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RESEARCH ARTICLE

Climate change and carbon sink: a bibliometric analysis

Li Huang[1] · Ke Chen[1] · Mi Zhou[1]

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Abstract
In recent years, climate change and carbon sinks have been widely studied by the academic community, and relevant research results have emerged in abundance. In this paper, a scientometric analysis of 747 academic works published between 1991 and 2018 related to climate change and carbon sinks is presented to characterize the intellectual landscape by identifying and revealing the basic characteristics, research power, intellectual base, research topic evolution, and research hotspots in this field. The results show that ① the number of publications in this field has increased rapidly and the field has become increasingly interdisciplinary; ② the most productive authors and institutions in this subject area are in the USA, China, Canada, Australia, and European countries, and the cooperation between these researchers is closer than other researchers in the field; ③ 11 of the 747 papers analyzed in this study have played a key role in the evolution of the field; and ④ in this paper, we divide research hotspots into three decade-long phases (1991–1999, 2000–2010, and 2011–present). Drought problems have attracted more and more attention from scholars. In the end, given the current trend of the studies, we conclude a list of research potentials of climate change and carbon sinks in the future. This paper presents an in-depth analysis of climate change and carbon sink research to better understand the global trends and directions that have emerged in this field over the past 28 years, which can also provide reference for future research in this field.

Keywords Bibliometric analysis · Climate change · Carbon sink · CiteSpace · Mapping knowledge domain

Introduction

Since the Industrial Revolution, the concentration of greenhouse gases in the atmosphere has been rising due to human activities, especially the combustion of fossil fuels, which has triggered global climate change characterized by warming (Lal 2004; Sitch et al. 2007; Lafforgue et al. 2008; Goh 2011). This has seriously affected sustainable development, and climate change has become one of the top ten ecological problems faced by human beings (Mendelsohn et al. 2006; Wheeler and Von Braun 2013; Nelson et al. 2014; Amin et al. 2015; Islam and Nursey-Bray 2017; Hisano et al. 2018; Salah et al. 2019; Lou et al. 2019; Zeng et al. 2019). How to slow down and adapt to climate change and protect the environment has become a topic given much attention in the international community. The United Nations Framework Convention on Climate Change defines "carbon sinks" as processes, activities, or mechanisms that remove carbon dioxide from the atmosphere, while those that release carbon dioxide into the atmosphere are called "carbon sources." Therefore, international action to address climate change is primarily aimed at reducing carbon dioxide emissions (sources) and increasing carbon dioxide uptake (sinks). So, "carbon sinks" have become a new topic of study and gradually entered the public consciousness. In the early 1990s, the USA, the United Kingdom, and the Netherlands took the lead in conducting research on climate change and carbon sinks (Schroeder 1991; Heathwaite 1993; Nabuurs and Mohren 1993), and then other countries followed up with more research in this field. In order to cope with climate change, scholars have been carrying out research on carbon sinks concerning terrestrial ecosystems (Piao et al. 2009a, b; Fang et al. 2001a, b; Gurney and Eckels 2011; Pan et al. 2011; Liu 2004; Gorham 1991), oceans (Jiao et al. 2016; Muller-Karger et al. 2005; Zhai and

Responsible editor: Philippe Garrigues

✉ Mi Zhou
zhoumi2011@syau.edu.cn

Li Huang
lilyhuang@syau.edu.cn

Ke Chen
chenkeyaya@syau.edu.cn

[1] College of Economics and Management, Shenyang Agricultural University, Shenyang 110866, Liaoning, China

Zhao 2016), grasslands (Liu et al. 2009; Ren et al. 2011), and rock weathering (Pu et al. 2015; Liu 2012).

Although many studies have been conducted, limited attention has been paid to outlining the trends of research in this field. Some empirical and qualitative review articles by experts have offered an overview of climate change and carbon sink research; however, they are limited in some specific aspects, such as regions, subjects, and ecosystems (González-Sánchez et al. 2012; Schaphoff et al. 2016; Aragao et al. 2014; Reid et al. 2009). Moreover, it is very difficult to effectively organize, summarize, and quantitatively analyze the development of a specific field among a large amount of studies on a large time scale in traditional review articles. Also, climate change and carbon sinks are interdisciplinary research fields, covering disciplines including environmental science, geography, forestry, atmospheric science, and ecological science. In order to create a comprehensive overview of the study of climate change and carbon sinks, bibliometric analysis is needed.

Bibliometric analysis can effectively describe the knowledge status, features, and trends in a certain discipline. Bibliometrics analysis includes qualitative and quantitative analysis of publications indexed by databases based on statistics and computing technology, collaborations among different countries and institutions, co-authorship and co-occurring categories, and keywords (Aleixandre-Benavent et al. 2017; Liu et al. 2019a, b). A quantitative analysis can help people who are interested in but unfamiliar with this field, including managers and researchers, to quickly grasp the basic status of this field. This technique has been widely used to measure the performance of various disciplines (Zhaohua et al. 2018; Ekundayo and Okoh 2018; Garrigos-Simon et al. 2018; Liu et al. 2019a, b). Furthermore, knowledge graphs combine information visualization technology with traditional scientometrics citation analysis to visually display the knowledge of a subject or field through data mining, information processing, scientific measurement, and graphic drawing. Therefore, using knowledge graphs, one can explore the development of and relationships between different pieces of scientific knowledge (Shiffrin and Börner 2004).

In order to provide a systemic and objective overview of research on climate change and carbon sinks, this study identifies bibliometric characteristics and visualizes relationships between articles in this field published in the journals of Web of Science between 1991 and 2018 by means of a scientometric analysis based on CiteSpace. The goals of this study include (1) identifying the basic characteristics of the literature, such as the number of articles and citations, research subject categories, and representative journals; (2) identifying the research power of this research area, such as representative countries, institutions, and authors; (3) recognizing the intellectual base according to frequently cited references; (4) uncovering the changing trends in research topics and hotspots over time; and (5) identifying opportunities for future research. Our findings could assist researchers around the world to better understand the current state and latest research in this field, inspiring further research.

Data collection and methodology

The Web of Science core collection contains more than 12,000 influential academic journals, the authority and importance of which have been widely recognized by the international academic community. It essentially covers the international authoritative academic journals that publish literature related to climate change and carbon sink research. This paper takes "Web of Science core collection" as the object database including the Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI) and sets TS = ("climate change" and "carbon sink") as the retrieval condition, with a time span of 1900–2018. The retrieved literature records were downloaded and saved as a plain text file in the format of "Full Record and Cited References," which was used as the sample data in the paper.

CiteSpace

The analysis tool used in this paper, CiteSpace, is one of the most influential pieces of software in literature information analysis. It focuses on presenting the structure and distribution of scientific knowledge in the context of scientific metrology, data analysis, and information visualization, allowing for the generation of different types of knowledge graphs and providing researchers with visual citations of the literature landscape (Chen et al. 2008). As a free piece of software, CiteSpace can be downloaded from the website http://cluster.ischool.drexel.edu/~cchen/citespace/download/.

CiteSpace users can specify the time period of the literature they wish to view, choose the nodes, and set up thresholds all on the same screen. Visual maps created by CiteSpace are composed of two elements, nodes and links, with the former representing authors, institutions, countries, terms, keywords, subject categories, cited references, and so on, while the latter represents the co-occurrence or co-citation relationship between nodes (Chen et al. 2014). Large nodes (determined by publication or citation frequency), those with purple rings (determined by centrality), and those with red inner rings (determined by burst) are usually identified as three major types of nodes which may influence the development of a scientific research domain (Chen and Wu 2017). Similarly, a thicker link shows a stronger relationship between two nodes in a connection. The general procedure for visualization analysis with CiteSpace is shown in Fig. 1.

To provide a systematic review of climate change and carbon sink research and achieve the expected objectives, three types of

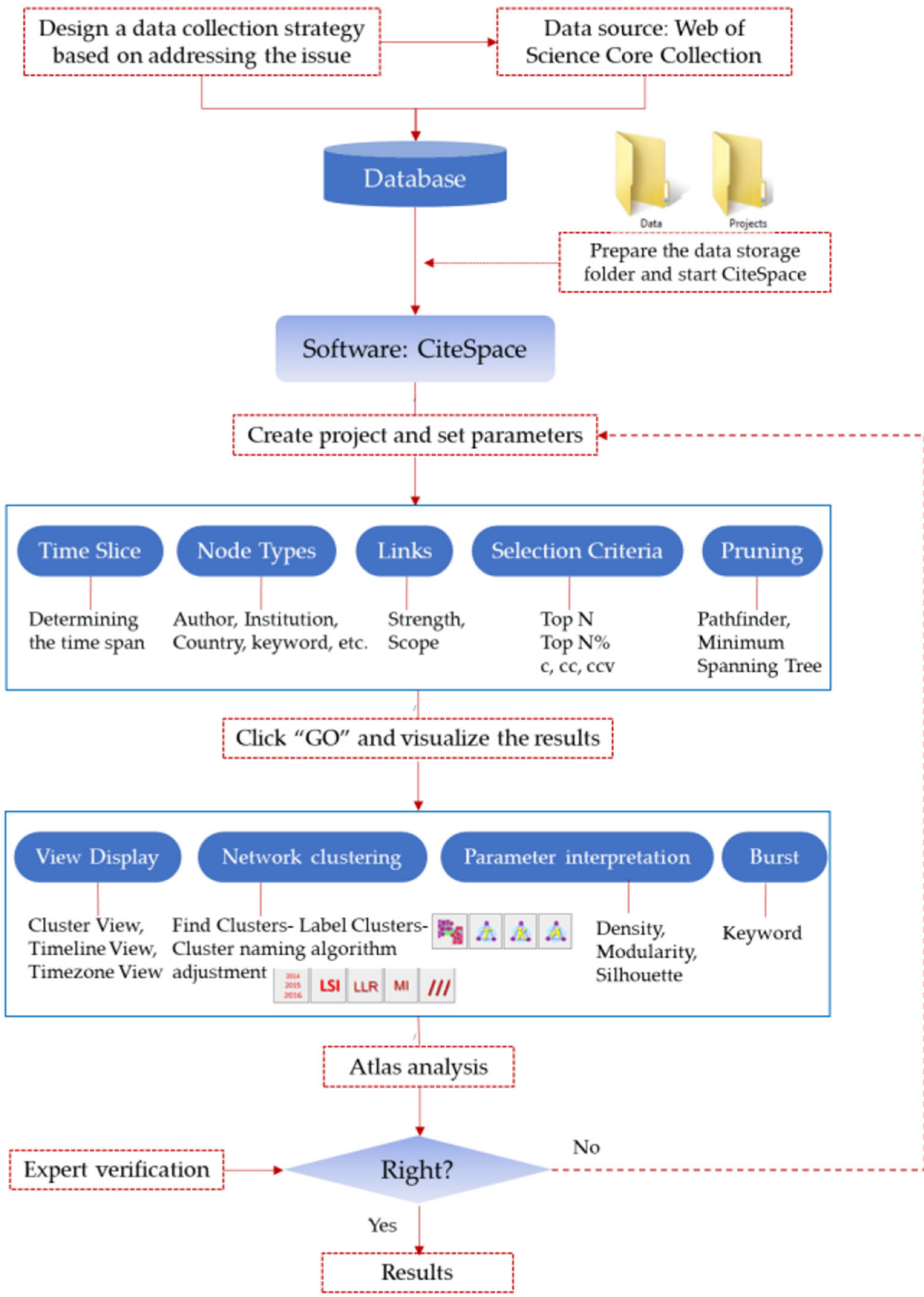

Fig. 1 Flow diagram of bibliometric analysis by CiteSpace

scientometric techniques provided by CiteSpace were applied in this study: collaboration analysis, co-citation analysis, and keyword co-occurrence analysis. Collaboration analysis takes author names, countries of affiliation, and institutional affiliation as the units of analysis and evaluates their publication contributions and academic influences by visualizing scientific collaboration networks (Chen and Wu 2017; Song et al. 2016; Fang et al. 2017). Document co-citation analysis provides insights into the intellectual structures of a knowledge domain and identifies the quantity and authority of references cited by publications (Chen et al. 2014, 2006a, b, 2010; Lee et al. 2016). In the process of this analysis, cluster views and timeline views are performed to reveal the conceptual structures and the evolution of scientific activity. In our study, an author co-citation network and a journal co-citation network are also generated to explore the most commonly cited authors and journals to find other influential points in the knowledge structure. Keyword co-occurrence analysis tracks the research hotspots, frontiers, and trends over time by establishing a network of co-occurring keywords that provide information about the core content of articles (Kim and Chen 2015; Zhu and Hua 2017). Specifically, the research frontiers and trends are identified by burst detection (Chen 2006a, b).

During execution, the parameters (e.g., time slice, node type, and pruning) in CiteSpace should be properly selected in accordance with the research objectives (Song et al. 2016). The parameters of the three analyses in this paper are set as follows:

The parameters of collaboration analysis in CiteSpace were set as:

(1) Time slicing from 1991 to 2018, years per slice = 1.
(2) Node type = country, institution, and author.
(3) We selected the top 50 most frequently occurring items from each slice for countries and institutions; for author, we selected the top 20 most frequently occurring items from each slice, which ensured that we obtained the most prominent authors.
(4) Pruning = pathfinder and pruning of the merged network. To obtain the most salient network, we chose pathfinder to eliminate redundant or counterintuitive connections (Song et al. 2016). The other settings remained set to the default settings.

The parameters of co-citation analysis in CiteSpace were set as:

(1) Time slicing from 1991 to 2018, years per slice = 1.
(2) Node type = cited reference, cited author, and cited journal.
(3) We selected the top 50 most-cited items from each slice for journals; for author, we selected the top 20 most-cited items from each slice. The node selection criteria when generating a document co-citation network included three sets of thresholds: the citation threshold (c), the co-citation threshold (cc), and the co-citation coefficient threshold (ccv). Referencing previous research on document co-citation by Chen in 2006 (Chen 2006a, b), these three sets of threshold levels are set as follows: (2, 1, 10), (3, 1, 0), and (3, 2, 10).
(4) Pruning = pathfinder and pruning of the merged network. The other settings remained set to the default settings.

The parameters of co-occurring analysis in CiteSpace were set as:

(1) Time slicing from 1991 to 2018, years per slice = 1.
(2) Node type = keyword.
(3) We selected the top 50 most frequently occurring keywords from each slice.
(4) Pruning = pathfinder and pruning of the merged network. The other settings remained set to the default settings.

H-index and impact factor

H-index, as the most common assessment tool in bibliometrics, is often used to evaluate the influence of journals, institutions, countries, and authors. It is a concise indicator proposed by Hirsch in 2005: A scientist has index H if H of his/her Np papers have at least H citations each, and the other Np-H papers have no more than H citations each, in which Np is the number of articles published during n years (Hirsch 2005). The H-index combines an assessment of quantity (number of articles) and impact (amount of citations). A higher H-index indicates greater academic impact. In this study, we use H-index to measure the academic achievements of different journals, institutions, and countries.

Another widely used tool in modern bibliometric research, impact factor (IF), is reported annually in the Journal Citation Reports (JCR) and is defined as: the impact factor of a certain journal in any given year is the average number of citations gained per paper published in that journal during the two preceding years. The official impact factor for this paper is drawn from the 2018 edition of Journal Citation Reports® in Web of Science.

In addition to the above two indicators, the number of citations a paper receives (TC) reflects the amount of influence a paper has. While the academic influence of a journal or country may vary between research fields, the average number of relevant citations per paper for a journal or country (TC/P) is a relatively suitable measure of the relative importance of the journal or country in a specific field (Ji et al. 2014). Therefore, these two indexes are also calculated in our paper.

Results

Basic characteristics of the literature

Quantity of articles and citations

The trends in the quantity of articles identified by WoS that were related to climate change and carbon sinks in the last 28 years are shown in Fig. 2. From the perspective of quantity, the research on climate change and carbon sinks has generally experienced a development process of slow growth (before 2000) to steady growth (2001–2012) to rapid growth (2013–present). In the early 1990s, relevant scholars began to pay attention to this research field, and research about climate change and carbon sinks appeared began to appear. However, as this field was in the initial stage of research, the amount of literature was relatively small before 2000. From 2001 to 2012, the research achievements gradually increased, and the number of published articles increased continuously each year, with an annual average of 21.4 articles. Since 2013, the number of papers has increased rapidly and maintained a

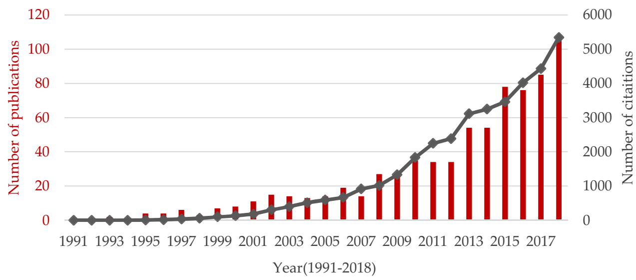

Fig. 2 Trends in the quantity of articles and citations identified by Web of Science (WoS) that are related to Climate Change and Carbon Sinks from 1991 to 2018

high growth rate. During the period from 2013 to 2018, the average annual publication volume was 75.67 articles, with an average annual growth rate of 14.65%. The increasing research results indicate that the research on climate change and carbon sinks is in its "growth stage" and has great potential for development.

The total number of citations was 36,341 over the period selected (1999–2018), and the average number of citations per publication was 48.65. The trends in the quantity of citations in the last 28 years are also shown in Fig. 2. Due to increasing concern about climate change, as well as the response of carbon sinks to climate change, it is obvious that the number of citations of papers about climate change and carbon sinks increased from 1991 to 2018, with two remarkable leaps in climate change and carbon sink research in 2013 and 2018. These trends reflect the increasing attention devoted to this area during the past decade.

Subject categories

All the articles covered one of 56 ISI identified subject categories in the WoS. The top 10 subject categories are showed in Table 1, including environmental sciences (272 articles, accounting for 36.41% of the total), ecology (187 articles, 25.03%), geosciences multidisciplinary (138 articles, 18.47%), meteorology atmospheric sciences (133 articles, 17.8%), forestry (86 articles, 11.51%), multidisciplinary sciences (77 articles, 10.31%), biodiversity conservation (70 articles, 9.37%), agronomy (36 articles, 4.82%), plant sciences (34 articles, 4.55%), geography physical (32 articles, 4.28%), and environmental studies (25 articles, 3.35%). The distribution of subject categories suggested environmental, geographical, forestry, atmospheric, and ecological issues were highly prioritized in research. The number of publications in each category reflects the development trends of climate change and carbon sink research in different domains. The numbers of publications in the categories of environmental sciences and ecology significantly increased after 2013, whereas the numbers of publications in other categories increased more gradually. Moreover, climate change and carbon sink research became more interdisciplinary over time.

Journals

The 747 selected articles on climate change and carbon sinks referenced in this study appeared in 203 journals. Table 2 lists the top 10 journals by number of articles on climate change and carbon sinks. As can be seen from Table 2, *Global Change Biology*, *Biogeosciences*, *Global Biogeochemical Cycles*, and *Agricultural and Forest Meteorology* are journals that publish more than 20 articles. Combined with the impact factors, it can be found that the journals with more than high impact factors that have more than 10 articles featured are *Global Change Biology*, *Proceedings of the National Academy of Sciences of the United States of America*, and *Nature*. In general, these journals cover related publications in the fields of geoscience, biological science, environmental science, agriculture, and forestry. This indicates that the research on climate change and carbon sinks has the characteristics of diversity and intersectionality and also reflects the systematic and complex development of research on climate change and carbon sinks.

As indicated by journal performance, there was a greater concentration of articles within the major journals. The top ten (4.93% of the 203 total) journals published 238 (31.86%) of the total of 747 articles and received 18,421 (50.69%) of the total 36,341 citations. *Nature* had the highest TC/P score (490.77), followed by *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* (312.53) and *Global Change Biology* (82.33), which are journals that also have relatively high volume of publications and impact factors. In addition, *Global Change Biology* holds the highest H-index of 38, a value far greater than that of any other journal.

Research power of climate change and carbon sinks

Author collaboration network and author co-citation network

Authors and their social relationships are the core elements of a research field, as well as an important embodiment of the research power of the field. Table 3 displays the top ten most productive authors. According to the data, Ciais P and Piao SL dominated the list of publications. Other relevant authors include Poulter B (10 articles), Cannell MGR (7 articles), Zhuang QL (6 articles), Arneth A (6 articles), and Wang T (6 articles). As for department or institution (Table 3), most of the authors in the top 10 list are affiliated with a department or institution related to ecology, geography atmospheric science, or the environment. This result is consistent with the climate change and carbon sink

Table 1 The article output of the top ten subject categories of forest carbon sequestration research

Subject category	1991–2018	Subgroups in different periods		
		1991–2000	2001–2008	2009–2018
Environmental sciences	272	15	49	208
Ecology	187	5	37	145
Geosciences multidisciplinary	138	3	19	116
Meteorology atmospheric sciences	133	10	31	92
Forestry	86	2	20	64
Multidisciplinary sciences	77	5	14	58
Biodiversity conservation	70	4	24	42
Agronomy	36	3	10	23
Plant sciences	34	3	5	26
Geography physical	32	3	4	25

output categories in Table 1. It should be noted that several of the top 10 authors are from the same institution; for example, Ciais P and Viovy N, Piao SL and Wang T, and Cannell MGR and Levy PE were co-authors of a number of relevant articles from the same institution.

Figure 3 is the collaboration network map of the authors of climate change and carbon sink research. Each node in the map represents an author, and the larger the node, the more articles the author has written. The connection between the nodes represents cooperation between the authors, and the thicker the line is, the closer the cooperation is. The author collaboration network in Fig. 3 consists of 193 authors and 342 collaboration links. The network has a large number of participants as well as a wide range of collaborations and shows the interdisciplinary nature of climate change and carbon sink research. Two typical author groups with remarkable team effects and outstanding research results make up a portion of the research on climate change and carbon sink. (1) A team of Ciais P, Piao SL, and Wang T (marked in the red circle) dedicated to the study of carbon balance, carbon cycle, and carbon budget of terrestrial ecosystems in China (Piao et al. 2009a, b, 2012a, b, 2018; Wang et al. 2014a, b; Yue et al. 2016). Since 2009, Ciais P and Piao SL have been committed to the study of carbon sinks and have cooperated closely with many scholars. (2) A group of authors led by Cannell MGR (marked in the blue circle) focuses on assessment of climate change as well as land-use change impacts on ecosystems and terrestrial carbon sinks (Cannell et al. 1999; Levy et al. 2004a, b; White et al. 1999, 2000a, bJudging from the color of the links, most of the cooperation between this research group happened between 1999 and 2004.

Table 4 lists the top 10 authors with a citation frequency greater than 50. It should be pointed out that in this analysis, only the first author is considered. The merged author co-citation network that contributes to climate change and carbon sink literature is shown in Fig. 4, which contains 300 nodes and 641 co-citation links. The top cited author is Pan Yd (123 citations) and followed by Houghton Ra (113 citations). Comparing Table 4 with the authors listed in Table 3, we can observe that Piao Sl and Ciais P appear in both tables,

Table 2 Top ten productive journals in terms of related studies

	Journals	Publications	%/747	TC[b]	TC/P[c]	h-index	IF[a]
1	Global Change Biology	63	8.43%	5187	82.33	38	10.171
2	Biogeosciences	35	4.69%	796	22.74	14	4.699
3	Global Biogeochemical Cycles	24	3.21%	1091	45.46	14	6.004
4	Agricultural and Forest Meteorology	23	3.08%	1249	54.30	14	5.317
5	Environmental Research Letters	20	2.68%	322	16.10	10	6.503
6	Proceedings of the National Academy of Sciences of the United States of America	17	2.28%	2253	132.53	14	10.60
7	Journal of Geophysical Research Biogeosciences	16	2.14%	432	27.00	8	4.319
8	Climatic Change	14	1.87%	561	40.07	10	4.783
9	Nature	13	1.74%	6380	490.77	12	45.819
10	Science of the Total Environment	13	1.74%	150	11.54	7	5.727

Note: *IF*[a] 5-year impact factor, impact factor data from the 2018 edition of Journal Citation Reports® in Web of Science. *TC*[b] the total citations for a journal. *TC/P*[c] average number of citations per paper for a journal

Table 3 Top 10 authors based on frequency

Author	Freq.	Institution
Ciais P	22	Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ- Université Paris Saclay
Piao SL	12	Department of Ecology, College of Urban and Environmental Science, Peking University
Poulter B	10	Institute on Ecosystems and Department of Ecology, Montana State University
Cannell MGR	7	Centre for Ecology and Hydrology, Bush Estate, Penicuik, UK
Zhuang QL	6	Department of Earth & Atmospheric Sciences, Department of Agronomy, Purdue Climate Change Research Center, Purdue University
Arneth A	6	Karlsruhe Institute of Technology, Department of Atmospheric Environmental Research
Wang T	6	Department of Ecology, College of Urban and Environmental Science, Peking University
Malhi Y	5	Environmental Change Institute, School of Geography and the Environment, University of Oxford
Viovy N	5	Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ- Université Paris Saclay
Levy PE	5	Centre for Ecology and Hydrology, Bush Estate, Penicuik, UK

indicating that they were not only the most productive authors but also the most influential authors. Pan Yd was widely cited and had a significant impact on the field despite the fact that he published fewer papers than the most productive authors did.

Country collaboration network

This study used CiteSpace software to analyze the countries and regions where climate change and carbon sink research is published in order to scientifically measure the geographical characteristics of research and development in this field. The analysis shows that the papers featured in the sample come from 72 countries around the world, mainly distributed in Europe, North America, East Asia, and Oceania.

Table 5 lists the top 10 most productive countries. The USA had the most publications (289 articles) and total citations (19,919 citations). China had the second highest number of publications (164 articles). However, the TC and TC/P for China were relatively low. Other productive countries include England (108 articles), Germany (90 articles), Canada (84 articles), France (58 articles), Sweden (57 articles), Australia (48 articles), Scotland (44 articles), and the Netherlands (43 articles) in turn.

Considering the TC/*P* value, the list appears more mixed, with countries such as England, Germany, France, Scotland, and the Netherlands also playing leading roles in the overall body of work. The striking case of Scotland, which had a high TC/P of 115.89, was partially due to a large number of citations of two articles, one that illustrates the possible responses of ecosystem processes to rising atmospheric CO2 concentration and climate change (Cramer et al. 2001) and another that assesses a key but poorly understood component of the global carbon cycle – Amazon forest responses to the intense 2005 drought (Phillips et al. 2009). The high TC/*P* value of England was the result of multiple high-quality articles. In addition, the USA holds the highest H-index of 68, a value far greater than that of any other country.

The network of collaborating countries consisted of 42 nodes and 72 links between 1991 and 2018 (Fig. 5). It can be found that there is close cooperation between the countries and regions with the highest number of published articles. It is worth mentioning that European countries play a crucial role in making connections with other countries due to their high betweenness centrality[1] (BC), including the Netherlands (0.54), Belgium (0.20), and Germany (0.15).

Institution collaboration network

The institution collaboration network consisted of 172 institutions and 321 collaboration links between 1991 and 2018 and is shown in Fig. 6. The relatively high maturity of the research community is indicated by the relatively tight structure and close relationships. The top 10 institutions that made the majority of contributions to the total outputs are presented in Table 6. The Chinese Academy of Sciences tops the list with 95 publications, while other institutions with a high number of publications include Peking University (29), University of Chinese Academy of Sciences (22), Lund University (22), and the US Forest Service (18).

It can be seen that China is the largest contributor to climate change and carbon sink research, with 3 institutions (ranked 1, 2, and 3; it should be noted that the University of Chinese Academy of Sciences is affiliated with the Chinese Academy of Sciences.). The second largest contributor to climate change and carbon sink research is the USA, also with 3 institutions (ranked 5, 8, and 9). The other four institutions are all located in Europe, and, among them, the Lund University and the Max-Planck-Institut für Eisenforschung Gmbh cooperate with other institutions the most closely.

[1] Betweenness centrality, an indicator to measure the importance of nodes in the network, is used by CiteSpace to measure the importance of literature. From the perspective of information transmission, the higher the value is, the more important the node is, and the greater the influence on network transmission is after removing these nodes.

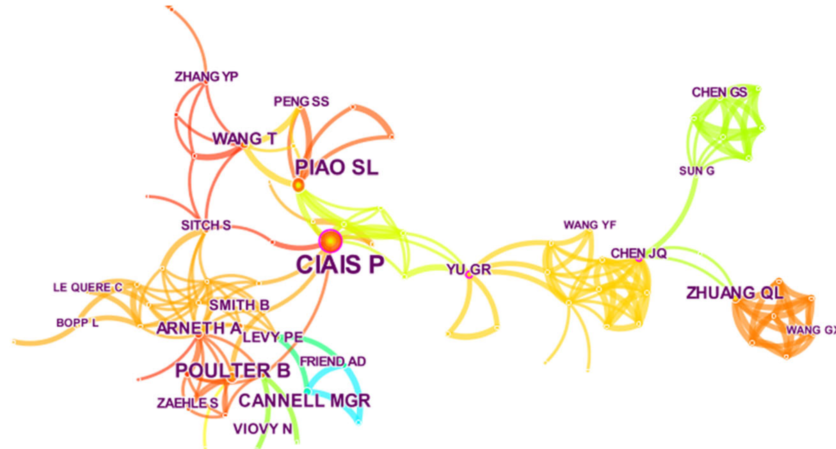

Fig. 3 The collaboration network of authors. Nodes represent authors. The size of a node is proportional to number of papers written by the author. The color of rings and links corresponds to the year

The intellectual base and research topic evolution of climate change and carbon sink research

Document co-citation network (DCN)

An intellectual base is the basis of knowledge evolution in a certain research field. It consists of a collection of co-cited documents, which is an evolutionary network, and a co-citation trajectory formed by the cited scientific literature (Chen 2006a, b). CiteSpace's cited reference analysis can be used to study the intellectual base of existing literature by describing the co-citation relationships among them. Figure 7 is a co-citation network map of the climate change and carbon sink research field. Each node in the figure represents a cited document, and the larger the node, the greater the number of citations. Among them, the purple circle highlights the nodes with betweenness centrality (BC) equal to or greater than 0.1. These nodes play a key role in the knowledge evolution of climate change and carbon sink research and are the most important intellectual bases in this field.

In Fig. 7, the largest node, which has the highest citation frequency, is "A large and persistent carbon sink in the world's forests," published in *Science* by Pan et al. (2011) (117). There were 11 key papers marked by purple circles (literature numbers K01-K11), as shown in Table 7. As can be seen from Table 7, a total of 7 of the 11 papers come from top journals *Science* and *Nature*, meaning that papers from these journals account for 64% of all key papers.

Table 4 Top 10 most cited authors with co-citation frequency

Author	Frequency	BC	Author	Frequency	BC
Pan Yd	123	0.04	Le Qc	72	0.05
Houghton Ra	113	0.36	Luyssaert S	69	0.01
Piao Sl	99	0.09	IPCC	66	0.00
Ciais P	94	0.09	Lal R	57	0.06
Sitch S	82	0.06	Cox Pm	56	0.23

Through reading the content of the literature, it can be found that most of these papers, which represent the intellectual base, put forward various analytical frameworks, prediction models, and research trends around the research on climate change and carbon sinks, laying a solid foundation for future research.

Journal co-citation network

Journal co-citation analysis refers to the phenomenon that occurs when two journals are cited by the same document. Co-citation of journals reflects correlations between various journals and disciplines. The intellectual base of a research field can also be obtained through journal co-citation analysis. The journal co-citation network for this study is shown in Fig. 8. The size of each node in journal co-citation network represents the co-citation frequency of journals in the sample. The influence of cited journals is primarily assessed by its citation frequency. Figure 8 shows that the journal co-citation network includes 211 nodes and 360 links. *Science* and *Nature* are the journals cited with the highest cited frequency (with 552 citations and 545 citations, respectively). Other top 5 journals with high cited frequency are *Global Change Biology* (with 507 citations), *Global Biogeochemical Cycles* (with 375 citations), and *Proceedings of the National Academy of Sciences of the United States of America* (with 352 citations).

According to the co-citation frequency, 80% (4/5) of journals with high influence are journals that publish the key literature listed in Table 8.

Research topic evolution

For this part, we execute the timeline view instruction after running clustering analysis and obtain the timeline map of the co-citation network (Fig. 9). Figure 9 shows the network, which consists of 914 references cited and 2640 co-citation links between 1991 and 2018. This was generated by

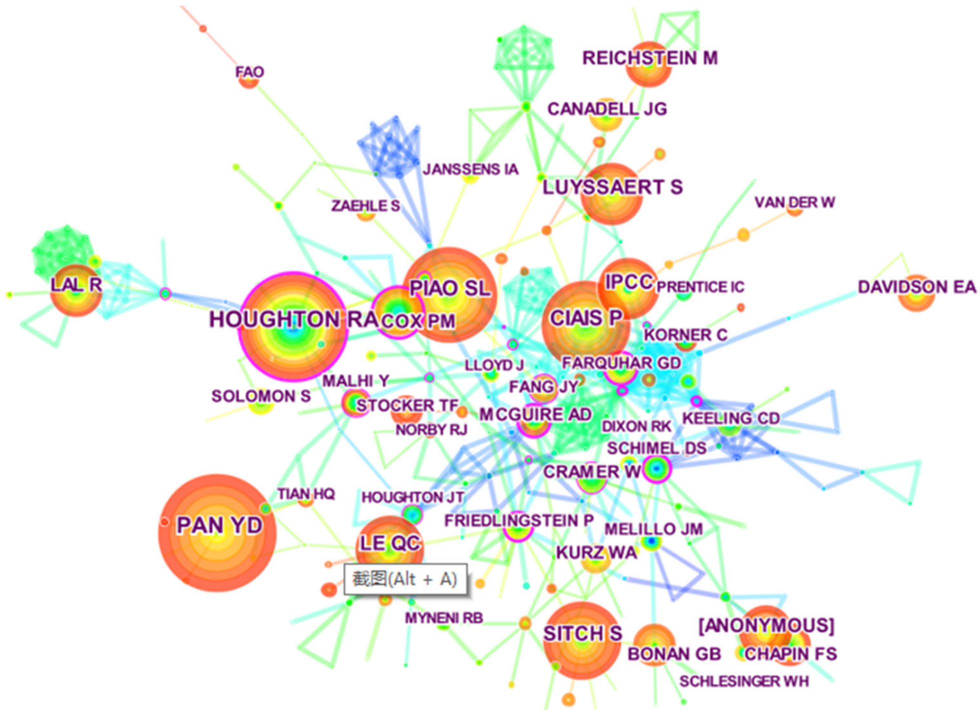

Fig. 4 The co-citation network of authors. Nodes represent authors. The size of a node is proportional to the citation frequency of the author. The color of rings and links corresponds to the year. Purple rings indicate high centrality

CiteSpace, using title terms and a log-likelihood ratio (LLR) weighing algorithm to label the clusters. LLR is an algorithm used to calculate and determine labels, which presents the core concept of each cluster. The reference is marked at the bottom of the node, and the thickness of the node indicates the citation frequency of the document. In this paper, only 6 clusters with a size above 50 are shown in vertical descending order in the graph (see Table 9 for summary of the clusters).

Modularity Q and mean silhouette are the two indexes reflecting the clarity of clustering boundary and the scale of clustering. The modularity Q value is 0.7984, which indicates that there is a clear boundary between different research topics concerning climate change and carbon sinks, while the mean silhouette value is only 0.2908, which is due to the diverse

Table 5 Top ten most productive countries in terms of relevant articles

	Country	Publications	%/747	TC[a]	TC/P[b]	H-index
1	USA	289	38.69%	19,919	68.92	68
2	China	164	21.95%	3968	24.20	29
3	England	108	14.46%	10,522	97.43	42
4	Germany	90	12.05%	6139	68.21	32
5	Canada	84	11.25%	3873	46.11	28
6	France	58	7.76%	3787	65.29	24
7	Sweden	57	7.63%	3078	54.00	22
8	Australia	48	6.43%	2847	59.31	21
9	Scotland	44	5.89%	5099	115.89	25
10	Netherlands	43	5.76%	3226	75.02	23

Note: *TC*[a] the total citations for a country, *TC/P*[b] average number of citations per paper for a country

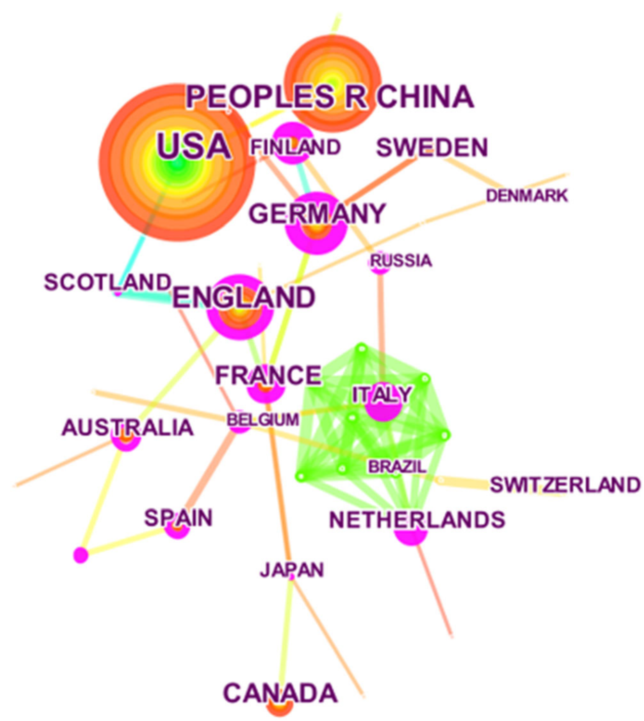

Fig. 5 The collaboration network of countries. Nodes represent countries. The size of a node is proportional to the amount of papers produced by the country. The color of rings and links corresponds to the year. The purple rings indicate high centrality

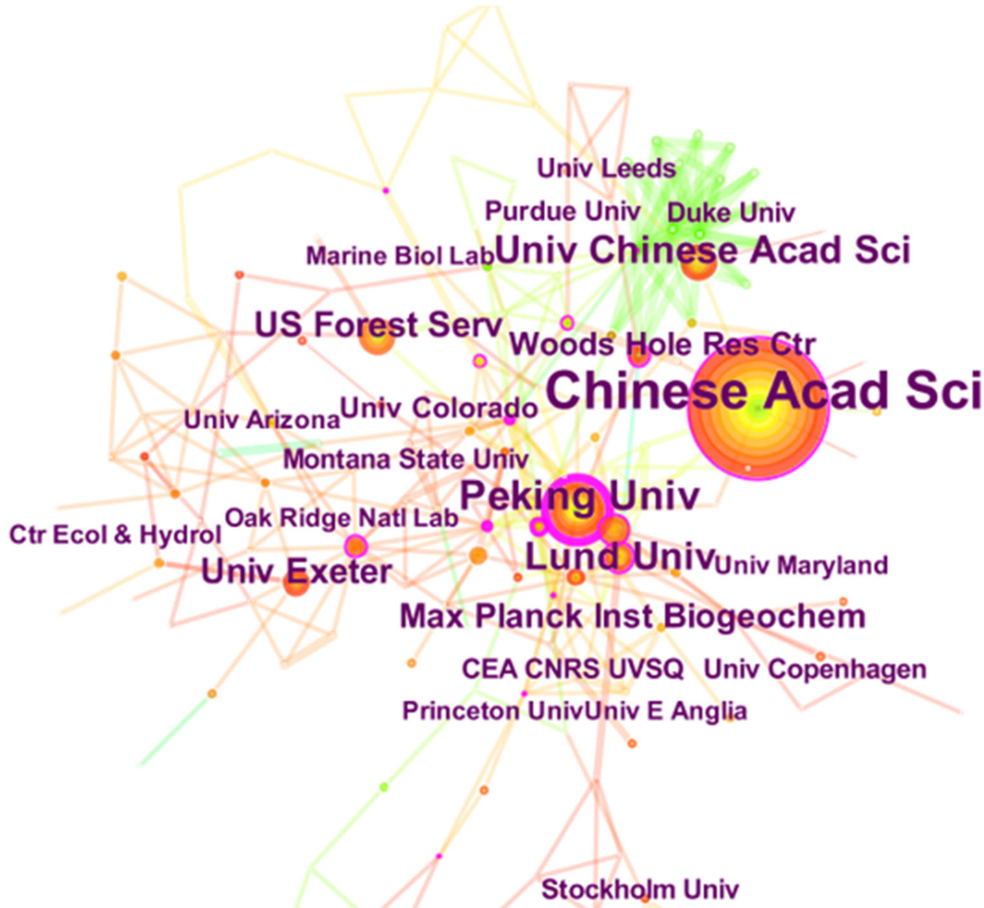

Fig. 6 The collaboration network of institutions. Nodes represent institutions. The size of a node is proportional to the amount of research published by the institution. The color of rings and links corresponds to the year. The purple rings indicate high centrality

perspectives and research paradigms applied to the fields of climate change and carbon sink research, leading to the existence of numerous small clusters.

In the timeline map, the flow of knowledge between clusters follows the distribution from dark to light, from cool to warm. Papers in the dark purple region were produced before those in the magenta region, followed by orange and yellow, representing the different stages of development of climate change and carbon sink research.

Based on the mean citation year for each cluster, the early clusters include #4 (model analysis) and #3 (reconciling apparent inconsistencies). However, these two clusters gradually became cold in the early twenty-first century. Recent clusters include #0 (multiple global change factor), #1 (carbon uptake), #2 (forest biomass carbon stock), and #5 (twenty-first century), in which cluster #0 is closely related to other clusters and #1 and #2 are currently active clusters that are closely correlated.

Table 6 Top 10 institutions based on frequency

	Institution	Country	Frequency	BC
1	Chinese Academy of Sciences	China	95	0.30
2	Peking University	China	29	0.24
3	University of Chinese Academy of Sciences	China	22	0.03
4	Lund University	Sweden	22	0.09
5	US Forest Service	USA	18	0.11
6	University of Exeter	England	17	0.10
7	Max-Planck-Institut für Eisenforschung Gmbh	Germany	15	0.19
8	Woods Hole Research Centre	USA	14	0.36
9	University of Colorado	USA	10	0.15
10	University of Helsinki	Finland	10	0.04

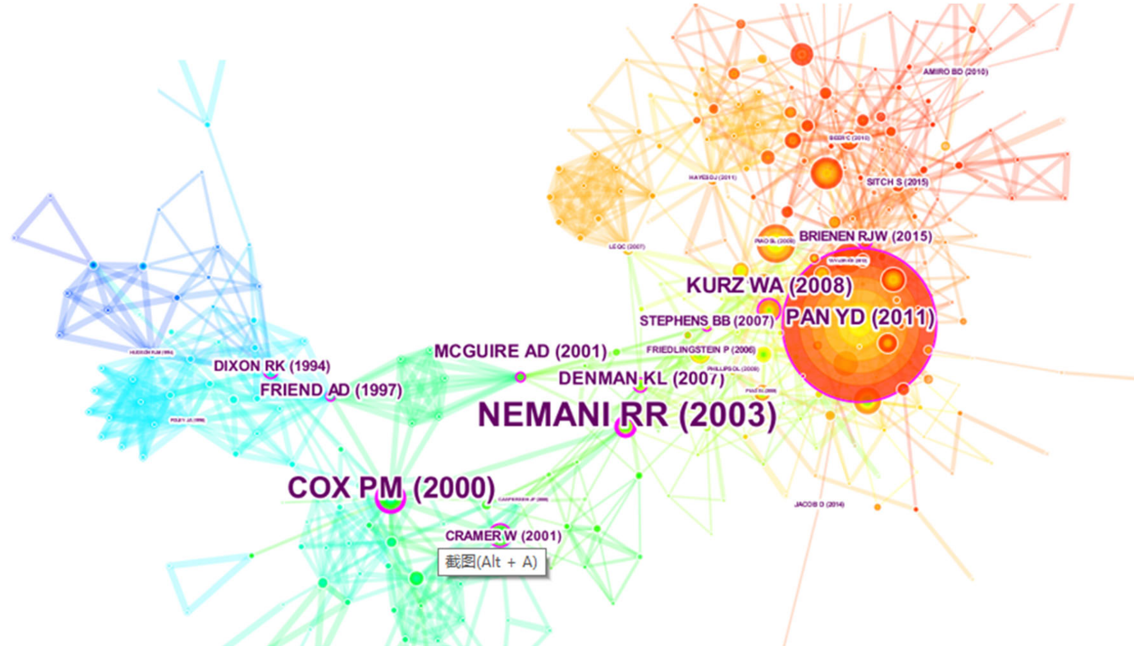

Fig. 7 A visualization of a document co-cited network for climate change and carbon sink research

The research hotspots in the fields of climate change and carbon sinks

Keywords facilitate the concentration and refinement of the core content of the literature in the field, so keywords that appear at high frequencies can reflect research hotspots in this field. Using CiteSpace's keyword co-occurring analysis, the keyword co-occurring map for climate change and carbon sink research was drawn to scientifically measure the main research hotspots in this field (as shown in Fig. 10). Each node in the figure represents a keyword. The larger the node, the higher the frequency of keyword occurrence; the more lines, the higher the frequency of keyword co-occurrence; additionally, the thickness of the connecting line is proportional to the closeness of the connection

As can be seen from Fig. 10 and Table 10, climate change has the highest frequency of occurrence as the topic subject of a search in the sample (422). The other keywords such as

Table 7 Key papers about climate change and carbon sink research

Num.	Author	Journal/book	Title	Year	BC
K01	Nemani Rr	Science	Climate-driven increases in global terrestrial net primary production from 1982 to 1999	2003	0.29
K02	Cox Pm	Nature	Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model	2000	0.26
K03	Pan Yd	Science	A large and persistent carbon sink in the world's forests	2011	0.19
K04	Kurz Wa	Nature	Mountain pine beetle and forest carbon feedback to climate change	2008	0.19
K05	Denman Kl	Climate Change 2007: The Physical Science Basis	Couplings between changes in the climate system and biogeochemistry	2007	0.16
K06	Mcguire Ad	Global Biogeochemical Cycles	Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO2, climate, and land-use effects with four process-based ecosystem models	2001	0.16
K07	Friend Ad	Ecological Modeling	A process-based, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0)	1997	0.15
K08	Cramer W	Global Change Biology	Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models	2001	0.13
K09	Dixon Rk	Science	Carbon pools and flux of global forest ecosystems	1994	0.13
K10	Brienen Rjw	Nature	Long-term decline of the Amazon carbon sink	2015	0.12
K11	Stephens Bb	Science	Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO2	2007	0.12

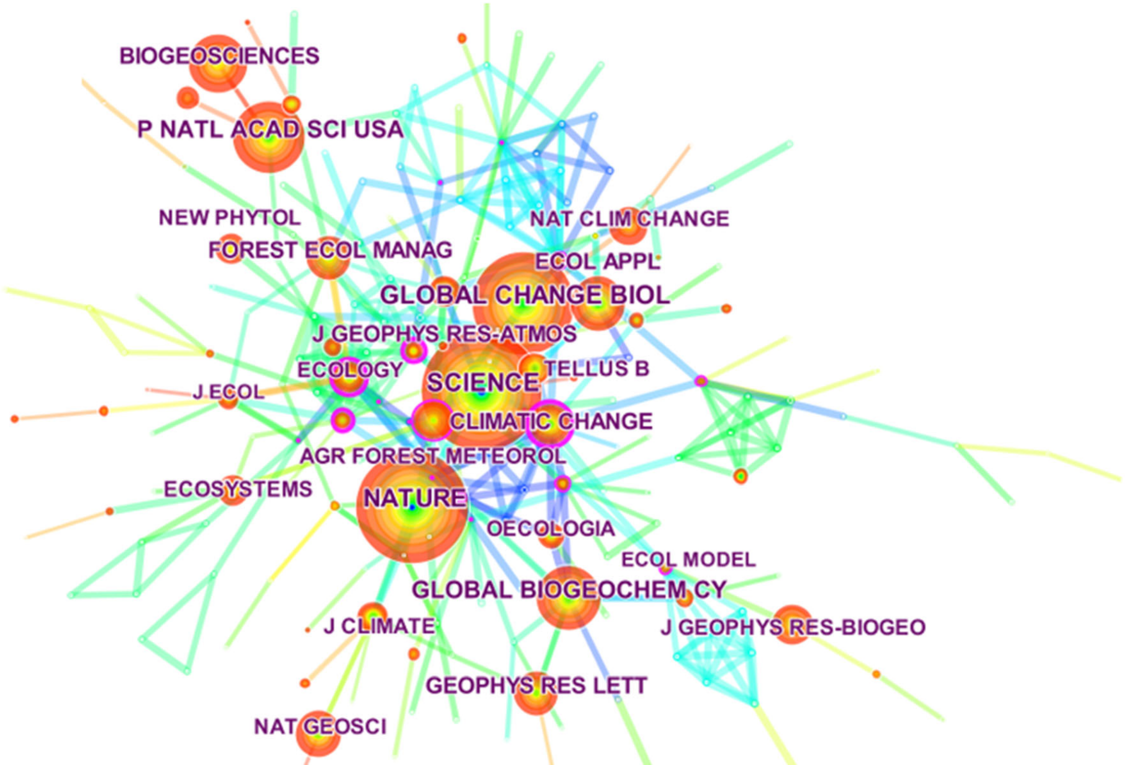

Fig. 8 A visualization of the journal co-citation network for climate change and carbon sink research

carbon sink (231; since CiteSpace cannot combine synonyms, we artificially combined the three words carbon sink sequestration and carbon sequestration into carbon sink), CO2 (168; we artificially combined the three words atmospheric CO2, CO2, and carbon dioxide into CO2), dynamics (83), model (79), and ecosystem (68) have also become significant nodes in the network because of their higher frequency of occurrence

Combined with other keywords that have a frequency greater than or equal to 30 and keywords with the strongest citation bursts, research hotspots in this field can be summarized as follows (as shown in Tables 10 and 11):

(1) The research hotspots before the twenty-first century (1991–1999) mainly focus on the role of and relationship between climate change, temperature, and atmospheric CO2. Since the end of the 1980s, global climate change issues have attracted increasingly widespread attention from the international community. The global warming over the past 50 years is largely due to human factors such as the massive burning of fossil fuels and deforestation, resulting in a significant increase in the concentration of greenhouse gases such as CO2 in the atmosphere. In the early 1990s, with the official signing and entry into force of the United Nations Framework Convention on Climate Change, the issue of climate change became a matter of great concern to all countries in the world. During this period, scholars mainly focused on keywords such as climate change, CO2, and other greenhouse gases. Keywords for this period mainly include climate change, temperature, atmospheric CO2, dioxide, ecosystem, CO2, growth, and carbon.

(2) The research hotspots in the early twenty-first century (2000–2010) moved from the sky to the ground, where they were many focused on forests and other terrestrial ecosystems. The key to the human response to climate change is to reduce the accumulation of greenhouse gases in the atmosphere. One way of doing this is to reduce greenhouse gas emissions (source); the other is to increase greenhouse gas absorption (sink). Reduction of greenhouse gas emissions is mainly achieved by reducing energy consumption and improving energy efficiency, but it often has a negative impact on the national economy of the country that is reducing greenhouse gases. Increasing greenhouse gas absorption and sinking are

Table 8 Top 5 most cited journals with co-citation frequency

Journal	Frequency	Impact factor
Science	552	43.644
Nature	545	45.819
Global Change Biology	507	10.171
Global Biogeochemical Cycles	375	6.004
PNAS	352	10.6

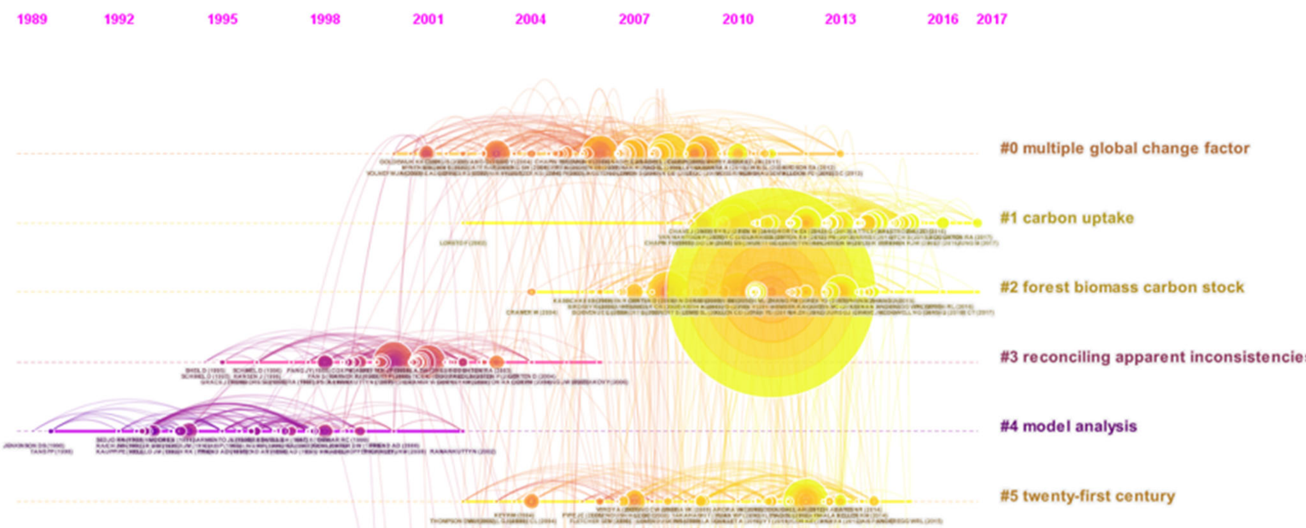

Fig. 9 Timeline view of co-citation network generated by the top 50 per slice during 1991 and 2018

mainly done using photosynthesis from forests and other plants to fix the CO_2 in the atmosphere into the plants and soils in the form of biomass, which plays an important role in reducing the accumulation of greenhouse gases in the atmosphere for a period of time. Keywords for this topic mainly include vegetation, terrestrial ecosystem, boreal forest, soil, carbon cycle, forest, photosynthesis, elevated CO_2, and land use; keywords with the strongest citation bursts include tropical forest, boreal forest, and deciduous forest.

(3) Recent research hotspots (2011–present) have gradually focused on the research of certain specific regions, such as China or arid and semiarid areas. Meanwhile, drought problems have attracted more and more attention from scholars. With the continuous deepening of relevant negotiations including the United Nations Framework Convention on Climate Change and the Kyoto Protocol, especially the implementation of the Clean Development Mechanism (CDM), carbon sink projects have great potential for development in developing countries. The carbon cycle in the ecosystem in China plays a very important role in global change, given the status of China as a major developing country. In recent years, with the constant change in the global climate, the effect of climate factors on arid and semiarid areas, where the ecological environment is fragile and easily affected by human activities, has become an important research topic. At the same time, the drought caused by warming has also begun to attract the attention of scholars during this period (Deslauriers et al. 2014; D'Orangeville et al. 2018; Logan and Brunsell 2015). The keywords used during this period include China, drought, productivity, and management.

Discussion

Main contributions

Eleven articles played key roles in the evolution of knowledge in the fields of climate change and carbon sink research. These articles are the most important pieces of the intellectual base in the field. They put forward various analytical frameworks, prediction models, and research trends around the research of climate change and carbon sinks, laying a solid foundation for future research. In terms of analytical frameworks, Dixon et al. (1994) suggested that forests could be carbon sinks or sources in the future (Dixon et al. 1994). Stephens et al. 2007's findings suggest that tropical ecosystems may currently be

Table 9 Summary of the clusters

Cluster ID	Size	Silhouette score	Label (LLR)	Mean (cite year)
0	91	0.687	Multiple global change factor	2006
1	86	0.705	Carbon uptake	2012
2	70	0.73	Forest biomass carbon stock	2011
3	64	0.889	Reconciling apparent inconsistencies	2000
4	56	0.966	Model analysis	1995
5	50	0.925	Twenty-first century	2009

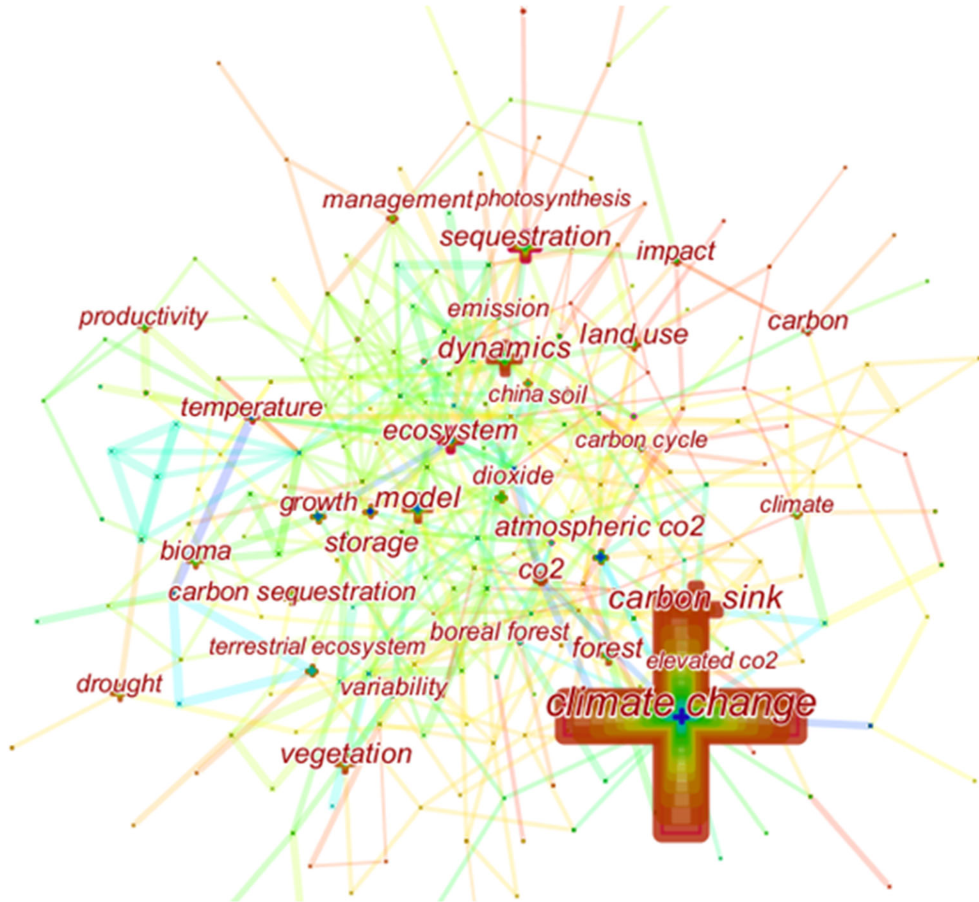

Fig. 10 A visualization of the keyword co-occurring network

strong sinks for CO2 (Stephens et al. 2007). Brienen et al. 2015's analysis confirms that Amazon forests have acted as a long-term net biomass sink, but they also find a long-term decreasing trend of carbon accumulation (Brienen et al. 2015), and these studies provide a starting point for analyzing climate change and carbon sinks from the perspective of different terrestrial ecosystems. As far as analytical models are concerned, Friend et al. (1997) described and tested a numerical process-based model of terrestrial ecosystem dynamics (Cramer et al. 2001). Cox et al. (2000) presented a fully coupled, three-dimensional carbon-climate model, indicating that carbon-cycle feedback could significantly accelerate climate change during the twenty-first century [60]. Mcguire et al. (2001) used a standard simulation protocol with four process-based terrestrial biosphere models to assess the concurrent effects of increasing atmospheric CO2 concentration, climate variability, and cropland establishment and abandonment on terrestrial carbon storage between 1920 and 1992 (Friend et al. 1997). Cramer et al. (2001) used six dynamic global vegetation models to illustrate the possible responses of ecosystem processes to rising atmospheric CO2 concentration and climate change (Cox et al. 2000). In addition, Kurz et al.

Table 10 Keywords of climate change and carbon sink research with frequency above 30

Keyword	Freq.	Keyword	Freq.	Keyword	Freq.	Keyword	Freq.
Climate change	422	Forest	64	Carbon	44	Variability	34
Carbon sink	118	Vegetation	60	Growth	43	Boreal forest	34
Dynamics	83	Storage	56	Productivity	41	Carbon cycle	33
Model	79	Land use	55	Management	36	Climate	32
Sequestration	68	Temperature	53	Drought	36	Terrestrial ecosystem	31
Ecosystem	68	Bioma	50	Soil	35	Elevated CO2	30
Atmospheric CO2	67	Carbon sequestration	45	Dioxide	34	China	30
CO2	67	Impact	45	Emission	34	Photosynthesis	30

Table 11 Top 16 keywords with the strongest citation bursts

Keywords	Strength	Begin	End	1991 - 2018
climate change	4.4338	**1991**	2004	
storage	3.3893	**1994**	1999	
net primary production	4.3485	**1994**	2011	
atmospheric CO2	10.6725	**1996**	2009	
dioxide	5.3014	**1996**	2005	
cycle	4.8832	**1996**	2002	
CO2	3.7487	**1997**	2007	
tropical forest	4.0963	**2000**	2003	
boreal forest	4.1042	**2001**	2006	
model	3.5144	**2002**	2004	
elevated CO2	4.4671	**2005**	2009	
deciduous forest	3.9758	**2005**	2006	
dynamics	3.781	**2006**	2008	
soil organic carbon	4.8259	**2010**	2013	
china	5.1052	**2012**	2015	
drought	4.5783	**2014**	2016	

(2008)'s findings suggest that insect outbreaks represent an important mechanism by which climate change may undermine the ability of northern forests to take up and store atmospheric carbon, which provided a unique perspective for future research (Nemani et al. 2003). Most of the articles above come from top journals with high influence, such as *Science* and *Nature*, which proves that these articles are documents of very high academic value.

Regarding research topics, this study identifies main research topics and summarizes their evolution over time. Six clusters were initially identified. Some early research topics such as "model analysis" were published before 2001 and gradually became less popular. This shows that the research on the analytical model has been relatively mature, and later scholars mainly estimated and analyzed carbon sinks in different ecosystems based on the mature model. The research studies on "carbon uptake" and "forest biomass carbon stock" have been emerging active topics in recent years. Although the focus of each topic is different, the contents are interrelated. This is mainly because studies of carbon uptake were mainly based on forests (Keenan et al. 2016; Detmers et al. 2015; Phillips and Brienen 2017; Van Gorsel et al. 2016; Yuan et al. 2014; Shevliakova et al. 2013; Reinmann and Hutyra 2017). Furthermore, forest biomass carbon stock is mainly achieved through the accumulation of forest carbon uptake activities. Scholars have conducted in-depth evaluations and analysis of the status, changes, and sustainable development of carbon stocks in different types of forests in different regions, such as forest biomass carbon in Europe, China, North America, the USA, Quebec, etc.(Seidl et al. 2014; Liu et al. 2017; Zhu et al. 2018; Nunery and Keeton 2010; Duchesne et al. 2016; Domke et al. 2016), decadal change of forest biomass carbon stocks in the Delaware river basin (Xu et al. 2016) and central Canada (Ter-Mikaelian et al. 2014), the forest biomass carbon stocks and variation in carbon-dense Tibetan forests (Sun et al. 2016), as well as carbon storage in mid-Atlantic old-growth forests (McGarvey et al. 2015).

In terms of research hotspots, this study contributes by categorizing research hotspots into three phases over the decades. Research hotspots in the first period (1991–1999) focused on the roles of and relationships between climate change, temperature, and atmospheric CO_2. The second period (2000–2010) focused on forests and other terrestrial ecosystems, which play an important role in reducing the accumulation of greenhouse gases in the atmosphere. Recent research hotspots (2011–present) have gradually focused on the research of certain specific regions, such as China or arid and semiarid areas (Wang et al. 2016; Chuai et al. 2012; He et al. 2015; Houghton and Hackler 2003; Justine et al. 2015; Li et al. 2017; Song et al. 2013; Song et al. 2018; Zhang et al. 2015). Additionally, drought and extreme weather conditions caused by warming have attracted more and more attention from scholars recently (D'Orangeville et al. 2018; Logan and Brunsell 2015; Fu et al. 2018). For example, the research of Van Gorsel et al. (2016) showed that the carbon sinks of large areas of Australia may not be sustainable in a future climate with an increased number of intense and lengthy heat waves (Van Gorsel et al. 2016). Huang et al. (2016) emphasized the leading role of semiarid ecosystems in interannual variability in global NPP and highlight the great impacts of long-term drought on the global carbon cycle (Huang et al. 2016). The research of He et al. (2018) revealed the strong impact of extreme droughts on ecosystem gross primary production, total ecosystem respiration, net ecosystem exchange, and latent heat flux (He et al. 2018). Overall, research in this field is becoming more abundant, specific, and in-depth.

Future research

The future research potential of climate change and carbon sinks was summarized given the current development trends of the studies. First, as discussed above, most of the current analysis and assessment of climate change and carbon sinks is based on existing mature methods and models, and the results are relatively reliable. However, the application of big data technology in research about this field can be improved. Big data is a growing technology field. Future studies could focus on applying big data technology to climate change and carbon sink research. For example, machine learning can be used to predict the amount of carbon sinks in various ecosystems under different climate scenarios, and the data can be visualized in the form of graphs. Second, most studies analyzed in this field focused on forest biomass carbon sinks. Some studies have found that forest carbon sinks are not as large as expected (Fang et al. 2001a, b; Fang 2000; Lewis 2006; Stephens et al. 2007; Nadelhoffer et al. 1999), while other studies have found that carbon sink efficiency does not increase as carbon emissions from human activities increase but instead shows a decreasing trend (Raupach et al. 2014). More studies are needed in the future to explore carbon sinks in other terrestrial ecosystems, such as wetlands, grasslands, marine carbon sinks, and rock weathering-related carbon sinks. Third, in addition to the drought issue mentioned in the research hotspots, there have been some controversial research hotspots in this field recently. For example, vegetation phenology plays a key role in terrestrial ecosystem nutrient and carbon cycles and is sensitive to global climate change. Compared with spring phenology, which has been studied extensively, autumn phenology is still poorly understood. Another example is year-to-year variations in the atmospheric CO_2 growth rate are mostly due to fluctuating carbon uptake by land ecosystems, but to what extent temperature and water availability control the carbon balance of land ecosystems across spatial and temporal scales remains uncertain, some scholars have made efforts in these aspects (Jung et al. 2017; Humphrey et al. 2018), but we need more research in this area. Finally, in terms of analytical framework, it is suggested that future research consider applying systematic scientific methods. The systematic approach is to use the principles of system theory to investigate the relationship between the whole and parts of a system. A systematic approach can be used to comprehensively examine the combined effects of climate change on ecosystems, including changes in weather conditions, ecosystem changes, and socioeconomic changes. The systematic approach is very challenging to apply. Despite the challenges the systematic approach presents, it is an important tool for studying climate change and carbon sinks, as it allows scholars to explore the establishment of multifactor, multi-scenario, and collective system simulation platforms.

Limitations

Although this study has made some contributions to the field, it also has some limitations. First, although the Web of Science database covers the majority of peer-reviewed journals, it may omit some relevant research on the topic. Multisource searching and a cross-comparison among different databases would be more convincing. Second, in this study, we analyzed the publications within strict limitations, in order to avoid obtaining irrelevant search responses. This work may be improved in the future in order to obtain more accurate results when searching for articles. Third, although we identified the main research themes and their evolution, deeper information on each research topic, such as the methodologies, theoretical background, and the main findings of each work, is still needed. Finally, it should be pointed out that CiteSpace software also has its own limitations, though this technology has been used for many bibliometric research studies. For example, the first author and corresponding author are not distinguished clearly. In addition, CiteSpace could be improved by allowing different knowledge domain visualization techniques to be combined to provide a comprehensive domain visualization map of climate and carbon sink research. For example, UCINET could be used to examine various attributes of the collaboration network, such as the average path between two nodes, clustering coefficients, and the degree of distribution. However, the findings of this paper are based on objective data and are stable, reliable, and, on the whole, not influenced by empiricism.

Conclusions

Taking SCI-E and SSCI of “Web of Science core collection” as the sample data source, this paper, based on bibliometric analysis and CiteSpace, provides a unique snapshot of the climate change and carbon sink knowledge domain. Although climate change and carbon sinks are evolving into popular research fields, a thorough bibliometric analysis revealing and visualizing the intellectual base, research topic evolution, and research hotspots in these fields has not been conducted. This initial effort has contributed to this field by identifying the intellectual base and providing a roadmap of evolution of research topics and hotspots, not only acknowledging current research developments in this field but also enlightening possibilities for future research.

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