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Review

A Bibliometric Analysis of the Research Progress and Trends during 2002–2022 on the Carbon Stocks in Terrestrial Ecosystems

Subinur Sawirdin [1], Aolei Tian [1], Lei Shi [2], Wentao Fu [1], Shengyuan Cheng [1], Ümüt Halik [1,*] and Jiye Liang [3,4,*]

[1] College of Ecology and Environment, Ministry of Education Key Laboratory of Oasis Ecology, Xinjiang University, Ürümqi 830046, China; 107552101140@stu.xju.edu.cn (S.S.); auto_tian@163.com (A.T.)
[2] College of Architecture and Urban Planning, Shandong Jianzhu University, Jinan 250101, China
[3] College of Pharmacy, Youjiang Medical University for Nationalities, Baise 533000, China
[4] College of Plant Sciences, XPCC Key Laboratory of Protection and Utilization of Biological Resources in Tarim Basin, Tarim University, Alar 843300, China
* Correspondence: halik@xju.edu.cn (Ü.H.); ljy_123123@126.com (J.L.)

Abstract: Improving the carbon storage in terrestrial ecosystems can effectively reduce atmospheric CO_2, which is one of the important ways of mitigating global climate change. The knowledge on terrestrial carbon stock research is relatively mature in the international community; however, the research pulse, hotspots, and trends in terrestrial ecosystems carbon stock research are not clear. To better understand the research focus and developmental directions of terrestrial ecosystems' carbon storage, we conducted a bibliometric analysis of 6305 research articles between 2002 and 2022, which were gathered from the Web of Science Core Database. The temporal distribution, country/region distribution, co-citation network, keyword evolution and clustering, journals, and authors of the literature were analyzed, and the knowledge domain was mapped using the CiteSpace visualization software. This study established the following three observations: (1) The number of publications on carbon stock research in terrestrial ecosystems continues to expand, and the trend in the number of publications proves that carbon sinks in terrestrial systems remain an important research topic internationally. (2) Important issues concerning terrestrial ecosystem carbon stock research have evolved from monitoring the carbon stock changes in terrestrial ecosystems to the mechanism of carbon stock formation for the realization of monitoring and management under global climate change. Furthermore, the research methodology has evolved from small-scale, fixed-point instrumental observations to large-scale remote sensing and model simulations, with diversifications in research content and methodology. (3) In the future, academic research on carbon stocks in terrestrial ecosystems will focus more on international and interdisciplinary cooperations, increasing the intensity in surveying and monitoring carbon stocks in terrestrial ecosystems, and realizing the accurate monitoring, assessment, management, and enhancement of carbon stocks from the integrated carbon stock computation system for "sky, air, and land." The results of this study comprehensively demonstrate the current status and development of the research on carbon stocks in terrestrial ecosystems worldwide, and provide a reference for future research on the sustainable management of terrestrial ecosystems within the context of global warming.

Keywords: terrestrial ecosystem; carbon stocks; climate change; forest ecosystem; bibliometric analysis

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1. Introduction

Carbon cycling in terrestrial ecosystems affects the stability of the global carbon cycle. As one of the most important carbon reservoirs worldwide, terrestrial ecosystems regulate regional climates by releasing and absorbing greenhouse gases such as CO_2 and N_2O, playing an irreplaceable role in the survival and development of organisms [1]. An in-depth exploration of the carbon stocks in forest ecosystems and the mechanisms affecting them will help to provide theoretical and practical support for responses to climate change

and the sustainable use and management of forest resources. Increasing the carbon storage in terrestrial ecosystems can effectively reduce atmospheric CO_2, which is one of the important ways of mitigating global climate change [2–5].

Since the signing of the Kyoto Protocol in 1997, there has been a focus on forests and an interest in planting trees to fix carbon [6]. Between the years of 1900 and 2020, the atmospheric CO_2 concentration increased from 285 to 414 ppmv, while the global average temperature increased by 1.09 °C [7]. To mitigate the global warming caused by the increase in greenhouse gas concentration, the international community has formulated policy measures such as the United Nations Framework Convention on Climate Change (1992) and the Paris Agreement (2015), among others. Especially in recent years, as a major global action towards carbon emission reduction, the world's major economies successively announced their "double carbon" (carbon peak and carbon neutral) autonomous emission reduction targets [8]. In September 2020, President Xi Jinping announced at the 75th session of the UN General Assembly that "China will strive to peak its carbon dioxide emissions by 2030, and strive to achieve carbon neutrality by 2060" [9,10] (referred to as the "dual-carbon" goal), incorporating it into the overall construction plan for China's ecological civilization [11]. In the global terrestrial ecosystem, forests provide a strong carbon sink function and potential to increase their carbon sinks compared to other ecosystem types such as grasslands, wetlands, and farmlands [12]. By effectively enhancing the carbon sequestration capacity in global forest ecosystems, the CO_2 released from fossil fuel combustion can be offset, slowing the process of global warming [13,14], and is therefore considered to be one of the most economical, safe, and effective ways of achieving the goal of "double carbon [15]." For this reason, forest carbon sinks have been an important topic in global academic and political circles since 1990, and the literature in this field has been increasing, along with a deepening and expanding content and scope of research. This research involves forest carbon stocks: their estimation methods, patterns and their influencing factors, formation and maintenance mechanisms, function enhancement pathways, and carbon sink management methodologies.

The research scale ranges from the sample plot scale, community scale, and regional scale to the global scale [16–19]. The research methodology has evolved from single-site monitoring to the establishment of multiscale and comprehensive ecosystem monitoring networks, ecological parameters and big data observations, and algorithms for high-precision remote sensing modeling [20,21]. The research results provide a basis for accurate assessments of forest ecosystem carbon stocks, and a theoretical reference for a steady and sustainable improvement in the forest carbon sink function under the goal of "double carbon." In the context of upgrading forest carbon stock measurement techniques and improving assessment methods, research concerning the carbon storage in terrestrial ecosystems has also increased rapidly and become crucial in the field of ecological environment under the influence of global warming. Owing to the wide range of disciplines and research scopes involved in this field, however, existing research concerning the pulse, hotspot, and trend of forest carbon stocks is unclear [22], and it is difficult to grasp the research direction in this field as a whole. This leads to the current research analysis presented in this report.

Within the development of modern information technology, knowledge mapping is an emerging field that can visualize intricate knowledge systems, understand the structural characteristics of each field, classify the rich knowledge network formed by the expansion of contemporary knowledge, and then predict the latest developing trends in the scientific and technological knowledge frontier [23]. Based on this framework, our study clarifies the structure and development in the fields of ecology, environmental science, and forestry by visualizing a bibliometric analysis, and envisions the research foundations, frontiers, and activity in this field through an objective summary and evaluation of the research background, key topics, and knowledge structure evolution, among others. With a clearer understanding of the knowledge structure and evolutionary trend of this thematic topic, our results provide a sound scientific reference for future research on the carbon storage in terrestrial ecosystems.

2. Data Sources and Research Methods

To ensure the relevance of the selected literature, data were extracted from the internationally recognized authoritative database, Web of Science (WoS) Core Collection. This publication database contains a wide range of research in the fields of engineering, science, management, social sciences, and humanities. WoS was used as a source database for analysis in the early developmental phase of the CiteSpace software, and has since been widely used in many influential review papers [24–26]. We applied the following search criteria: Keywords: ecosystem AND carbon storage OR carbon stock; Language: English; Literature type: Article. The search topics were soil science, forestry, environmental science, and climate change. To ensure the recall rate and quality of the articles, we adopted topic-specific retrieval. The logical operator "AND" was used to associate ecosystem with carbon storage, while the logical operator "OR" was used to associate different expressions of the same concept. To consider only appropriate and representative articles, we manually screened each article from the search results stepwise by reading the title, abstract, keywords, and other related contents, and then deleted the literature that deviated from the topic and discipline (e.g., the abstract mentioned carbon but the content did not focus on carbon storage). Considering the rapid development in this field, ensuring that the viewpoints of the reports were close to the current research status and the results had not been overturned, and further avoiding inaccurate analyses caused by the excessive number of articles, the year of the initial search was set as 2002. A total of 6,305 articles were obtained from the published literature (retrieval dates 2002–2022) by manually screening the titles and abstracts, and eliminating the literature not related to the field of terrestrial carbon stock research (Figure 1).

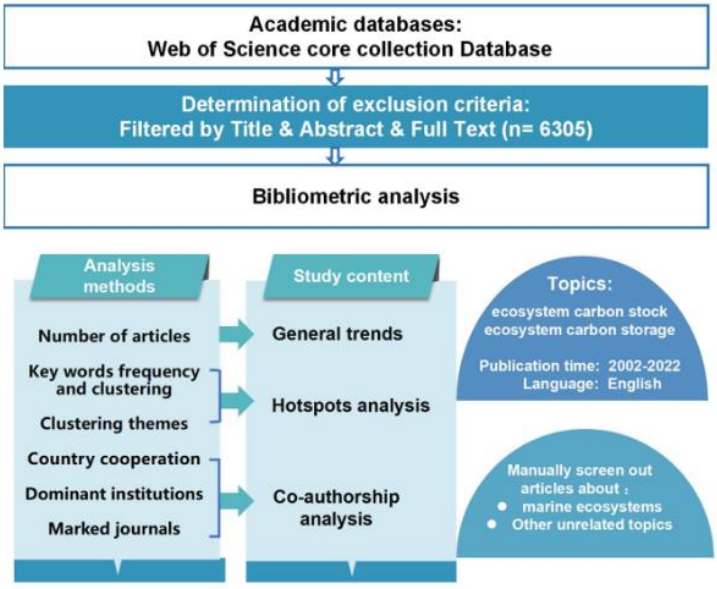

Figure 1. The research framework and procedures of the bibliometric analysis used in this research.

In our research, the CiteSpace 6.2.R2 (https://citespace.podia.com/citespace-standard, accessed on 9 May 2023) and Origin 2019b (https://www.originlab.com/2019b, accessed on 24 August 2023) software were applied to analyze the current research status of the carbon storage in terrestrial ecosystems, and to identify the hotspots and trends in this topic through keyword frequency, keyword clustering, and research co-citations. CiteSpace also analyzed the overall research dynamics and cooperative relationships among the main research countries, institutions, journals, and authors. Compared to other bibliometrics software, the advantage of CiteSpace is that it visualizes the citation relationships among documents in the form of citation networks, enabling a more intuitive understanding of a field's knowledge structure and evolutionary trends. Secondly, CiteSpace can analyze

evolutionary paths and research themes, revealing dynamic changes in research fields. In addition, it provides a network analysis function to show the collaborative relationships among authors or structures, helping users to understand composition and collaboration patterns for research teams or academic circles. Most importantly, CiteSpace helps users to discover research trends, important areas, and research hotspots from a large amount of studies through exploratory discoveries and insights. Lastly, the Origin 2019b software (OriginLab Corporation, Northampton, MA, USA) was used to create graphs and charts to easily visualize the data obtained from WoS and CiteSpace.

3. Results and Discussion

3.1. Publication Trend Analysis

Over time, the number of articles reveals the developmental trends and publishing rate in a research field. Internationally, the number of publications on the carbon storage in terrestrial ecosystems has been growing rapidly overall (Figure 2), but the number of documents published in 2022 was lower than the growth trend. We have two hypotheses: the first is that scientific research has been constrained by funding and resources, possibly due to the impact of the global pandemic, which has led to a reduction in the capacity and opportunities for researchers to conduct research in the field. The second is that the growth rate for further research may slow when a field is already relatively saturated and the main core questions have already been answered. In addition, the resolution of some key questions may require more time and in-depth research, which may also contribute to the recent decline in the number of publications. We believe that this may have been affected by the global pandemic. From 2002 to 2007, the number of published documents steadily increased yearly, making a large contribution to the foundation of technical terms and later research directions. The content mainly focused on the estimation and comparative study of carbon storage macroconcepts within a local scope. Since 2008, the number of publications has shown rapid growth. The research content has been further innovated and developed through convenient, efficient, and novel research methods that can be applied at larger scales. Additionally, research fields have gradually become more refined, exhibiting closer interactions with disciplines such as geography, remote sensing, microbiology, biogeochemistry, and atmospheric sciences. This interdisciplinary collaboration magnifies the overall understanding within the field and enhances the search for solutions through cooperative research projects, data sharing and integration, joint publications and conferences, and education and training.

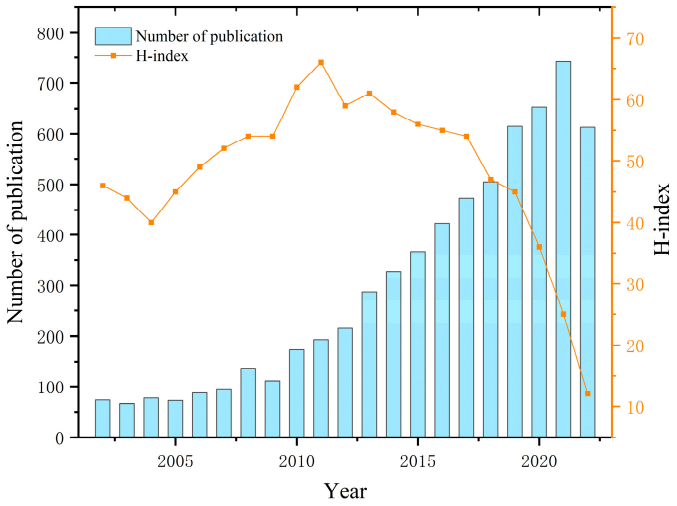

Figure 2. Articles published between 2002 and 2022 on carbon storage in terrestrial ecosystems.

The H-index is one of the most conveniently used indicators for evaluating the academic influence of a group or individual [27]. Figure 2 shows, contrary to the number of

publications, that the average citation rate of articles and the expansion in research have been decreasing since the peak of the citation rate in 2011, but the number of publications during the same period has been increasing. This may indicate that, as the number of articles published increases, researchers have more reference articles to choose from, and older articles are gradually replaced by a few newer review articles. It may also indicate that, as the number of publications continues to grow, ecology has gradually become more intertwined with other subject areas, resulting in a gradual dispersal of citations to other disciplines and thus a lower citation rate for articles within the field.

3.2. Research Hotspots and Trends

Keywords provide important information on research trends and frontiers, revealing the direction of a research field [28]. A map showing keyword time zones allows for visualizing the frequency of keyword usage and trends in different time periods. In their temporal evolution, several popular keywords underwent changes during the research period (Figure 3). The implications of these keywords throughout time primarily include the evolution of research themes, which can reflect changes in academic interest and focus in particular research areas, and secondly, by identifying the keywords that have appeared frequently in the recent past, we can track the current themes that have received widespread attention and keep abreast of the latest developments in academia, along with speculations on possible future research trends and directions.

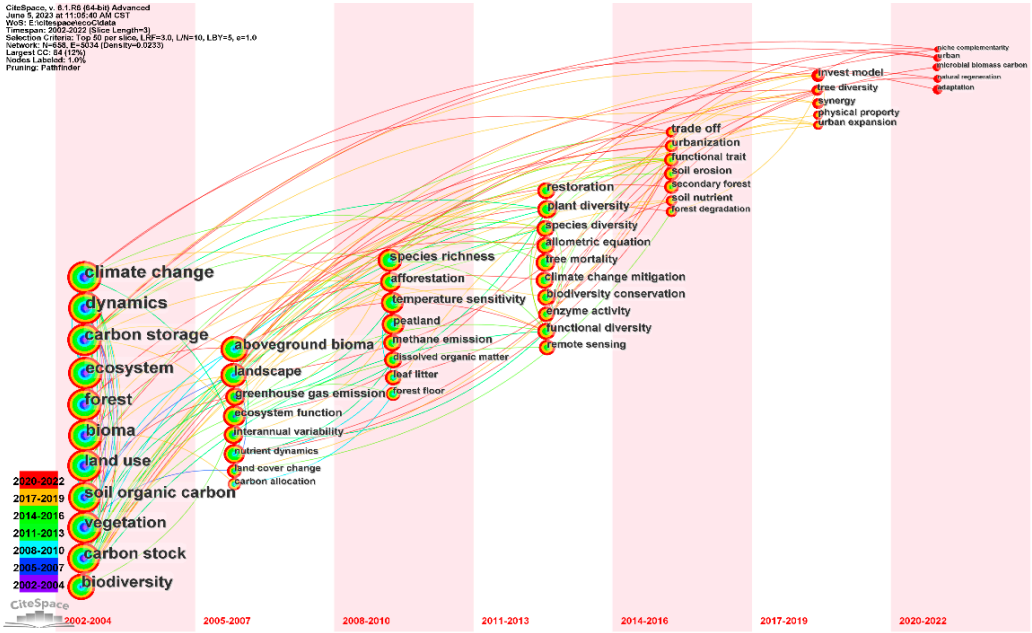

Figure 3. The time zone evolution map of important keywords in the terrestrial ecosystem carbon storage research.

In the CiteSpace software, "climate change" was the keyword phrase with the highest frequency of occurrence, appearing 1259 times in total. Climate change is a fundamental research foundation for terrestrial ecosystem carbon storage [29]. Under the trend of global warming, increasing carbon storage has become one of the key strategies for mitigating climate change. Therefore, in the study of terrestrial ecosystem carbon storage, "climate change" is directly related to "carbon sequencing", "ecosystem", "forest", and other keywords, gradually evolving into "international variability", "temperature sensitivity", and "tree mortality", indicating that quantifying interannual changes in temperature and vegetation sensitivity and adaptability to temperature under the influence of climate change are the main themes that have been expanded. Within this theme, researchers generally need a variety of methods, such as meteorological data and model simulations, to assess

the changes in vegetation cover and the associated changes in the carbon cycle and carbon stocks. These studies can provide a scientific basis for understanding the mechanisms by which vegetation responds to climate change, predicting the future trends in carbon stocks, and developing adaptation strategies. From the keyword time zone map, we found that keywords related to urbanization appeared in every phase, starting from the 2014–2016 phase, indicating that balancing the urbanization process and maximizing the ecosystem's carbon storage capacity have gradually become some of the more important themes.

Figure 3 shows that research concerning the carbon storage in terrestrial ecosystems has steadily changed from the macro- to the micro-scale, and involves multidisciplinary research. Research has gradually focused more on the impact of human activities (such as land use changes and urbanization, etc.) related to the carbon cycle of ecosystems, predicted the impacts of climate change, and explored effective adaptation and mitigation measures. Through continuous innovation in research methods, advanced technologies such as remote sensing, model simulation, and molecular ecology can be used to discover the hidden characteristics of ecosystem carbon stocks and improve the accuracy and ease of ecosystem carbon stock measurements.

Keyword clustering can divide the research directions and topics within a research field. Figure 4 indicates that the key research topics on terrestrial ecosystem carbon storage were mainly focused on the following 19 aspects: 0—carbon dioxide, 1—eddy covariance, 2—carbon storage, 3—soil response, 4—temperature sensitivity, 5—grazing exclusion, 6—soil organic carbon, 7—InVEST model, 8—soil carbon, 9—ecosystem services, 10—carbon stocks, 11—tropical forest, 12—net primary productivity, 13—elevated CO_2, 14—carbon sequestration, 15—carbon budget, 16—synergies, 17—organic carbon, and 18—Loess Plateau.

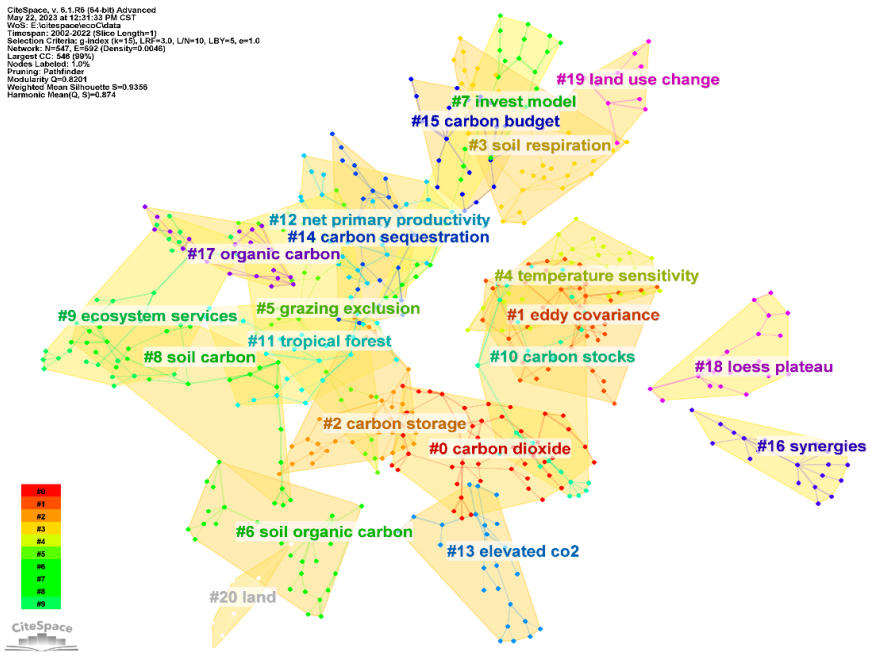

Figure 4. Keyword clustering map of terrestrial ecosystem carbon storage research.

3.3. Research Areas and Current Status of Carbon Stocks in Terrestrial Ecosystems

Figure 5 summarizes the cited relevant literature and generates a timeline visualization of the literature co-citation clustering. Research co-citation clustering can reveal the basic knowledge and important research topics in a research field to a certain extent, which is a collection of academic works cited by academic groups in the same field, and different research contents may be dispersed from the common research themes. The nodes in the cluster represent highly co-cited articles. The red nodes represent papers that were cited suddenly, i.e., papers with the highest change in citation frequency during a certain

time period. These constitute core papers with significant influence and visibility within the entire co-citation network [30]. Eight important clustering themes among them were obtained; the color of each cluster is shown to change with time. Thus, we classified these eight clustering themes into three research phases: early, midterm, and recent.

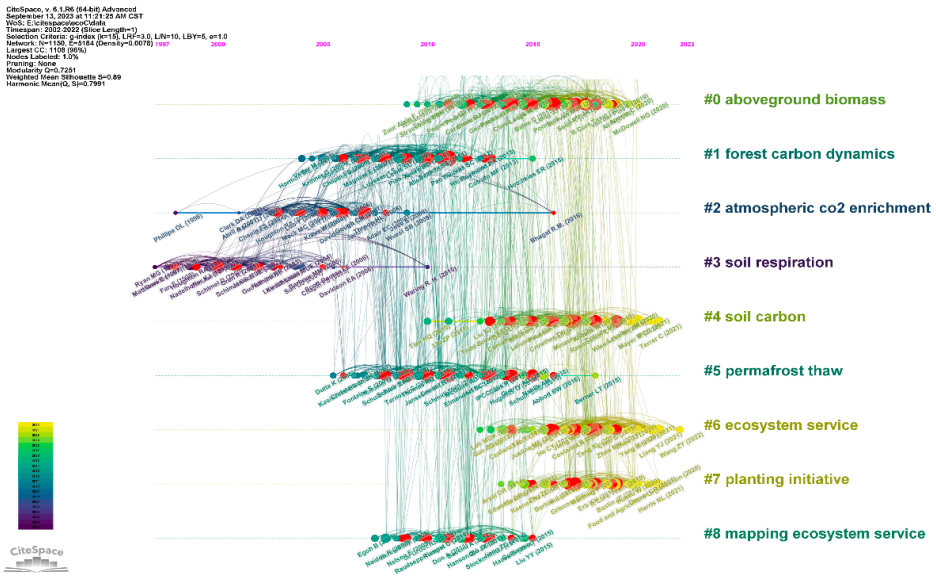

Figure 5. A timeline visualization of the co-cited literature in research field of terrestrial ecosystem carbon stocks.

3.3.1. Early Basic Clusters

The early development cluster is the research hotspot from 1997 to 2016 in the field of the carbon stocks in terrestrial ecosystems, including 2—atmospheric CO_2 enrichment and 3—soil respiration, which includes a total of 277 citations in this phase. The main research in this early stage was on developing a system for carbon sink and source assessment methods [31,32]. In this phase, the uncertainty of the carbon exchange between the atmosphere and land with long-term climate change was determined through eddy correlation [33], carbon balance modeling [34], and soil respiration monitoring [35], focusing on carbon exchange patterns and the mechanisms of global and regional forest ecosystems [36], and clarifying that the evolution of forest carbon sinks is largely a result of land use changes over time and a response to environmental changes [37–39]. Eddy correlation was the method most widely used in this stage [40]. This method can provide real-time gas flux data and capture the changes in the gas exchange between ecosystems and the atmosphere on short time scales [37], but with the disadvantage that there may be certain measurement errors in practical applications due to the influence of micro-meteorological conditions and instruments, together with other factors. While the carbon balance model has the advantage that regional statistical correlation can be modeled based on empirical relationships and measured data, the feedback effect from forest ecosystems on global climate change has not been addressed [41]. Additionally, the carbon balance model is static and therefore limited in its application [42]. Future research will be focused on understanding the response mechanisms and adaptation strategies of ecosystems based on the model's limitations, including the study of the carbon stocks and gas exchange changes in ecosystems of different vegetation types and in different geographic regions [43], and on further improving the ecosystem model to more accurately describe and predict the carbon cycle and carbon stock changes in ecosystems [44].

3.3.2. Midterm Development Clusters

The clusters developed during the midterm period, from 2004 to 2018, are the research hotspots in the field of the carbon stocks in terrestrial ecosystems, including 1—forest

carbon dynamics, 5—permafrost thaw, and 8—mapping ecosystem service, which include a total of 311 citations in this phase. The midterm phase focused on the drivers of carbon stocks and impact assessments among different ecosystems. This stage mainly explored the scale and distribution of carbon storage and its drivers in different ecosystems through remote sensing technology, the sample inventory method, and ecosystem modeling [45–47]. Remote sensing technology can estimate the carbon stock sin forest ecosystems and the effect of land use changes on carbon stocks over large areas, and demonstrated gradual improvements in its spatial, temporal, and spectral resolution. There are, however, large errors in its estimations [48]. The sample inventory method can express data realistically and accurately, but the number of sample points and its coverage limit this method. Lastly, ecosystem modeling, which allows for simulation and prediction under different scenarios and conditions, has some uncertainty in parameter estimation due to ecosystem complexity and unpredictability [49].

Currently, the evaluation of the carbon sequestration effect is not yet based on an unified system. Various aspects concerning the evaluation of the carbon sequestration effect may develop in the future [50], but this will require the emergence of more perspectives and models. Further, continuous improvement in the measured data on the basic physical and chemical properties of global forests and understory soils will be necessary, so as to create a more complete and systematic database related to the estimation of carbon stocks [51–53]. More long-term and dynamic carbon density data will need to be obtained to reduce the uncertainty in static carbon density values and improve the accuracy of carbon stock estimations [45].

3.3.3. Recent Persistent Clusters

The recent persistent clusters are the research hotspots from 2007 to 2023, including 0—aboveground biomass, 4—soil carbon, 6—ecosystem service, and 7—planting initiative, which, together, include 436 citations. In this recent phase, the research content and scale have been gradually enriched, and the main research has focused on how to realize the stabilization and sustainable growth of carbon stocks through different measures [54]. The main research direction is to put theory into practice through remote sensing technology, sample plot investigations, and socioeconomic assessments, all of which will establish the accurate monitoring and management of carbon sinks at the global scale [55–57]. For large-scale carbon stock simulations and predictions, management, and control, the socioeconomic impacts of forest ecosystems on the provision of ecosystem services may also be increasingly involved in the future [58,59]. This includes assessing the contribution of forest ecosystem carbon stocks to human well-being, as well as studying the patterns and mechanisms of the sustainable use of forest resources, by assessing the effects of forest fragmentation on biodiversity, ecological processes, and functions [60,61]. Additionally, greater engagement with the disciplines of economics, finance, and management may be needed to more effectively control forest ecosystems, which could occur through the perspectives of budgetary forecasting, governmental management, and policy enactment [62–65].

3.4. Country Cooperation Network Analysis

To a certain extent, the number of publications produced by various countries reflects their national influence and importance in this field, as research papers often represent the collaborative work of multiple authors and institutions from different geographical regions. In the CiteSpace software, centrality indicates that an institution is the central node, and the higher the centrality, the more important and influential its research. It can be seen from Figure 6 and Table 1 that, for research concerning the carbon storage in terrestrial ecosystems, the United States has the largest number of papers (2129) and was also the first country to study this field, with a H-index of 141. Both indicators are far higher than those of other countries, indicating that the United States has contributed the most to this research field. Next is China (1740), which has experienced a rapid increase in its number of publications in this field during recent years, becoming the country with the field's fastest

development rate. China's centrality is 0.01, however, which means that China has fewer cooperative relationships with other countries in this research field. Moreover, China's research on the carbon stocks in terrestrial ecosystems started late and is lagging behind. Figure 6 shows the co-operation between the top 20 countries in terms of the number of papers published, from which it can be seen that the United States and China are the countries that co-operate with each other the most. In contrast, the United Kingdom has the highest centrality, indicating its significant influence in this field. The implication of this is that there are frequent and significant collaborative relationships between the United Kingdom and other countries in this area of research, which can be explained by the fact that the United Kingdom has a wide range of partners in terrestrial ecosystem carbon stock research and actively promotes cooperation and the exchange of knowledge internationally.

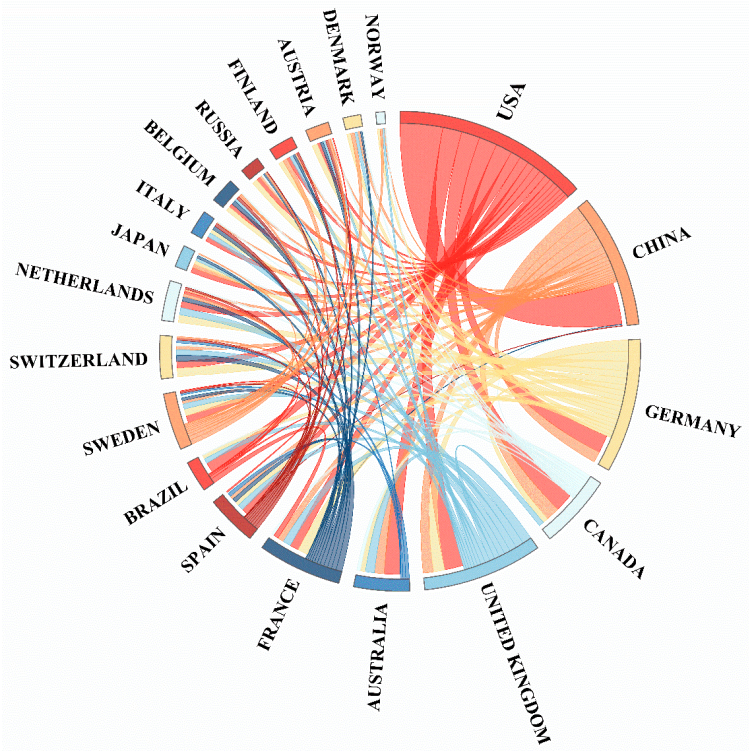

Figure 6. Co-operation between the top 20 countries concerning the research on carbon storage in terrestrial ecosystems.

Table 1. Top 10 countries on the number of published papers and their main research directions.

Country	Publications	Centrality	H-Index
USA	2129	0.08	141
China	1740	0.01	84
Germany	607	0.07	77
Canada	523	0.02	66
United Kingdom	432	0.12	75
Australia	384	0.10	59
France	305	0.09	62
Spain	273	0.08	47
Brazil	259	0.01	51
Sweden	254	0.10	54

3.5. Marked Journals

Journals are the carriers of research achievements and the main sources of scientific exchange [66]. We analyzed the top ten journals in the field of terrestrial ecosystem carbon storage research and report the number of papers published, the country to which they

belong, and the number of citations. Among the 6305 publications identified, 2319 were contributed by the top ten journals, accounting for 36.8% of the total number of published articles, indicating that the articles on the carbon storage in terrestrial ecosystems are mainly concentrated in a few journals. This may lead to a possible tendency for researchers to submit their findings to journals that have a strong reputation and influence in the field, leading to a bias that makes research within the same field more focused on a particular viewpoint, methodology, or theoretical framework. This would be at the expense of other potential research directions and perspectives. Among the top ten journals in terms of the number of published articles on terrestrial ecosystem carbon storage, four journals were established in the Netherlands. This means that the Netherlands plays an important role in facilitating cooperation and exchange among scholars from various countries and regions, and has a long-standing commitment to the publication of relevant research in this field. As shown in Table 2, *Forest Ecology and Management*, *Forests*, *Global Change Biology*, *Agriculture Ecosystems Environment*, *Journal of Geophysical Research Biogeosciences*, and *Biogeosciences* are the six journals with the largest publication volume.

Table 2. Top 10 journals ranked according to the number of publications on carbon storage in terrestrial ecosystems.

Journal	Country	Publications	Co-Citation Count	Impact Factor
Forest Ecology and Management	Netherlands	490	16,877	3.7
Forests	Switzerland	252	2160	2.9
Global Change Biology	United Kingdom	249	24,744	11.6
Agriculture Ecosystems Environment	Netherlands	213	9733	6.6
Journal of Geophysical Research Biogeosciences	USA	204	5155	3.7
Biogeosciences	Germany	203	8432	4.9
Science of the Total Environment	Netherlands	191	4957	9.8
Ecological Indicators	Netherlands	184	4794	6.9
Ecosystems	USA	178	7818	3.7
Environmental Research Letters	United Kingdom	155	3250	6.7

Trends in journals reflect changes in the level of scholarly interest in different topics and fields. Research hotspots and the importance of some subject areas change over time, and when particular topics or fields become the focus of scholarly attention, these journals are likely to attract more manuscript submissions, which can lead to rapid growth in their publication volume. The top five journals with the largest numbers of articles on the carbon storage in terrestrial ecosystems showed different development trends (Figure 7). In the early development stage (2002–2011), focused on the carbon storage in terrestrial ecosystems, *Forest Ecology and Management* and *Global Change Biology* were among the journals experiencing rapid development, which coincided with the stage when "climate change", "forest", "ecosystem", and "management" became popular keywords. The evolution of these keywords indicates the deepening and expanding research on the carbon stocks in terrestrial ecosystems, from simple descriptions and measurements to more complex mechanisms and modeling. *Forest Ecology and Management* is the journal with the most research achievements; *Forests* is one of the relatively young potential stock journals. Although the journal was established relatively late, it showed a rapid trend in growth and ranked second in terms of publication volume among the major journals; nevertheless, the journal's impact factor was low. In contrast, the ranking of co-citations and impact factor (excluding self-citations) in *Global Change Biology* were the highest, indicating that the journal has a strong influence and high reference value.

3.6. Competitive Authors

The top 10 authors with the largest numbers of articles in this field on WoS are listed in Table 3. These authors are the most professionally active in the field of terrestrial ecosystem carbon storage. However, in the articles produced by these researchers, we did not take

into account the author order, which means that, as long as the name appeared in the author column, then we calculated the authors' H-index relative to the number of articles published by the authors listed in the table. The H-index accounts more comprehensively for the number of publications and citation frequency of an author's articles, and a high H-index reflects a researcher's influence and visibility in the academic community.

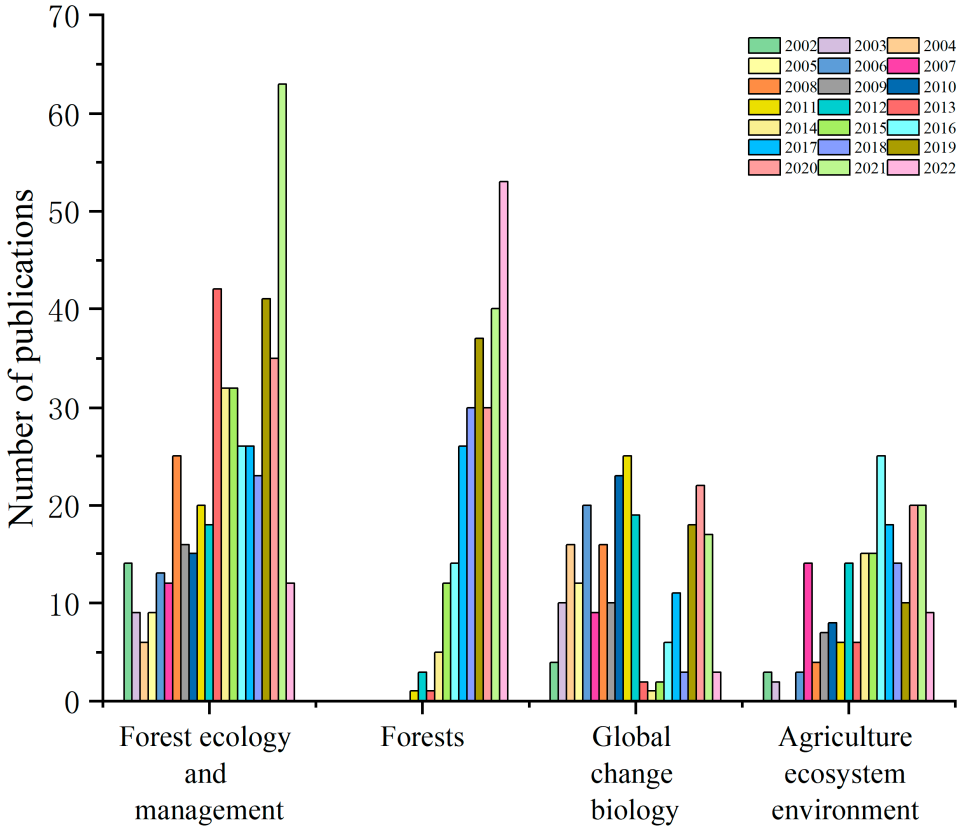

Figure 7. Temporal trends in the top five research journals on terrestrial ecosystem carbon stocks.

Table 3. Top 10 authors based on publications in the field of terrestrial ecosystem carbon stocks during 2002–2022.

Author	Institution	Country	Publications	H-Index
Ciais, Philippe	Centre National de la Recherché Scientifique	France	39	24
Luo, Yiqi	Cornell University	USA	36	18
Kurz, Werner A	Canadian Forest Service	Canada	27	19
Law, Beverly Elizabeth	Oregon State University	USA	26	25
Tian, Hanqin	Nanjing University of Information Sci & Technology	China	25	19
Penuelas, Josep	Autonomous University of Barcelona	Spain	25	15
Woodall, Christopher W	United States Forest Service	USA	25	12
Piao, Shilong	Chinese Academy of Sciences	China	24	16
He, Nianpeng	Chinese Academy of Sciences	China	24	15
Kellomaki, Seppo	University of Eastern Finland	Finland	24	15

From Table 3, it can be seen that the researchers with the most research achievements are Philippe Ciais [67], who established an innovative atmospheric retrieval inversion method for the global carbon budget and discovered the importance of the carbon budget relationships between land and sea systems and land carbon sinks in the northern hemisphere. Luo Yiqi's research [68] focused on solving how global changes alter the structure and function of terrestrial ecosystems and how terrestrial ecosystems regulate climate change. Luo et al. discovered invariant functions in global ecosystems and successfully

applied reverse analysis methods to ecology for the first time. Werner A. Kurz [69] has been dedicated to studying the impacts of natural disturbances, forest management, and land use changes on the forestry carbon balance for many years, leading the development of the Canadian Forestry Carbon Balance System (CBM-CFS3). Beverly E. Law [70] prioritizes landscape conservation using process models and ecological standards to reduce greenhouse gas emissions and protect biodiversity in rapidly changing climates. Tian Hanqin [71] developed a global ecosystem carbon cycle model that integrates the effects of land use, vegetation dynamics, climate change, and human activities on ecosystem carbon storage and exchange. By using these models, the changes in carbon sinks and sources in different ecosystems worldwide can be assessed and used to predict future carbon cycles. Josep Penuelas [72,73] conducted in-depth research on plant physiological processes and carbon cycling mechanisms; his research focuses on the response of plant adaptability and reactivity to environmental changes, especially the effects on climate change, air pollution, and land use changes. Penuelas' research reveals the importance of plant growth, photosynthesis, respiration, and water/nutrient utilization processes in the carbon cycle. Christopher Woodall [74] has made significant contributions in terms of developing methods to estimate forest carbon storage. His research covers various types of forest habitats, geographical ranges, and land use changes; Woodall et al. developed advanced models and methods for estimating the carbon storage in forest ecosystems [75]. Piao Shilong's research [76–78] focuses on global vegetation dynamics and carbon cycling in terrestrial ecosystems, and has characterized vegetation growth and corresponding carbon absorption changes in different regions and vegetation types by analyzing remote sensing data and ground observations. He Nianpeng [79,80] used the improvement in ecosystem carbon storage measurement methods as a breakthrough to construct datasets containing key parameters for different regions in China. Based on this result, he was able to carefully evaluate the carbon and nitrogen storage in all components of China's terrestrial ecosystem. Seppo Kellomaki's research [81] focuses on the physio-ecological and biochemical processes of trees, and he studied key physiological processes such as photosynthesis, respiration, water use, and nutrient cycling in trees, along with their impacts on ecosystem function and carbon cycling.

4. Conclusions and Future Research Directions

In this study, 6305 research articles on the carbon stocks in terrestrial ecosystems listed in the WoS Core Database that were published from 2002 to 2022 were taken as the study objects. The current research status and patterns were analyzed from the annual trends in the number of papers, the main research focus, the distribution of disciplines, and the research hotspots and fronts. Using the method of visualizing research information, we found the following conclusions:

(1) Carbon stock research showed an expanding trend during 2002–2022. The research in various countries showed important research trends in different fields, the number of publications and citations rose, and the cooperation between countries showed a developing trend, especially for the United States and China, which exhibited the strongest cooperation, and the United Kingdom, which had the highest degree of centrality.

(2) The most frequently occurring keyword phrase was "climate change", and this gradually evolved into "interannual variability", "temperature sensitivity", "tree mortality", "temperature sensitivity", and "tree mortality", indicating that quantifying the interannual variability in temperature and vegetation sensitivity and the adaptation to temperature under the influence of climate change were the main themes extended. Balancing the urbanization process and maximizing the carbon storage capacity in ecosystems have gradually become two of the more important themes.

(3) Through a citation analysis, we categorized the clusters related to the carbon storage in terrestrial ecosystems into early basic, midterm development, and recent persistent clusters. Most of the research has focused on carbon sink and source assessment

methods, carbon stock drivers, and the accurate monitoring and management of global carbon sinks. The research methods have gradually evolved from the early eddy correlation method, carbon balance modeling, and soil respiration monitoring to remote sensing technology and ecosystem modeling.

In short, the current research on the carbon stocks in terrestrial ecosystems centers on carbon stock estimation methods, stock patterns, their influencing factors, and maintenance mechanisms. In the future, research on the carbon stocks in terrestrial ecosystems can prioritize the construction of multiscale and universal monitoring networks and a comprehensive assessment system, the development of a comprehensive analysis framework for the carbon pool that includes all components of the ecosystems, and the promotion of integrated research on the monitoring, assessment, upgrading, management, and finance of terrestrial ecosystems' carbon stocks, by the means of policy guidance, interdisciplinary collaboration, and international cooperation.

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