appears later, building upon the previous two clusters and showing close connections with Cluster #4.

For estimating forest biomass carbon stocks, the most cited and central paper is Pan (2011) [3]. This study estimates global forest biomass carbon stocks from 1990 to 2007, detailing the variations in biomass carbon stocks over time and space, and identifying major risks to maintaining substantial global carbon sinks [3]. Other significant citations in this area are strongly related to Pan (2011) [3], extending and refining the methods for estimating forest biomass carbon stocks. Notably, research on carbon stock estimation in tropical regions is particularly prominent, with studies by Lewis (2009) [29], Saatchi (2011) [30], Baccini (2012) [31], and Chave (2014) [24] focusing on tropical forests. Besides remote sensing and field data integration, Chave (2014) [24] improved the allometric model for estimating aboveground biomass in tropical forests by including variables such as tree diameter, total height, and wood density. This model, which accounts for different vegetation types in the tropics, enhanced the accuracy of biomass carbon stock estimates [24].

For estimating forest soil carbon stocks, the key cited literature often focuses on accurately estimating soil organic carbon stocks, with many studies concentrating on tropical forests. Remote sensing-based soil covariates and machine learning ensemble models are commonly used [32,33]. R language, often used in these estimations, has a highly cited reference manual by the R Core Team [21]. Additionally, Wiesmeier (2019) [34] developed a set of indicators for soil organic carbon storage by identifying measurable biological or abiotic characteristics at various spatial scales, providing a rapid method for estimating and predicting soil organic carbon storage. Since 2016, research in this theme has increasingly considered both biomass and soil organic carbon storage to assess changes in forest ecosystem carbon stocks over long time scales [35], with some studies forecasting future forest carbon sequestration capabilities [26,36]. Notably, the recent representative literature in this theme has emerged from Chinese authors, with a shift in focus from tropical regions to China and temperate forests. Representative studies include Tang (2018) [37], Lu (2018) [38], and Yao (2018) [26], with Yao (2018) not only estimating carbon stocks in Chinese forests but also predicting forest biomass carbon stocks up to the end of 2040 [26].

Based on these existing studies, the forefront of research in this theme focuses on analyzing the factors affecting soil carbon storage and the impact of forest management practices on future forest carbon stocks. Li (2020) [39] and Hofhansl (2020) [40] found that forest species diversity influences soil carbon storage, with Li (2020) [39] also identifying the impact of climate factors and forest floor litter carbon-to-nitrogen ratios on soil carbon storage. In terms of forest management, Mayer (2020) [41] summarized the effects of 13 common forestry management practices on soil organic carbon storage, while Cai (2023) [42] assessed the changes in forest vegetation and soil carbon stocks under different climate scenarios for China's afforestation and reforestation projects.

Theme 2: Impact of Human Activities on Forest Carbon Stocks. This theme includes clusters #1 (Carbon Sequestration), #3 (Magnitude Distribution), and #7 (Forest Soil), totaling 97 nodes. Research in this theme primarily focuses on the effects of deforestation and land use changes on soil organic carbon stocks, as well as the impact of reforestation on soil carbon stocks after forest cutting. Clusters #1 and #3 emerged earlier and cover a

broader range, focusing on changes in soil carbon stocks due to land use changes, while Cluster #7 narrows down to the effects of deforestation on soil organic carbon storage and the recovery of soil organic carbon stocks post-reforestation. Clusters #1 and #3 provide the foundation for research in Cluster #7.

Around the year 2000, significant studies by Houghton (1999) [27], Houghton (1999) [43], and Post (2000) [25] quantified carbon release from different land use changes, highlighting the substantial impact of deforestation and the conversion of forests to agricultural land on soil carbon stocks. Houghton (1999) [43] collected land use and deforestation data to model carbon changes, providing crucial insights into the effects of human activities on global carbon cycles. Subsequently, studies by Murty (2002) [44] and Lal (2005) [2] focused on soil carbon changes following the conversion of forests to agricultural land, both concluding that such land use changes reduce soil carbon stocks over long time scales. Murty (2002) [44] analyzed factors causing soil carbon stock changes and the impact of different tillage and farm management practices.

After 2008, research in this theme began comparing soil organic carbon stock changes in primary forests, converted agricultural lands, and reforested lands, emphasizing the importance of primary forests. Studies by Luysaert (2008) [6], Don (2011) [45], and Poeplau (2011) [5] highlighted the critical role of primary forests in carbon storage, noting the rapid carbon release after forest degradation and the slow process of carbon storage recovery through reforestation. Poeplau (2011) [5] described forest soil organic carbon stocks as a fragile “slow storage, fast release” carbon pool.

Recent research in this theme has focused on changes in carbon stocks due to reforestation after deforestation and agroforestry systems. Bárcena (2014) [46] examined soil carbon stocks and influencing factors in reforestation, finding that the recovery process is slower in Northern Europe compared to tropical and temperate regions, with forest age, prior land use, forest type, and soil depth affecting carbon storage capacity. Lorenz (2014) [47] analyzed the capacity of agroforestry systems to increase soil carbon storage, highlighting its positive impacts on sustainable agriculture and environmental protection.

Theme 3: Mangrove Carbon Stocks. This theme corresponds to Cluster #5 (Mangrove Forest), encompassing 31 nodes. Mangroves, growing in coastal wetlands, have a unique growth environment and vegetation structure that results in high biodiversity [48], making mangrove carbon stock studies distinct from other forest ecosystems. The most cited early literature in this theme is Donato (2011) [49], which addressed the challenges of quantifying mangrove soil carbon stocks and provided a process for estimating carbon stocks based on tree and deadwood biomass, soil carbon content, and depth. The study highlighted the high carbon density of mangrove ecosystems and their crucial role in carbon cycling and climate regulation [49]. Later high-impact studies by Murdiyarso (2015) [50], Atwood (2017) [51], Sanderman (2018) [52], and Hamilton (2018) [53] expanded on this research, offering more detailed regional data.

The most significant recent study in this theme is Kauffman (2020) [48], which estimated the total global carbon stocks in mangrove ecosystems and identified climate, soil depth, and vegetation structure as key factors influencing mangrove carbon stocks. This study provides valuable support and reference for developing climate change mitigation policies.

Theme 4: Existing Research Discrepancies. This theme corresponds to Cluster #6 (current status), comprising 22 nodes. Early research in this theme emerged in the late 20th century when there was significant debate on whether forest ecosystems were carbon sources or sinks [4,54], and a substantial portion of the global carbon budget remained unexplained [55]. Articles in this theme aimed to identify and address these research discrepancies [54,55], guiding further investigation into forest ecosystems' roles in the global carbon cycle [4,54] and emphasizing the importance of forests in carbon storage [56].

Foundational papers include Johnson (1992) [54], Kauppi (1992) [55], and Dixon (1994) [4]. Kauppi (1992) [55] refuted the prevailing hypothesis of non-tropical forests as neutral in carbon release and absorption, using European forest data to highlight the signif-

icance of forest biomass in carbon storage. Turner (1995) [57] and Huntington (1995) [58] further emphasized forest ecosystems' potential as significant carbon sinks through analyses of U.S. Forest data. This theme primarily pointed out unresolved issues and contradictions, and by the early 21st century, the debate over forests as carbon sources or sinks had largely been resolved. Consequently, few new papers have been categorized under this theme post-2000, with Schlesinger (2020) [59] being a notable exception, updating a comprehensive book on Earth's biogeochemistry relevant to this theme.

3.3.3. Research Frontiers

To identify papers within specific years that experienced a sudden increase in citation frequency, revealing deeper developments and emerging research frontiers in the field, the burst detection algorithm as demonstrated in Section 2 is used. Table 4 presents the top 25 articles with the highest burst intensities and their corresponding burst periods. The last row represents the timeline from 1993 to 2023 where the red part indicates the burst period.

Table 4. Top 25 articles with the strongest citation bursts. The final column of the table represents a timeline from 1993 to 2023. The dark green colour indicates the period before the article was published, light green represents the period after the article was published but before or after a citation burst occurred, and red signifies the period during which the article experienced a citation burst.

Articles	Strength	Begin	End	1993–2023
Houghton, 1999 [27]	16.84	1999	2004	
Jandl, 2007 [60]	22.7	2007	2016	
Magnani, 2007 [61]	20.94	2007	2016	
Luyssaert, 2008 [6]	30.7	2008	2016	
Canadell, 2008 [62]	17.46	2008	2016	
Pan, 2011 [3]	83.8	2011	2016	
Saatchi, 2011 [30]	22	2011	2016	
Donato, 2011 [49]	20.11	2011	2016	
Laganière, 2010 [63]	19.99	2011	2016	
Schmidt, 2011 [64]	19.12	2011	2016	
Lewis, 2009 [29]	18	2011	2016	
Keith, 2009 [65]	16.96	2011	2016	
Don, 2011 [45]	16.53	2011	2016	
Batjes, 2014 [22]	23.47	2014	2022	
Chave, 2014 [24]	44.67	2014	2022	
Griscom, 2017 [66]	23.19	2017	2023	
Atwood, 2017 [51]	20.91	2017	2023	
Murdiyarso, 2015 [50]	20.78	2017	2022	
Alongi, 2014 [67]	19.61	2017	2022	
Minasny, 2017 [68]	18.72	2017	2023	
Tang, 2018 [37]	22.6	2018	2023	
Wiesmeier, 2019 [34]	22.18	2019	2023	
R Core Team, 2019 [21]	21.11	2019	2023	
Bastin, 2019 [36]	20.58	2019	2023	
Mayer, 2020 [41]	20.08	2020	2023	

The paper with the strongest citation burst is by Pan et al. (2011) [3], with a burst intensity of 83.8, occurring from 2011 to 2016. This paper is also the most cited in the WOS database within this analysis. It includes contributions from the two key authors mentioned in Section 3.2.1, Philippe Ciais and Jingyun Fang. Utilizing forest inventory data and long-term ecosystem carbon research, the study estimated global forest carbon stocks to be 861 ± 66 Pg, with about 44% stored in soil up to 1 m depth and 42% in aboveground and belowground biomass. The study also estimated that the global forest carbon sink was 2.4 ± 0.4 Pg of carbon per year from 1990 to 2007 [3]. It highlighted significant variations in carbon sinks across regions and time periods, with temperate forest carbon sinks increasing by 17% from 2000 to 2007, while tropical forest carbon absorption decreased by 23% due

to deforestation [3]. Overall, this research underscores the importance of global forests as carbon sinks and provides critical estimates for different regions and biomes, offering valuable references for future carbon management and climate change policies.

The second highest burst intensity is associated with the paper by Chave et al. (2014) [24], with a burst intensity of 44.67 from 2014 to 2022. This paper improved existing models by analyzing a global dataset of tree measurements from 58 sites, incorporating tree diameter, total height, and wood density as covariates, to create an allometric model for estimating the aboveground biomass of tropical trees [24]. This model enhances the accuracy of tropical forest biomass estimates, crucial for assessing forest carbon stocks and formulating climate change mitigation policies and measures to reduce deforestation and degradation. The paper's sustained citation burst over eight years indicates broad recognition and continuous use in the field.

Two papers had the longest burst periods, spanning nine years from 2007 to 2016: Jandl et al. (2007) [60] and Magnani et al. (2007) [61]. Jandl et al. (2007) [60] focused on the effects of forest management activities, such as logging, thinning, fertilization, drainage, species selection, and natural disturbance control, on soil carbon stocks. The study emphasized that proper forest management can promote soil carbon accumulation, which is significant for mitigating climate change and achieving carbon sequestration goals [60]. Magnani et al. (2007) [61] examined the carbon stocks of northern forests, demonstrating that boreal forests, particularly coniferous forests, serve as substantial carbon sinks, playing a crucial role in the global carbon cycle. The study also highlighted the notable impacts of increased atmospheric CO₂, rising temperatures, changes in management practices, and nitrogen deposition on the carbon balance of established northern temperate forests [61].

The most recent paper to exhibit a citation burst is by Mayer et al. (2020) [41], with a burst intensity of 20.08, still ongoing since its publication in 2020. This paper, related to Jandl et al. (2007) [60], provides a more detailed and in-depth analysis of the effects of 13 common forestry management practices on forest soil organic carbon (SOC) stocks [41]. It highlights the negative impact of logging on SOC, notes that conversion from primary to secondary forests generally decreases SOC, especially if the land was previously used for agriculture, and suggests that increasing tree species diversity may positively influence SOC in temperate and subtropical forests [41]. The findings are crucial for guiding forest management and ecosystem protection, providing a scientific basis for sustainable forestry management and soil conservation to promote ecosystem health and mitigate climate change.

Additionally, it is noteworthy that the papers with the longest burst periods and the most recent burst both address the impact of forest management practices and land use changes on forest carbon stocks, indicating that this topic has been a long-standing and significant research focus in the field of forest carbon stock studies.

4. Discussion

The analysis above reveals that the research field of forest carbon stocks has rapidly developed over the past 30 years, featuring many outstanding authors and forming a representative large group centered around Philippe Ciais, alongside several smaller author groups. Before 2000, the field was in its infancy with relatively few publications and many conflicting conclusions about whether forests act as carbon sources or sinks. Post-2000, the number of publications increased significantly, entering a phase of rapid development with many studies focusing on long-term estimates of forest carbon stocks. Represented by Lal (2005) [2], research clearly divided forest ecosystem carbon stocks into biocarbon and soil carbon, highlighting the critical role of forest ecosystems in the carbon cycle. Scholars gradually recognized forests as significant carbon sinks, epitomized by the 2011 landmark paper "A Large and Persistent Carbon Sink in the World's Forests" [3], which provided global estimates of forest carbon stocks and total carbon sinks from 1990 to 2007. Additionally, the impact of human activities on forest carbon stocks has become a key focus, especially with the implementation of various forest management measures

and environmental policies over the past decade. Recently, reforestation measures have particularly gained attention regarding their influence on soil organic carbon stocks.

The estimation of forest carbon stocks has evolved significantly, with the adoption of various methods reflecting the increasing complexity and scale of research in this field. Traditional methods include sample plot surveys, which utilize actual statistical data and historical documents. This involves measuring tree species, diameter at breast height, tree height, and forest age in sample plots, using biomass conversion factors or continuous functions to calculate biomass, or estimating soil organic carbon stocks based on soil profile data and regional soil type area references. However, they are often labor-intensive and limited in scope, making them less feasible for large-scale studies. In response to these limitations, the field has seen a growing adoption of advanced technological methods, particularly remote sensing and mathematical modeling. Common remote sensing methods include MODIS data and high-resolution airborne LiDAR data. In recent years, machine learning models such as random forest and logistic regression have increasingly been used for global forest carbon stock estimation and prediction. The use of the R language has become prominent, with the guidebook “R: A Language and Environment for Statistical Computing” [21] being one of the most highly co-cited references in this field.

The analysis of global research trends in forest carbon storage provides valuable insights, yet it is not without its limitations. One major shortcoming is the reliance on publication data from prominent databases, which may introduce biases towards English-language and high-impact journals, potentially overlooking relevant studies published in other languages or less accessible venues. This bias may skew the understanding of global research trends and underrepresent contributions from certain regions or disciplines. Additionally, the analysis focuses on quantitative measures, such as publication counts and citation frequencies, which may overlook the qualitative impact of individual studies. The clustering analysis, while effective in identifying key themes, is dependent on the accuracy of citation networks, which may be influenced by publication biases and the inclusion criteria of the databases used. Furthermore, the study does not account for the interdisciplinary nature of forest carbon storage research, which spans multiple fields such as ecology, climate science, and environmental policy, potentially leading to an underrepresentation of relevant studies. Future research should aim to integrate more diverse data sources and employ a multi-dimensional approach to better understand the complexities of this evolving field.

5. Conclusions

In summary, this study provides a comprehensive bibliometric analysis of global research on forest carbon stocks, addressing key research questions regarding trends, contributors, research themes, and future directions in this critical field. The primary objective was to map the development of research on forest carbon stocks, identifying the main trends, influential authors and institutions, key research themes, and emerging hotspots that shape the current landscape of this domain.

Since the first paper on forest carbon stocks appeared in the 1980s, this research field has undergone three stages: initial development, slow growth, and rapid expansion. The overall volume of publications has increased, attracting the attention of scientists worldwide. This trend is driven not only by the growing importance of climate change but also by advancements in remote sensing technology, programming languages, and machine learning techniques. Initially, the United States led this field, maintaining the highest number of publications. China’s rapid development in this area, particularly post-2010, positions it as another leading nation in forest carbon stock research.

The analysis identified several key contributors and collaborative networks that have shaped the development of this research field. Authors such as Philippe Ciais have formed large, influential groups that dominate the landscape of forest carbon stock studies. The collaboration between researchers from various institutions, particularly those from China and the United States, has been instrumental in advancing the field. Institutions like the Chinese

Academy of Sciences and the United States Department of Agriculture have emerged as central nodes in the global research network, reflecting their significant contributions to the growth in this field.

In the future, the research on forest carbon stocks is likely to focus on the impact of forest management policies on carbon sequestration, particularly the restoration of soil carbon stocks following reforestation efforts. As global climate governance goals such as carbon peaking and carbon neutrality become increasingly urgent, researchers will likely continue to explore the contributions of various forest types, including tropical, temperate, and mangrove forests, to global carbon sinks. Additionally, the integration of interdisciplinary approaches, combining ecological, technological, and policy perspectives, will be crucial in addressing the complex challenges of forest carbon management. The ongoing advancements in remote sensing, machine learning, and statistical modeling will continue to enhance the accuracy and scalability of carbon stock estimation methods, making significant contributions to the global fight against climate change.

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