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Review

Research Development, Current Hotspots, and Future Directions of Blue Carbon: A Bibliometric Analysis

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Abstract: The blue carbon ecosystem has a strong capacity for carbon sequestration, but its research progress and development are still unclear. This study used CiteSpace to conduct a visual analysis, based on the analysis of 908 articles retrieved from the Web of Science Core Collection. The results showed that blue carbon research has gone through an early exploratory stage based on the scientific concept research, a research stage on the carbon sequestration process of the diverse blue carbon ecosystems, and a blue carbon protection and restoration stage based on climate change and human activities. The blue carbon theoretical framework has been continuously improved and the subject is currently more focused. The hot research topics are different at different stages. In the early stage, they focused on the types of blue carbon ecosystems and the process of carbon sequestration. Blue carbon research has developed from a single ecosystem type to multiple ecosystem types, and from concept recognition to system assessment research. Recently, research on the response, restoration and protection of blue carbon ecosystems has become a hotspot under the combined effect of human activities and climate change. In the future, it is necessary to strengthen the scientific research on blue carbon, to protect the integrity of the ecosystem structure and service functions, and to make a greater contribution to the global carbon neutrality strategy.

Keywords: blue carbon; bibliometric analysis; CiteSpace; research development; hotspots; future directions

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1. Introduction

Global climate warming is a major issue closely related to human survival and development, and it results mainly from carbon emissions [1]. The fifth report of the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) pointed out that the use of fossil energy by humans and the constant changes in the way that land is used have led to an upward trend in carbon emissions. To combat global climate warming, carbon sequestration and storage processes need to be focused on reducing carbon emissions. As a result of the Earth's self-regulating mechanism, part of the artificially emitted CO_2 remains in the atmosphere, while another part is absorbed by the terrestrial and marine ecosystems. It is estimated that of the approximately 7.8 petagrams of carbon per year (PgC/year) of artificial CO_2 emissions, about 2.3 PgC/year is absorbed by the ocean, 1.5 PgC/year is absorbed by land, and the remaining 4.0 PgC/year stays in the atmosphere [2]. Therefore, it follows that the ocean is an important place for the processes of carbon fixation and storage.

In 2009, the GRID-Arendal, the UN Environment Programme, the UN Food and Agriculture Organization, UN Educational, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission and other institutions jointly released the "Blue Carbon: The Role of Healthy Oceans in Binding Carbon" report, which proposed the concept of blue carbon, namely the carbon captured by marine organisms, and confirmed the crucial role of the ocean in global climate change and carbon cycle processes [3]. This concept has attracted widespread attention from governments, scientists, environmental groups and the public. In the study of the mechanism of marine carbon sequestration and carbon storage, researchers have found that the ocean can achieve carbon storage through physical, chemical and biological mechanisms, including the solubility pump [4], carbonate pump [5], biological pump [6,7], micro-biological carbon pump [8], etc., which provides a theoretical basis for blue carbon research. Blue carbon encompasses the carbon sinks of marine habitats, such as coastal zones, wetlands, swamps, estuaries, offshore, shallow seas and deep seas. Due to the lack of maintenance of marine habitats, an average of 2–7% of the blue carbon capacity disappears every year, and the rate of disappearance is increasing [3]. Since blue carbon is under serious ecological threat, the current status assessment of blue carbon, the formulation of countermeasures and policy formulation have become the focus of research. American scholars have described and evaluated the distribution and the carbon sequestration potential of seagrass, tidal flat wetlands and mangroves worldwide [9,10], providing inspiration for research on blue carbon in other countries. Afterwards, researchers in Australia [11,12], the United Kingdom [13,14], South Korea [15,16] and other coastal countries have conducted extensive research and evaluation on the status, existing problems and countermeasures of their own blue carbon storage and/or sequestration capacity. With the gradual global increase in research on blue carbon, international organizations, such as Conservation International, the International Union for Conservation of Nature, the Intergovernmental Oceanographic Commission, and UNESCO, have cooperated with governments at all levels to promote blue carbon policies worldwide. Policy research on blue carbon focuses on the connection between the trading market of global carbon emissions and the blue carbon plan, policy support for the implementation of the local blue carbon plan, and establishment of the local blue carbon trading market [17–24].

At present, research on blue carbon focuses mainly on blue carbon quantification, ocean carbon sequestration and carbon storage mechanism, and blue carbon management strategies. There are also review articles on blue carbon research [25–28], but these reviews are generally based on the existing research. There are few articles that use bibliometric methods to examine the research progress and development context of this research field.

Bibliometrics is a common quantitative analysis method, which is based on the principles of mathematics and statistics. It takes many features of the available literature as the research object, investigates their distribution structure, quantitative relationship and change laws, and visualizes the results of bibliometrics through knowledge graphs. It is a well-established method of literature analysis and information mining [29,30]. The CiteSpace bibliometric analysis software was designed and developed by Dr. Chaomei Chen from Drexel University (Philadelphia, PA, USA) [31]. It is used for the measurement and visualization of bibliographic information and is widely used in various fields [32–37]. Therefore, the CiteSpace 5.8.R3 software is used in this study as an auxiliary means to investigate the current progress in international research on blue carbon, aiming to determine the main directions of the current related research and make new breakthroughs, in order to promote the future development of blue carbon research and improve the human well-being.

2. Materials and Methods

2.1. Data Sources

The Web of Science (WoS) website was used as the literature search platform, selecting the "WoS Core Collection" as database, setting the retrieval strategy to Subject = (blue-carbon) and the document type to articles, with a retrieval time span from 1985 to 2021, obtaining 915 retrieval results. The retrieval results were screened one by one, and after excluding the irrelevant articles, 908 valid articles were included in this study. The filtered articles were downloaded and saved as plain text files in the format of "full record and cited references" and used as the data samples for literature analysis.

2.2. Data Processing and Analysis

Analysis was performed using the CiteSpace 5.8.R3 visualization software. In the software, the country, institution or author options were selected for analysis of the research cooperation network; the keyword option was selected for the analysis of the keyword co-occurrence and emergence; the reference option was selected for the co-citation network analysis so as to obtain the statistical data and visual maps of the blue carbon research field, and to analyze its research status, themes, hotspots and frontiers.

In order to generate a visual map, the pathfinder pruning method was selected to simplify complex networks and to highlight the key points of analysis [38]. The settings of other parameters selected were the system default settings. In the visual graph, "Density" represents the strength of the connection between nodes, the larger the node or the font, the higher the frequency of the occurrence; the change in the color of the node or the font from cool to warm represents the time of the research from old to recent; the circle layer of nodes represents the annual rings, the purple circle layer is the centrality of focus (centrality > 0.1), and the width of the annual ring refers to the size of the centrality, so as to reflect the mechanism and the influence of countries/institutions/authors/keywords, etc. [31].

3. Results and Discussion

3.1. The Development Path of Blue Carbon Research

3.1.1. Literature Output Trends

The statistical analysis of the annual publication volume of 908 articles obtained from the WoS (Figure 1) reveals that the research on the development of blue carbon was relatively slow before 2016, with an average annual publication volume $\leq$24 articles and a cumulative publication volume of 69 articles, accounting for 7.6% of the total published volume. During this period, scholars put forward the basic concept and main ecosystem types of blue carbon, including mangroves [39], macroalgae [40], seagrass [41], mudflat [42], salt marshes [43], etc., and obtained their respective carbon storage capacity estimates. From 2016 to 2017, the development of blue carbon research accelerated in only two years, with an annual publication volume of $\geq$60 articles, and a cumulative number of 135 articles, accounting for 14.9% of the total number of articles published. The research content in this period is a continuation of the previous period. It also focuses on carbon storage assessment. In addition, we found that scholars expanded their research in four aspects. The first is the research scope and blue carbon ecology. The carbon storage capacity of coastal ecosystems has been assessed in Africa, the United Arab Emirates and other countries [44–47], and the important role of shellfish and coral reefs in carbon storage has been established [48]. Then, there was the expansion of the monitoring and evaluation methods using environmental-DNA [49], pan-sharpening algorithms [50], etc., to calculate the carbon storage capacity. After that, the driving factors in the process of carbon sequestration have also been studied. Climate change and the human land use have been the main driving factors [51,52], including nutrient load [53], biological and physical disturbance [54,55], sediment salinity [56], etc. Finally, blue carbon management strategies have been developed to provide new ideas for increasing carbon sinks, including reducing anthropogenic nutrient input, restoring top-down bioturbation population control, and restoring hydrological connectivity [57,58]. In 2016, the ocean blue carbon was included in the national strategies of China and other countries, and in 2017, its inclusion in the special report of the UN IPCC promoted the acceleration of blue carbon research at this period. From 2018 to 2021, blue carbon research entered a period of rapid development, with a total of 704 articles published, accounting for 77.5% of the total, indicating that blue carbon research has become increasingly popular. At this period, there are deeper studies on the carbon sink mechanism, blue carbon quantification methods, and blue carbon management. It is worth noting that the microbial carbon pump theory provides scholars with new perspectives and ideas for studying the carbon storage capacity of the ocean [59,60]. It is undeniable that the digital publication, new journals and the emergence of the Chinese academic sector have led to the growth of the total output of scholarly publication [61], which interferes with the statistical analysis of the annual publication volume. However, under the background of global carbon neutralization, the blue carbon theoretical framework has been continuously improved, its research depth and breadth have been expanded, and its research will remain active.

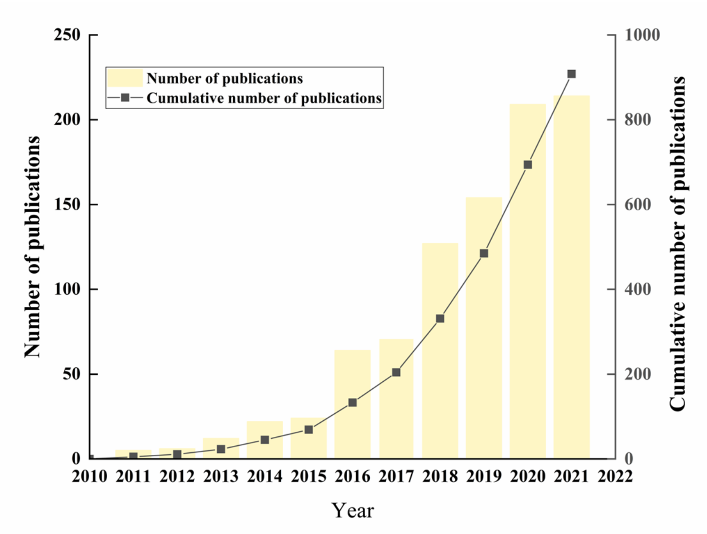

Figure 1. Annual and cumulative publications of blue carbon research.

3.1.2. Main Research Force

The analysis of the countries of publication revealed that 908 research articles were published by 85 countries and regions, and the United States, Australia and China ranked in the top three for the number of published articles (Figure 2), with 289, 234 and 160 articles, respectively, accounting for 31.8, 25.8 and 17.6%, respectively, of the total published volume. Based on the national population at the end of 2021, the per capita number of articles published in Australia was 910/100 million, which was much larger than 87/100 million in the United States and 11/100 million in China. Density represents the strength of the connection between nodes in the visual graph. The density of the connection strength between the network nodes of the countries from which the literature comes from is 0.16, indicating that most countries or regions participate in blue carbon research in the form of cooperation with other countries or regions. The analysis of the thickness of the connection between nodes revealed that the United States has close cooperation with Spain, Australia has close cooperation with South Korea, India and other countries, while China, Japan and other countries have relatively weak cooperation with other countries, suggesting that the international cooperation needs to be strengthened. The centralities of the network nodes of such countries as the United Kingdom, the United States, France, Malaysia, Italy, Wales and Indonesia are all greater than 0.1, indicating that these countries have an important position in the scientific research cooperation of blue carbon.

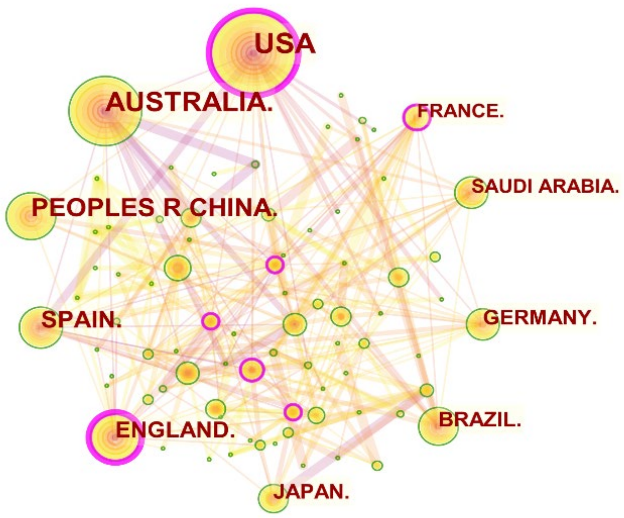

Figure 2. Analysis of the network of blue carbon scientific research cooperation by country.

The analysis of the publishing institutions showed that 908 research articles were published by 263 institutions, and Deakin University, Edith Cowan University and University of Queensland ranked the top three in the number of published articles (Figure 3), all located in Australia, with 57, 56 and 47 articles, respectively. The density of the connection strength between the network nodes of the institutions was found to be 0.014, indicating that the overall cooperation between institutions is relatively loose. As for the centrality of the document affiliation network nodes, those of Oregon State University, Florida International University, Smithsonian Environmental Research Center, University of Western Australia, Hokkaido University and Chinese Academy of Sciences are all larger than 0.1, involving Australia, the United States, Japan and China, which shows that these institutions play an important role in blue carbon scientific research cooperation. In general, universities perform better in blue carbon scientific research than scientific research institutes and companies in the environmental field.

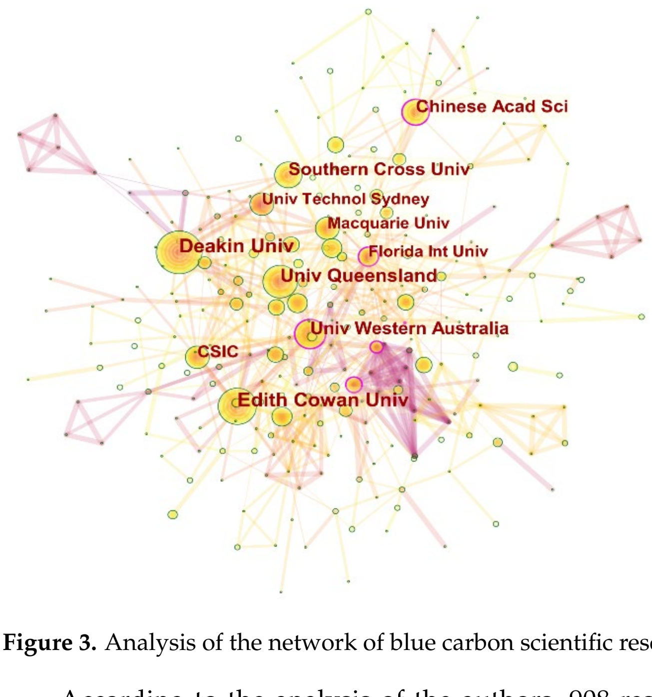

Figure 3. Analysis of the network of blue carbon scientific research cooperation by institution.

According to the analysis of the authors, 908 research articles were published by 373 authors, with Catherine E. Lovelock from Australia and Carlos M. Duarte from Saudi

Arabia tied for first place with 31 papers, and Oscar Serrano from Australia second with 30 papers (Figure 4). The density of the connection strength between the network nodes of the authors was found to be 0.0089, indicating that the cooperation structure among scholars is loose. The centralities of the network nodes of the authors of the articles are all less than 0.1, indicating that there is no team with strong centrality, and the research results on blue carbon are still in a process of accumulation. It is not possible to use the publication volume as the only indicator to judge the contribution of a country, an institution or an author to blue carbon research. Factors such as the number of published papers per capita, the strength of cooperation and the number of active scientists should be comprehensively considered.

Figure 4. Analysis of the network of blue carbon scientific research cooperation by author.

3.2. Topic Identification and Evolution in Blue Carbon Research

A co-citation relationship occurs when two or more articles are cited by one or more articles at the same time. Cluster analysis of the co-citation network can reveal the changes of research topics at each period [62,63]. The clusters were labelled using the title themes and a log-likelihood weighting algorithm, resulting in 14 clusters whose research themes are shown in Table 1 in descending order. The modularity Q and the weighted mean silhouette S are two indicators that reflect the clarity of the cluster boundaries and cluster size [64]. The modularity Q was found to be 0.73, indicating that there is a clear boundary between different research topics in blue carbon research. The weighted mean silhouette S was found to be 0.86, revealing a higher degree of homogeneity among different research topics in blue carbon research. There are six clusters with more than 35 citations in total. The research topics include the accumulation rate, mangrove–salt marsh ecotone, mangrove forest, European coastal blue carbon storage benefit, carbon outwelling and carbon sequestration capacity.

Table 1. Co-citation network clustering groups of articles.

Cluster ID	Size	Silhouette	Begin Year	End Year	Mean Year	Top Terms (LLR, *p*-Level)
0#	107	0.82	2011	2020	2016	Accumulation rate (367.08, <0.01);
1#	97	0.78	2011	2020	2015	Mangrove–salt marsh ecotone (231.40, <0.01)
2#	76	0.76	2009	2020	2015	Mangrove forest (518.49, <0.01);
3#	42	0.96	2007	2012	2010	European coastal blue carbon storage benefit (82.18, <0.01)
4#	42	0.95	2012	2020	2016	Carbon outwelling (220.54, <0.01)
5#	35	0.90	2008	2014	2011	Carbon sequestration capacity (238.20, <0.01)
6#	30	0.93	2009	2016	2011	Critical issue (91.21, <0.01);
7#	29	0.93	2013	2020	2017	Greenhouse gas abatement (178.52, <0.01)
8#	25	0.92	2011	2016	2013	Coastal resilience (102.38, <0.01)
9#	24	0.93	2012	2020	2015	Organic matter (220.97, <0.01)
10#	20	0.96	2012	2020	2016	Kelp detritus (218.42, <0.01)
11#	17	0.92	2007	2014	2012	Seagrass bed (98.44, <0.01)
12#	11	0.99	2016	2020	2018	Integrating blue carbon (74.31, <0.01)
13#	8	0.97	2016	2020	2018	Nutrient accumulation (88.11, <0.01)

Based on the average years of each cluster, combined with the analysis of the literature output trends above, the overall evolution can be divided into the following three periods. Before 2016, there was an early exploratory period of blue carbon research on topics including mangrove–salt marsh ecotone, mangrove forest, European coastal blue carbon storage benefit, carbon sequestration capacity, critical issue, coastal resilience, organic matter and seagrass bed. It follows from the research topics at this period that scholars elucidated key concepts and problems of blue carbon research from the macro level [65], and identified the main types of blue carbon ecosystems, including mangroves, salt marshes, seagrass beds, etc. [39–43]. Additionally, they established that the coastal blue carbon ecosystems have a strong carbon sequestration capacity. Vegetated coastal ecosystems are of interest for their ability to capture carbon dioxide and store organic carbon. Although their global area is smaller than that of the terrestrial forests by one to two orders of magnitude, the contribution of coastal vegetated habitats per unit area to the long-term carbon sinks is much larger [25]. It is noteworthy that mangrove–salt marsh ecotone, mangrove forest and organic matter have remained among the hot research topics.

From 2016 to 2017, research themes were more focused on the diversity, complexity and the systematicness of blue carbon ecosystems. The research on the carbon sequestration mechanism and mechanism became the focus of research. The protection and management of blue carbon began to gather attention for research topics including the accumulation rate, carbon outwelling, greenhouse gas abatement and kelp detritus. The coastal blue carbon is mainly composed of the biomass carbon captured by habitats, such as mangroves and organic carbon stored in sediments (or soils). The accumulation rate is an indispensable parameter in assessing the biomass accumulation or carbon storage in sediments (or soils) [66–68]. In the study of blue carbon sequestration mechanisms, besides the sediment (or soils) burial mechanisms, the outward migration of the dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), particulate organic carbon (POC) in blue carbon habitats (i.e., the lateral volume or lateral output) and marine storage mechanisms cannot be ignored [69]. On the other hand, at this period, the types of blue carbon ecosystems were expanded. It follows from the topic of "kelp detritus" that blue carbon not only includes the carbon fixed by higher plants, such as mangroves, salt marshes, and seagrass beds, but also the aquaculture carbon sink produced by algae, shellfish and other organisms [48,70,71]. Blue carbon ecosystems help mitigate climate change by sequestering carbon. Many countries with blue carbon resources have advocated for the reduction in greenhouse gas emissions and implemented the blue carbon restoration projects using carbon financing mechanisms [57,72]. The topics at this period have also been continuously studied. Among them, articles on the topic of the accumulation rate have received the largest number of citations, with a total of 107 articles. The research topic started in 2011 and has continued for 10 years.

From 2018 to 2021, the blue carbon research began to enter the phase of blue carbon protection and restoration for the purpose of responding to climate change and human activities, and the research topics focused on integrating blue carbon and nutrient accumulation. The two aforementioned periods focused on research on the concept, mechanism and type of blue carbon ecosystem, which provides a knowledge base for policy management research at this period. The marine ecosystems play an important role in carbon sequestration and nutrient accumulation [73,74]. In order to identify the indirect and direct drivers of changes in the state of blue carbon ecosystems, researchers have investigated management strategies of blue carbon ecosystems in the Philippines, Indonesia and other countries and have found that the concept of "blue carbon" has not been fully incorporated into the current management plans [75–78]. In addition, in the past decade or so, blue carbon protection projects have been conducted worldwide, and the research on long-term monitoring of large-scale blue carbon restoration projects, evolution patterns, and contributions to the climate change is relatively weak. Challenges remain in the development of long-term sustainable blue carbon conservation measures and policies to improve the human well-being and mitigate climate change. In the future, breakthroughs will be an important direction of marine ecology in theories and methods for the protection and sustainable restoration of marine carbon sink functions under the dual interference of human activities and climate change.

3.3. Hotspot Analysis of Blue Carbon Research

The analysis of the co-occurrence of keywords can offer detailed information about the research fields and can monitor the hotspots and frontiers of the research fields [31]. The CiteSpace software was used to extract high-frequency keywords in the literature during the research period, 449 keyword nodes and their 1638 links were obtained. The keywords with a frequency of $\geq$50 times are summarized in Table 2. The keyword co-occurring network is shown in Figure 5. It reveals that the research hotspots in recent years have focused on the types of blue carbon ecosystems, carbon sequestration processes, and protection and management strategies. According to the earliest years when the keywords appeared, most of the high-frequency keywords appeared before 2016, indicating that the knowledge system of blue carbon research was basically formed in the early exploration period. The subsequent large number of literature has remained close to that basic knowledge.

The blue carbon ecosystems have efficient carbon sequestration capacity, which can potentially mitigate the increase in the concentration of atmospheric carbon dioxide and serve to achieve carbon neutrality. In the study of the types of blue carbon ecosystems, various high-frequency keywords appeared, such as forest, sediment, salt marsh, biome, coastal wetland, vegetation, and mangrove forest, indicating that the coastal zone is a hot spot for research on marine carbon sinks [10,25,57,77,79–82]. The coastal zone is controlled by the sea water and tides, and also has higher wetland plants, such as salt marsh grass and mangroves. The carbon sequestration capacity per unit area of the ecosystems composed of higher plants in these wetlands is more than 10 times higher than that of terrestrial ecosystems [25]. These ecosystems only account for 0.2% of the global ocean area, but the carbon buried in their sediments may account for 50% of the total carbon storage in marine sediments [83]. This type of blue carbon ecosystem can be destroyed by human activities and can also be increased through conservation and restoration. Coastal mangroves, salt marshes and other ecosystems have high productivity and artificial controllability, and they have become hot research objects [84–88]. In the research on the carbon sequestration process, such high-frequency keywords as sequestration, dynamics, organic carbon, storage, accumulation, etc. appeared. The marine ecosystems include far-sea ecosystems and coastal ecosystems, and are the interaction zones of the hydrosphere, lithosphere, atmosphere and biosphere. Multi-interface processes are an important feature of the ocean. They include not only such interface processes in a vertical direction, such as water–air, sea–air, soil–air, soil–water, etc., but also those in a horizontal direction, such as estuaries–tidal flats and offshore–distant seas. Carbon in the marine system is exchanged, transported and transformed through multi-interface processes, thus determining the carbon pool budget of the marine ecosystem [82]. From the high-frequency keywords, it follows that the organic carbon fixation, storage and accumulation processes have received considerable attention, especially the vertical carbon fixation process, which has become a hot research topic. Regarding the protection management strategies, there are high-frequency keywords, such as climate change, sea level rise, emission, stock, growth and conservation. Climate change and human activities are the main driving forces for the degradation of the carbon sink function of the global blue carbon ecosystem. On the one hand, global climate change leads to the rise of the sea level and shrinkage of the blue carbon ecosystem, which in turn leads to changes in the growth and succession of plants, and particularly, alters the production and decomposition related to the carbon cycle. On the other hand, human activities have changed the land use patterns. For example, the discharge of wastewater during the production and operation activities, results in the eutrophication of coastal waters [52,89,90]. Under the background of climate change, the protection of the functions of the blue carbon ecosystem and the formulation of management strategies have become research hotspots.

Table 2. Statistics of high-frequency keywords in blue carbon research.

Serial Number	Frequency	Year [1]	Keywords
1	168	2011	climate change
2	159	2012	forest
3	133	2012	sequestration
4	122	2012	dynamics
5	118	2014	organic carbon
6	112	2014	ecosystem
7	100	2014	sediment
8	90	2016	storage
9	89	2014	organic matter
10	84	2013	ecosystem service
11	82	2013	carbon sequestration
12	80	2012	biome
13	71	2016	salt marsh
14	70	2013	coastal wetland
15	68	2014	accumulation
16	66	2015	sea level rise
17	64	2015	impact
18	56	2013	vegetation
19	56	2015	mangrove forest
20	55	2015	wetland
21	55	2014	nitrogen
22	54	2016	coastal
23	53	2014	emission
24	52	2016	community
25	50	2017	stock
26	50	2014	growth
27	50	2012	conservation

[1] The year in which the keyword first appeared.

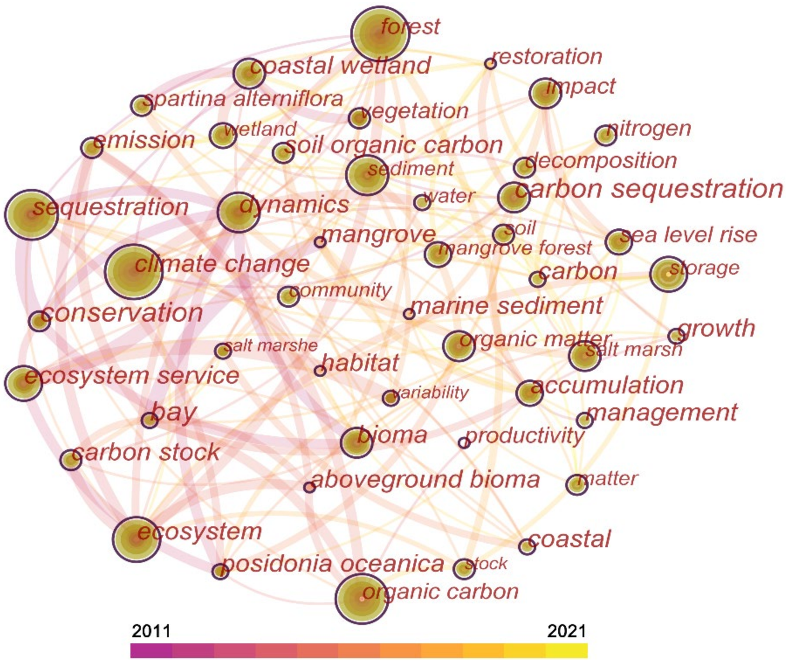

Figure 5. A visualization of the keyword co-occurring network for blue carbon research.

Further analysis has been conducted on the emergence of keywords. The emergence of keywords refers to the rapid increase in the frequency of keywords in a certain period of time, reflecting the research hotspots or new research trends in this period, and revealing the evolution of the current research hotspots in blue carbon [31]. The data in Table 3 reveal that there are 15 emerging keywords in blue carbon research. The depth and the breadth of the research content in all aspects are increasing over time, and new research hotspots are constantly emerging.

Table 3. Keyword emergence information of blue carbon research.

Keywords	Strength	Begin Year	End Year	Keywords
conservation	3.77	2012	2017	
carbon sequestration	6.22	2013	2016	
carbon sink	2.54	2013	2015	
ecosystem service	3.05	2014	2014	
seagrass bed	3.07	2016	2017	
variability	2.61	2017	2017	
sequestration capacity	3.46	2018	2018	
tidal wetland	3.01	2018	2019	
respiration	3.61	2019	2021	
storage	2.76	2019	2019	
carbon	2.70	2019	2019	
litter decomposition	2.66	2019	2019	
florida	2.66	2019	2019	
temperature	3.27	2020	2021	
macroalgae	2.79	2020	2021	

The first emerging keyword appeared in 2012. After 2 to 7% of the blue carbon ecosystems disappeared annually, people began to pay attention to the protection of blue carbon ecosystems, realizing that the marine ecosystem has a long-term and sustainable capacity to sequester carbon and a strong function to protect the ecosystem. From 2012 to 2015, the emergent keywords included conservation, carbon sequestration, carbon sink and ecosystem service, indicating that the key concepts and issues of blue carbon ecosystems and the estimation of the carbon sequestration in marine ecosystems were the research hotspots at this period. At the same time, the emerging words had existed for a long time, indicating that these keywords have received extensive attention and research was active at this period. The emergence intensity of the keyword "carbon sequestration" is as high as 6.22, which may be due to the research on monitoring methods being a potential research turning point in the study of carbon storage, such as the analysis of stable isotope traceability [81], radiotracer age [91], chemical biomarker [92], and aerial image [93]. From 2016 to 2017, the emerging keywords were seagrass bed and variability, and the blue carbon ecosystems represented by seagrass beds were extensively studied [53,67,94]. The distribution of the blue carbon ecosystems and their temporal and spatial patterns were the research hotspots at this period. Overall, from 2012 to 2017, blue carbon research transitioned from concept identification to ecosystem assessment. From 2018 to 2021, the number of emerging keywords increased compared with the previous two periods, including sequestration capacity, tidal wetland, respiration, storage, carbon, litter decomposition, Florida, temperature and macroalgae. The blue carbon ecosystem represented by tidal wetlands and macroalgae has been widely studied, which shows that the research of blue carbon ecosystem has expanded from coastal ecosystem to marine fishery ecosystem. The research also focused on the decomposition characteristics of the mangrove litter and the impact of the climate change, such as the impact of the temperature increase on carbon accumulation in blue carbon ecosystems at this period. At the same time, we noticed that the keyword Florida appeared in the emergent information. Sheehan, L, working on the highly urbanized Tampa Bay in Florida, USA, assessed and quantified the existing carbon stocks, identified the trajectories of the future carbon sequestration in coastal habitats related to the climate change and the sea level rise and found that the wetland restoration projects have additional benefits for climate change mitigation and adaptation [95]. It can be seen that the maintenance of the carbon sequestration potential of blue carbon ecosystems involves the protection, management and restoration of blue carbon ecosystems, and is also a research hotspot at this period.

The evolution of the keywords and hotspots indicate that, in just ten years, blue carbon research has developed from a single ecosystem type to a variety of ecosystem types, and from concept recognition to system assessment research. The investigations have actively responded to the ecosystem degradation problems disturbed by human activities and climate change, and management strategies have been proposed. In fact, the research system is still expanding and deepening.

3.4. Prospects for Future Research

The term "blue carbon" first appeared in 2009 to describe the huge contribution of marine ecosystems to the global carbon sink [3], and it has made a great difference internationally in mitigating and adapting to the climate change. Despite the unfavorable factors, such as the rise of the sea level and climate change, without human damage, the total area of blue carbon ecosystems, such as coastal wetlands, will still increase to a certain extent by the end of the 21st century [96]. In addition, the modelling of the estimated emissions scenarios shows a net increase in global carbon accumulation [97]. However, it is still necessary to strengthen the scientific research on blue carbon, to protect the integrity of its ecosystem structure and service functions in order to make greater contributions to the global carbon neutrality strategy.

At present, the concept of "blue carbon" has not been fully incorporated into the management plans of some coastal countries [75–78]. In addition, the research on long-term monitoring, evolution patterns, and contributions to the climate change of blue carbon ecosystem is relatively weak. Challenges remain in the development of long-term sustainable blue carbon conservation measures and policies to improve the human well-being and mitigate climate change. Peter I. Macreadie et al. [27] assembled leading experts in the field to agree upon the top-ten pending questions in blue carbon science, including the following: how does the climate change affect carbon accumulation in the blue carbon ecosystem? What is the global importance of macroalgae (including calcifying algae) as blue carbon sinks/sources? How does the human disturbance affect carbon accumulation in blue carbon ecosystems? What is the distribution of blue carbon ecosystems and their spatial and temporal patterns? How do the organic and the inorganic carbon cycle processes affect carbon emissions? How to estimate the source of the carbon in a blue carbon system? What are the factors that affect the rate of carbon burial in blue carbon ecosystems? What is the exchange rate of greenhouse gases between the blue carbon ecosystem and the atmosphere? How to reduce the uncertainty in blue carbon estimates? How can the management measures maintain and improve blue carbon sequestration [27]?

We, in response to these problems, suggest that the future blue carbon research and management policies focus on strengthening the following aspects.

(1) Establishment of a network of the field observation and research on blue carbon ecosystems.

Typical blue carbon ecosystems should be selected on a global scale, and the field observation and research stations established. With multi-site networked observations and field experiments, researchers should fully understand the service functions of blue carbon ecosystems, elucidate the basic laws and specificities of the ecosystem carbon processes, elucidate the key factors and mechanisms driving changes in blue carbon sink/source patterns, elucidate the temporal and spatial patterns and mechanisms of the carbon burial rates and greenhouse gas emissions, and conduct systematic research on the types of communities with strong carbon sequestration capacity in blue carbon ecosystems.

(2) Systematic quantification and prediction of the blue carbon sequestration function.

By simulating human activities and climate change and using the data of geographic information system and land remote sensing, researchers are expected to establish a model to predict the function and changes in blue carbon storage capacity under different climate change scenarios in the future, to clarify the response and adaptation mechanism of the blue carbon ecosystem to future climate change and human activities, to improve the scientific understanding of the mechanism of the increase in the blue carbon sink and the ability to predict its future carbon sink capacity, and highlight its comprehensive ecosystem service function.

(3) Building of a demonstration area of comprehensive research for blue carbon ecosystem services.

By systematically understanding the key driving factors affecting the carbon sequestration function of blue carbon ecosystems, the governments of various countries are supposed to formulate the regulations and standards for the restoration of blue carbon ecosystems, support the scientific and technological researchers to develop the corresponding carbon sequestration and increase technology in order to establish the ecological management strategies for carbon ecosystems in demonstration areas suitable for different blue carbon ecosystems, and to practice ecological management schemes that maximize the service function of blue carbon ecosystems.

4. Conclusions and Limitations

This study used the CiteSpace software to conduct a quantitative bibliometric analysis of the literature in the field of blue carbon research from 2011 to 2021. The following conclusions were drawn from the analysis of the number of publications, country of publication, institution, author, co-citation, and co-occurrence and emergence of keywords.

(1) The publication volume of blue carbon research shows an increasing trend, and the publication volume has increased significantly since 2016.

(2) Countries or regions mainly participate in blue carbon research through cooperation. The United States, Australia, and China are the more active countries in the field of blue carbon research; Deakin University, Edith Cowan University and University of Queensland are more active institutions in the field of blue carbon research; Catherine E. Lovelock, Carlos M. Duarte, and Oscar Serrano are among the most active authors in blue carbon research.

(3) Blue carbon research has mainly gone through three periods. Before 2016, it was in the early exploratory period, focusing on the concept of blue carbon and on research on the main ecosystem types, basically forming a knowledge system for blue carbon research. From 2016 to 2017, the most studies were conducted on the diversity, complexity and systematicness of blue carbon ecosystems focusing on the carbon sequestration mechanism, and more attention was paid to the protection and management of blue carbon. From 2018 to 2021, there was a carbon conservation and restoration research phase with the aim of coping with the climate change and human activities.

(4) The research hotspots in the early period of blue carbon research were related to the blue carbon ecosystem types, carbon sequestration processes, etc. Blue carbon research has developed from a single ecosystem type to a variety of ecosystem types, and from concept recognition to system assessment research. Recently, research on the response, restoration and protection of blue carbon ecosystems has become a research hotspot under the dual interference of human activities and climate change. The research on long-term monitoring, evolution patterns, and contributions to the climate change of blue carbon ecosystem is relatively weak.

(5) Ocean blue carbon research is both an opportunity and a challenge. By establishing a blue carbon ecosystem field observation and a research network, systematically quantifying and predicting the blue carbon sequestration function, and constructing a comprehensive research demonstration area for the blue carbon ecosystem service function, a clearer scientific understanding of blue carbon can be achieved to better reach the goal of carbon peaking and improve human well-being.

The articles we collected were on the topic search "blue-carbon", and those irrelevant were removed. Hence, the search was precise. Although this study allowed us to draw some conclusions about blue carbon research, it also has certain limitations. First, it may have overlooked some relevant research on the topic, especially as older documents in the WoS do not have abstracts or keywords, even though the "WoS Core Collection" database selected includes more than 12,000 journals with good reputation and high influence around the world. The multi-source searches and the cross-comparisons between different databases will be more compelling. Second, while we have identified the main research topics and their evolution, more in-depth information on each research topic is still needed, such as the methodology, theoretical background, and main findings of each work. Finally, it is worth mentioning that the CiteSpace software also has its own limitations, but this method has been used in many bibliometric studies. Nevertheless, the findings of this study not only are based on objective data, but are also stable and reliable, and generally unaffected by empiricism.

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