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Review

A Systematic Review and Global Trends on Blue Carbon and Sustainable Development: A Bibliometric Study from 2012 to 2023

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Abstract: Halfway through *Transforming Our World: The 2030 Agenda for Sustainable Development*, only 15 percent of the goals have been reached. As a carbon storage and climate change mitigation mechanism, blue carbon is closely related to sustainable development goals and plays an important role in the global carbon cycle. In spite of its great potential, blue carbon still faces several challenges in terms of achieving the Sustainable Development Goals. Herein, this review aims to retrieve all known impacts of blue carbon on sustainable development through research published on the Web of Science from 2012 to 2023 using a sequence of bibliometric analyses. Keywords such as "blue carbon" and "sustain*" (including "sustainability", "sustainable", etc.) were used for article extraction. CiteSpace, a science mapping tool, was used to capture and visually present the bibliometric information in the research about blue carbon and sustainable development. Upon reviewing the existing literature, no study has concentrated on bibliometrically analyzing and visualizing studies about blue carbon and sustainable development. This study sets out to fill this gap by examining the key areas of concentration in published works on blue carbon and sustainable development from 2012 to date. Moreover, the integration of blue carbon and sustainable development may help to develop supportive policies for marine carbon sinks. Despite the valuable contribution of this study to the blue carbon and sustainable development body of knowledge, generalizations of the results must be made cautiously due to the use of a single database, which in this case is the Web of Science.

Keywords: blue carbon; sustainable development; CiteSpace; bibliometric analyses; climate change

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1. Introduction

In 2015, the United Nations General Assembly adopted a global agenda, *Transforming Our World: The 2030 Agenda for Sustainable Development* (hereinafter referred to as the *2030 Agenda*), which is intended to "make the world a better place by 2030" [1,2]. It consists of 17 Sustainable Development Goals (SDGs) and 169 concrete targets related to poverty eradication, food security, health, education, gender equality, clean water resources, climate action, etc. [3–5]. By the second half of 2023, the road to sustainable development by 2030 still faces considerable challenges [6,7]. According to the latest data, only 15% of targets are progressing according to plan, while 48% show moderate or severe deviations from the planned path, and the most concerning fact is that 37% of targets experienced stagnation or regression [8,9]. There is an urgent need to accelerate, sustain, and transform the SDGs over the next few years to create a more peaceful, prosperous, and secure future for all [6].

Adopting the 2030 Agenda for Sustainable Development requires balancing sustainable growth with the fight against climate change [10]. A close connection exists between blue carbon and sustainable development goals. The concept of blue carbon refers to a process, activity, and mechanism uses for ocean activities and marine organisms to absorb and fix CO_2 from the atmosphere or as the biologically−driven carbon flux and storage in marine systems amenable to management [11–13]. Considering the current global challenge of increasingly severe climate change [14], integrating blue carbon with the SDGs is particularly important. As part of the SDGs, the importance of marine conservation and marine ecosystems has been highlighted, and blue carbon, as an important component of marine ecosystems, has been incorporated into the sustainable development agenda [15–17]. Protecting blue carbon ecosystems supports SDG 14 (Conserve and sustainably use oceans, seas, and marine resources for sustainable development) and further supports other SDGs (see Figure 1). As part of achieving the SDGs, the preservation and restoration of blue carbon ecosystems are important to ensure the long-term sustainability of the planet.

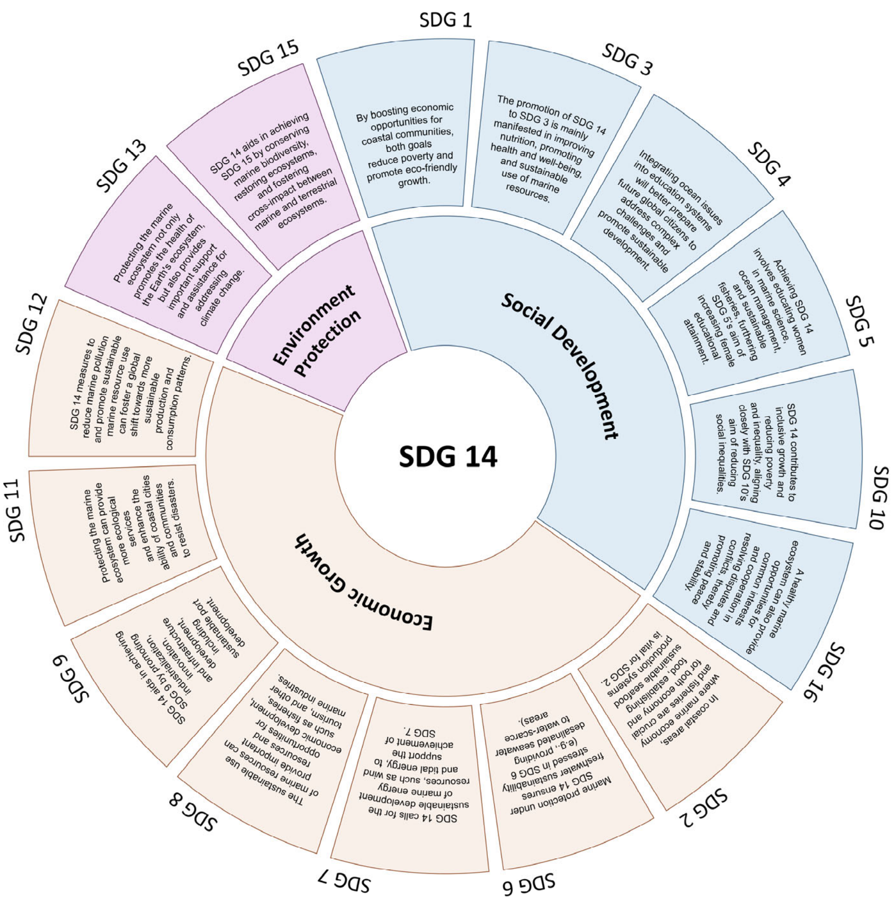

Figure 1. The supporting role of SDG 14 for other goals [18–45] (Source: analysis and summary by the authors).

SDG 14 focuses on conserving and sustainably using the oceans, seas, and marine resources, including reducing marine pollution, protecting ecosystems, minimizing ocean acidification, and so forth [46]. Despite the boom in academic research on blue carbon, the theoretical vacuum between blue carbon and the SDGs is still unclear. A notable example of this can be seen in the marginalization of SDG 14's implementation. SDG 14 is yet marginalized in global policies, including those within the United Nations system [47].

Global funding allocations for SDG 14 are significantly lower than those for other SDGs, according to the *Global Sustainable Development Report 2023* [48]. It is worth noting that four objectives of the SDG 14 concerning marine conservation and management expired in 2020, yet the relevant indicators show that most countries have made very limited progress in this regard [48]. In light of these challenges, countries need to examine ways to improve marine conservation and management to fulfil SDG 14.

It is estimated that approximately 11.5 billion tons of carbon are sequestered from the atmosphere through blue carbon habitats [49]. Blue carbon and its implementation should provide a potential contribution to implement SDG 14. Thus, the aim of this study is to summarize the current stage of the study on blue carbon and sustainable development through a systematic analysis and visualization of the relevant literature. Additionally, the study will place a particular focus on the main findings of current literatures identifying the gap between theory and practice in adaptation SDGs in blue carbon.

This study is divided into four sections: introduction, data and methodology, results and discussion, and conclusions. First, we explain the background and purpose of the study. Second, the Web of Science (WoS) was chosen for literature databases with keyword searches; we screened out literature samples related to blue carbon and sustainable development, and classified and analyzed these samples. Third, we used the visualization tool CiteSpace to conduct in–depth analyses and visual presentations of collaboration networks among institutions, countries, authors, as well as citation networks in order to provide a comprehensive picture of the study landscape and relationships. The final section summarizes the major findings and conclusions of the study and highlights the future research for blue carbon and sustainable development. We also present a recommendation of this study for academics and practitioners, with important references for the future direction of the field.

2. Materials and Methodology

2.1. Research Methods

This study aims to review and analyze the links between blue carbon and sustainable development so as to gain a comprehensive understanding of the current stage of the study in this area. CiteSpace software (6.3.R1 Advanced (2024–2025), https://citespace.podia.com/, accessed on 19 December 2023; it is a Java–based visualization tool developed for capturing and visually presenting the bibliometric information of scientific publications) was used to conduct a comprehensive and in–depth analysis of the literature [50,51]. In this section, we describe the research methods and tools used in this study.

Firstly, we selected the WoS as our data source since it is widely used [52–60]. To obtain scholarly publications related to blue carbon and sustainable development, detailed search strings based on the specific objectives and content of this study have been developed and applied to the selected databases. The relevant inclusion and exclusion criteria were used as a filter to obtain data sets that met the study's objective to ensure the completeness and accuracy of the literature search. Then, the data were examined using the bibliometric tool CiteSpace software. As part of the automated cluster identification feature of CiteSpace software, the article used the setting Extract Cluster Labels = Keywords and displayed cluster labels using the log–likelihood ratio (LLR). The time period was set to 2012.01–2023.12 (Years Per Slice = 1), and other factors were maintained at their default settings. CiteSpace uses visualization tools such as network diagrams, timelines, and keyword co–occurrence analysis to provide researchers with insights into citation relationships between scientific literature, topic evolution, and hotspots of research [55,61]. Thirdly, we conducted an in–depth analysis of the literature related to blue carbon and sustainable development and generated visualization charts and results. The possible research gaps or future development paths are identifiable and will provide scientists with scientific support and guidance, all while enabling them to gain a thorough grasp of the research study's advancement in this field.

2.2. Materials and Data Collection

It is imperative that academic databases are utilized for academic research, and several databases are available to researchers, including Scopus, WoS, Google Scholar, etc., which provide literature and citation information for various disciplines [62]. Selecting an appropriate database for conducting a review study requires consideration of a wide range of factors [62,63]. Because the study is a review study and the research topic is "Blue Carbon and Sustainable Development", which is an interdisciplinary topic, we used the WoS database to collect research materials. The WoS database was chosen because it provides journal articles, conference papers, and patents in a wide range of disciplines [52,63]. Research results in the database are derived from high–quality academic journals, ensuring that researchers have access to reliable and authoritative data [63].

The selected WoS databases were thoroughly searched, extracted, and screened. Due to our focus on peer–reviewed scholarly output, we only consider journal articles, excluding books, book chapters, conference papers, and theses published between 2012 and 2023. Firstly, we entered TS = ("blue carbon") AND AB = (sustain*) into the search bar, and 206 results were returned. To ensure the completeness and accuracy of the literature required for the review study, the following are required: typing TS = ("blue carbon") OR TI = ("blue carbon") in the search bar, 1933 documents were obtained, and then typing SUSTAIN* in the result list yielded 226 results. Finally, after filtering out 36 documents (non–journal, irrelevant, and non–English), we obtained 190 valid documents (see Figure 2).

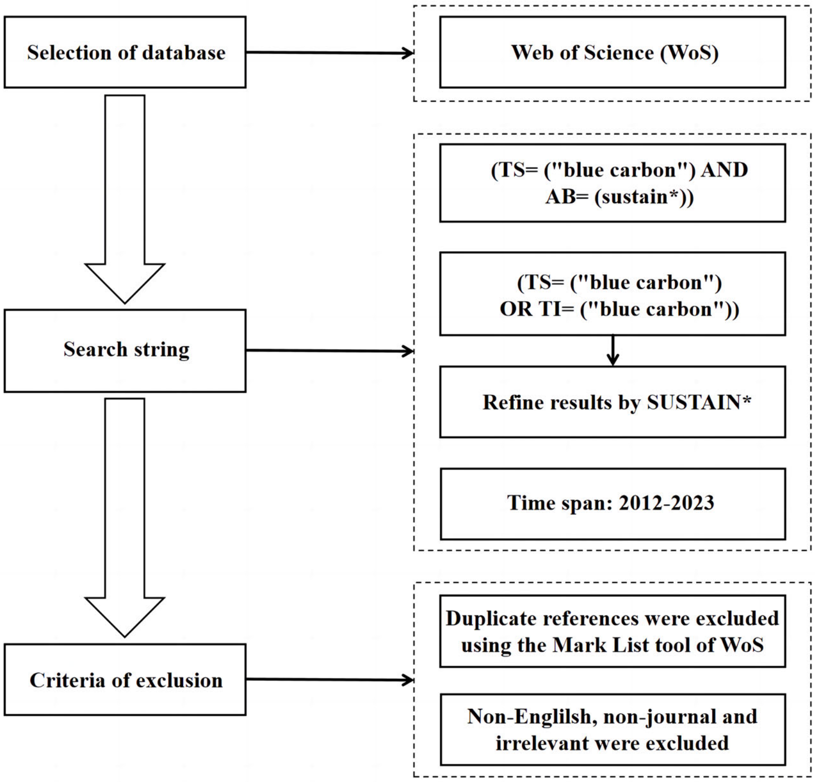

Figure 2. Literature selection procedure using the search string (Source: own illustration).

3. Bibliometric Results, Data Analysis, Visualization, and Discussion

3.1. Exploring Research Landscape

An important method for analyzing the status and trend of a research topic over time is to analyze the time–series distribution of the literature [64]. Research in a particular field can be assessed based on the number of papers that have been published, which can be a comprehensive indicator of the level of attention that researchers have paid to that field [65]. Research publications can provide insight to a field's overall level, trend, speed, and stage of development as well as reflect the research priorities of researchers at different points in time [66,67]. The statistical analysis of the number of papers published every year allows us to identify the current research status of the field and predict the future research prospects [68]. Figure 3 shows the temporal distribution of the number of papers, based on annual statistics. According to the characteristics of the annual publication, the research in this field is divided into two stages: embryonic stage (2012–2018) and development stage (2019–2023).

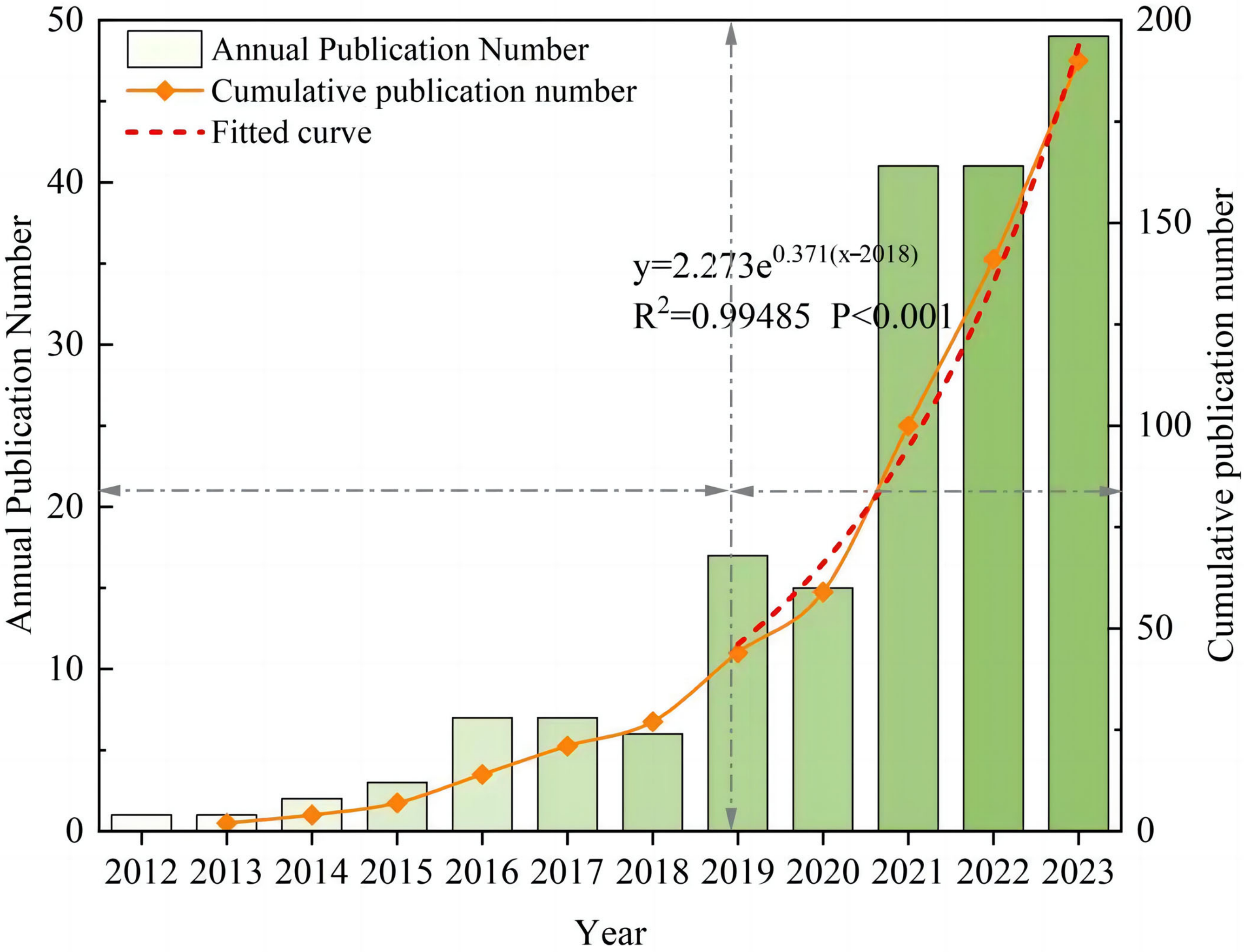

Figure 3. Trends in the number of publications from 2012 to 2023 (Source: Web of Science, accessed on 12 January 2024).

3.1.1. Stage I: Embryonic Stage (2012–2018)

Between 2012 and 2018, we can observe a slow development of the research field. This stage is characterized by the growth in publications each year, but the rate of growth is relatively slow, indicating that the research field has not yet matured and is still exploring its research directions and establishing its research foundations. *Blue Carbon: The Role of Healthy Oceans in Binding Carbon*, published by the United Nations Environment Programme (UNEP) in 2009, has received significant attention [12]. It presented new ideas for reducing carbon emissions and stimulated discussions regarding ocean–based CO_2 removal. From 2012 to 2015, the focus of the research is on determining the role that coastal ecosystems such as seagrass and mangroves play in carbon sequestration and conservation [69–74]. Moreover, the concept of blue carbon is a recurring theme, emphasizing the importance of carbon storage in these ecosystems for mitigating climate change [69–76]. From 2016 to 2018, due to the *2030 Agenda* and the Paris Agreement, research has been primarily focused on examining how blue carbon relates to the SDGs [77], as well as how to translate blue carbon into practical policies and actions [78–80]. The *2030 Agenda* integrates the three dimensions of sustainable development (economic, social, and environmental) and emphasizes the importance of protecting and restoring marine ecosystems [1]. The *2030 Agenda* places particular emphasis on blue carbon, which is the capacity of marine ecosystems to absorb and store carbon. Researchers were prompted to consider how the research on blue carbon might contribute to the achievement of the SDGs. In 2016, the Paris Agreement entered into force, reducing global greenhouse gas emissions and combating climate change. A key component of this Agreement was to reintroduce marine ecosystems as sinks and reservoirs of greenhouse gases, including blue carbon [43]. A growing number of researchers have begun to examine the role of marine ecosystems in sequestering carbon and the potential contribution of blue carbon in addressing climate change and sustainable development.

3.1.2. Stage II: Development Stage (2019–2023)

In this stage, the number of publications is significantly higher than in previous years, with the exception of 2020, when it is comparatively low. A possible explanation for the anomaly observed in 2020 is the worldwide spread of the COVID-19 pandemic. A number of factors caused research output to decline during that period, including the closure of laboratories, the restriction of personnel movement, diminished funding, and a variety of other factors [81–83]. Blue carbon's relationship with sustainable development was studied by both academics and policy makers. According to the Intergovernmental Panel on Climate Change (IPCC) report, while advances have been made on certain fronts, such as the use of zero–carbon technologies to mitigate climate change [6], terrestrial carbon sinks are currently saturated, and terrestrial carbon sequestration is not permanent [84]. Humans must therefore search for new carbon sinks outside of terrestrial carbon sinks for growth. The international community has recognized blue carbon as an important means of achieving "carbon neutrality [85]". Research on blue carbon and sustainable development is becoming an important foundation for policy–making and practice to meet the SDGs target. The growth trend reflects researchers' continued interest and focus in this field. Generally, research activities in this field are moving towards a more in–depth direction.

3.2. Analyzing Global Collaborative Networks in Research

3.2.1. Global Cooperation of Institutional Research

In accordance with the contents of the original software infrastructure, the node type was set as "Institution" and generated the institutional cooperation network (see Figure 4). This network seeks to represent institutions' research status and close collaboration by leveraging collaborative relationships. The collaborative network map enables us to gain a clear understanding of the academic output and the relationship between these institutions.

As shown in Figure 4a, universities are dominant in this field of research. In particular, the University of Queensland and the National University of Singapore have performed well. They are able to engage in deeper research because of university research facilities, extensive research resources, and highly qualified researchers. However, the involvement of non–university institutions, such as the Center for International Forestry Research, may facilitate cross–collaboration between different areas of expertise. As a result of this diversity, interdisciplinary research and cross–sector collaboration are fostered, enabling new perspectives and solutions to be developed for complex problems. Figure 4b shows that institutions with a high degree of cooperation are generally clustered in clusters #0, #1, and #3. Clearly, these clusters are at the core of the institutional collaboration network, and their members closely cooperate and form a strong sub–network.

Based on the clustering information provided in Table 1, a number of representative keywords for cluster #0, including "map of worlds", "Falkland Islands", "sub–Antarctic", "land–ocean carbon", and "climate change mitigation", indicate that the research focus covers geographical mapping, regional studies of the Falkland Islands and sub–Antarctic regions, as well as carbon exchange dynamics between terrestrial and marine ecosystems. A major focus of this cluster is likely to be the development of strategies and mechanisms for mitigating climate change, especially in relation to carbon sequestration and storage in coastal and marine environments. It is evident from the inclusion of the label "land–ocean carbon" that there is interest in developing a better understanding of how the carbon cycle operates across different ecosystems and how these systems interact to influence global carbon budgets. "Climate change mitigation" indicates the cluster focuses on reducing greenhouse gas emissions and improving carbon sinks, which are crucial to resolving the global climate crisis. As indicated by the label "macroalgae", Cluster #1 focuses on the importance of large marine algae to coastal ecosystems, especially mangroves. "REDD" is the representative label for Cluster #3, which emphasizes the role played by coastal ecosystems in sequestering carbon and mitigating climate change.

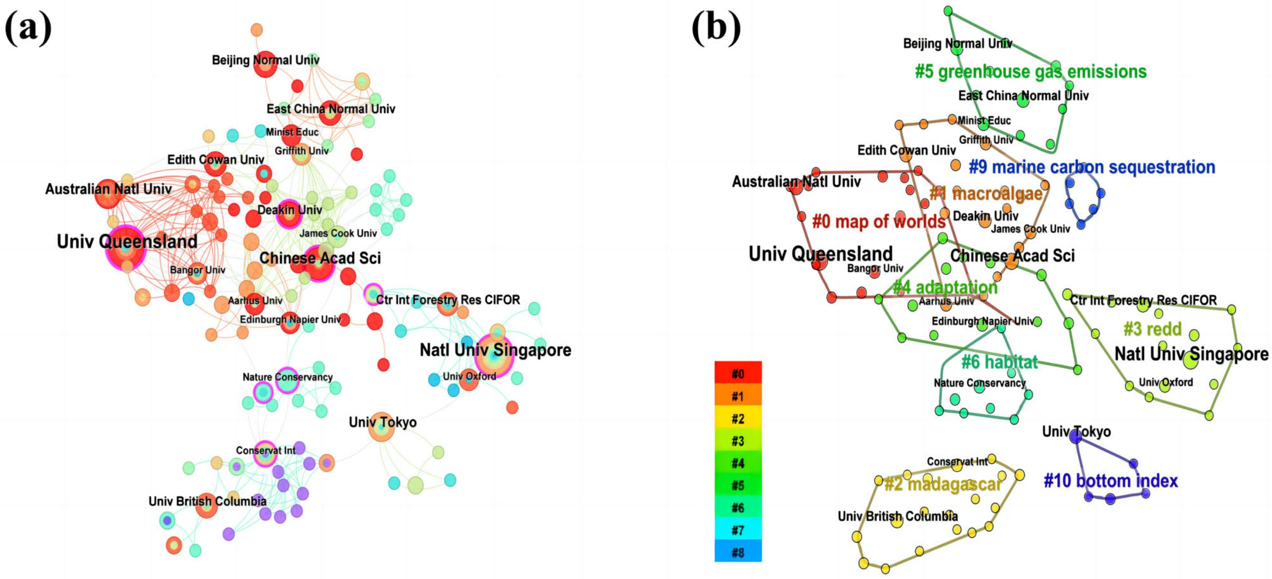

Figure 4. Network of collaborating institutions (**a**,**b**). (**a**) Tree–ring nodes. Nodes are sized according to the number of publications they have. A larger node indicates a greater number of publications. (**b**) Clustering nodes. An individual cluster is represented by a different color. When the threshold is set to 3, a total of 20 institutions are displayed (Source: CiteSpace and the authors' research).

Table 1. Clustering information of institutional cooperation networks (Source: CiteSpace and the authors' research).

Cluster ID	Size	Silhouette	Label (LLR)	Mean (Year)
0	23	0.952	map of worlds (3.52, 0.1); Falkland Islands (3.52, 0.1); sub–Antarctic (3.52, 0.1); land–ocean carbon (3.52, 0.1); climate change mitigation (3.52, 0.1)	2020
1	21	0.933	macroalgae (6.82, 0.01); conservation (3.39, 0.1); posidonia oceanica (3.38, 0.1); biogeochemical cycles (3.38, 0.1); coastal systems (3.38, 0.1)	2018
3	16	0.989	REDD (4.65, 0.05); seaweeds (2.83, 0.1); MPA (2.83, 0.1); Payments for Ecosystem Services (2.83, 0.1)	2016

Even though high levels of collaboration are concentrated within the core clusters, the overall number of collaborations is relatively low. While the core institutions have close collaborative relationships, the overall collaborative network is far from reaching its full potential. Perhaps this is due to the complexity of the issues in the field, which requires collaboration across disciplines and institutions.

3.2.2. Global Cooperation of National Research

Assessing the robustness of a nation's research endeavors requires a thorough analysis of its cooperation network diagram. As a result of this analytical approach, valuable insights into the collaborative landscape within the field of scientific exploration can be obtained [86]. As illustrated in Figure 5, by configuring the node type as "Country" within the original software framework, we were able to construct and visualize a comprehensive representation of the country cooperation network. By using this visualization, we can examine the collaborative landscape and dynamics of international research cooperation.

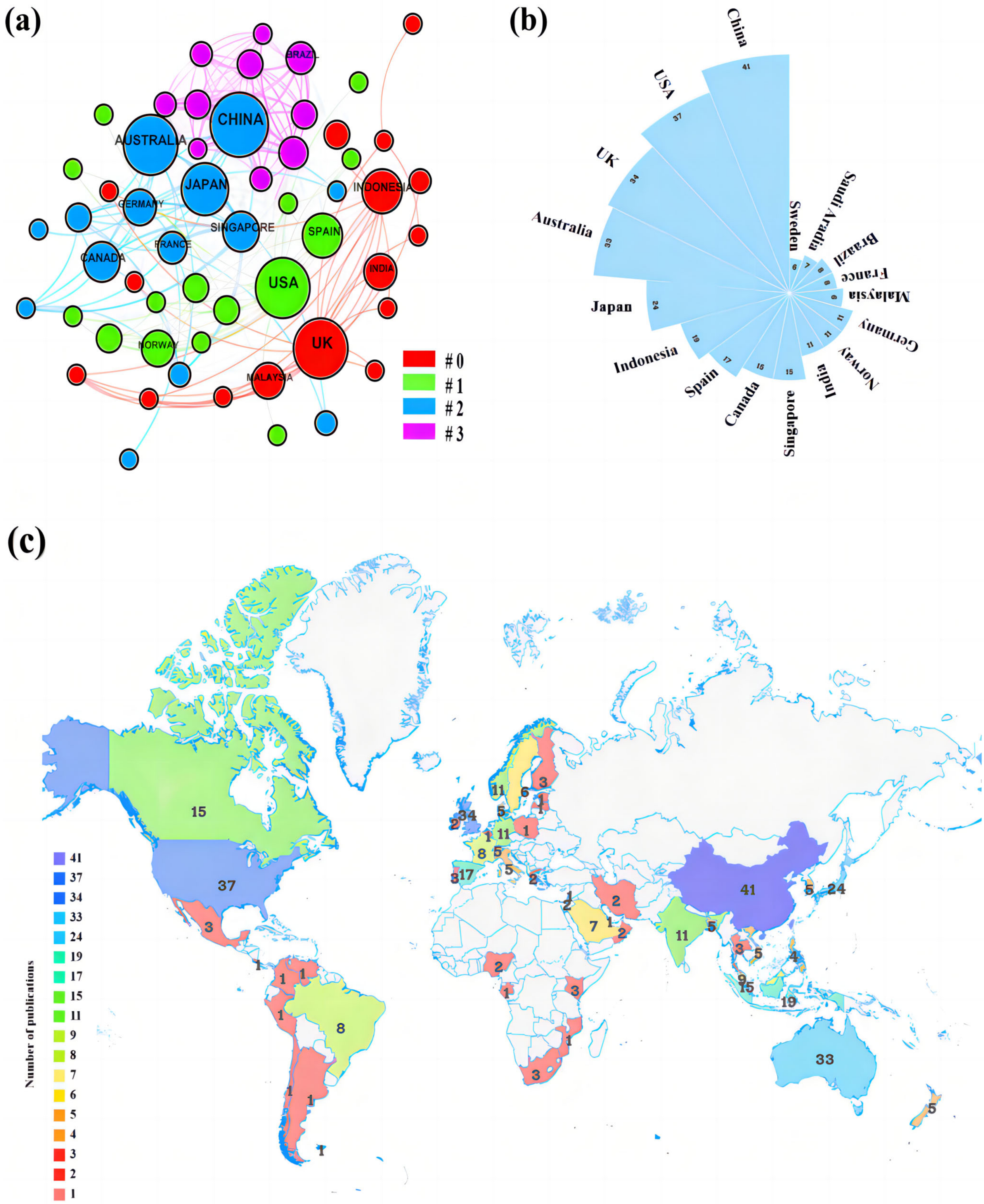

Figure 5. Network of collaborating countries (**a**,**b**) and geographical distribution (**c**). When the threshold is set to 8, 15 nations are displayed in (**a**) (Source: CiteSpace and the authors' research).

Observing the interconnections between major countries and discerning the relative size of the nodes within the graph provides a nuanced understanding of the depth and breadth of scientific research cooperation. Figure 5a illustrates clusters within the network as a result of varying node colors. While nodes are sized according to the number of publications, the larger the node, the greater the number of publications. This provides a clear understanding of the magnitude of research output across countries. Figure 5b shows that 17 countries have contributed more than five publications with authors from different countries. There are 41 publications from China, 37 from the United States, 34 from the United Kingdom, and 33 from Australia. This demonstrates the active involvement of these nations in collaborative scientific research, indicating their importance to the advancement of knowledge within their respective fields. Furthermore, the visualization presented in Figure 5c delves into the geographical distribution. Compared to Europe, Africa appears to have a relatively low level of participation in its country networks. In Africa and South America, the number of publications falls short of 10, suggesting potential opportunities for further collaboration and engagement.

As can be seen from Figure 5a and Table 2, the largest Cluster #0 includes UK, Indonesia, Malaysia, and India, with the representative label "coastal ecosystems", indicating that these countries are leaders in coastal ecosystem research. Cluster #1 includes USA, Spain, and Norway, with the representative label "mangrove", which indicates a focus on mangrove ecosystems. In Cluster #2, China, Australia, Japan, Singapore, Canada, Germany, and France are listed, with labels such as "heavy metals", "marine resources", "data integration", "forest", and "sea level rise". In Cluster #3, Brazil is represented by representative labels such as "climate variability", "floating macroalgae", "policy", "carbon export", and "carbon management", which reflect the collaborative priorities and objectives.

Table 2. Clustering information of national cooperation networks (Source: CiteSpace and the authors' research).

Cluster ID	Size	Silhouette	Mean (Year)	Label (LLR)
0	16	0.513	2018	coastal ecosystems (5.79, 0.05); adaptation (2.88, 0.1); UNFCCC (2.88, 0.1); mitigation (2.88, 0.1); negative emissions biotechnologies (2.88, 0.1)
1	16	0.767	2018	mangrove (5.19, 0.05); seagrass (3.46, 0.1); restoration (3.45, 0.1); remote sensing (3.29, 0.1); Rhizophora (2.18, 0.5)
2	14	0.645	2019	heavy metals (2.86, 0.1); marine resources (2.86, 0.1); data integration (2.86, 0.1); forest (2.86, 0.1); sea level rise (2.86, 0.1)
3	13	0.856	2018	climate variability (4.63, 0.05); floating macroalgae (4.63, 0.05); policy (4.63, 0.05); carbon export (4.63, 0.05); carbon management (4.63, 0.05)

3.3. Exploring Citation Impact

3.3.1. Co–Citation Analysis: Exploring the Impact of Literature

Citations provide a visible and traceable link between scientific publications [87]. An analysis of literature co–citations is an important research method that can provide us with insights into key literature and academic trends in a particular field. Identifying important research findings and academically influential scholars can be accomplished through the analysis of the citation relationships between the literature [88]. The results of this analysis enable us to gain an understanding of the research field and guide the direction of our research and decision–making [89].

Based on the original software base settings, the node type was designated as "Reference", and we were able to generate the co–citation network (see Figure 6). In order to identify key literature, we leveraged the co–citation network and obtained the 10 most cited references, which we then ranked in descending order based on frequency of citations (see Table 3).

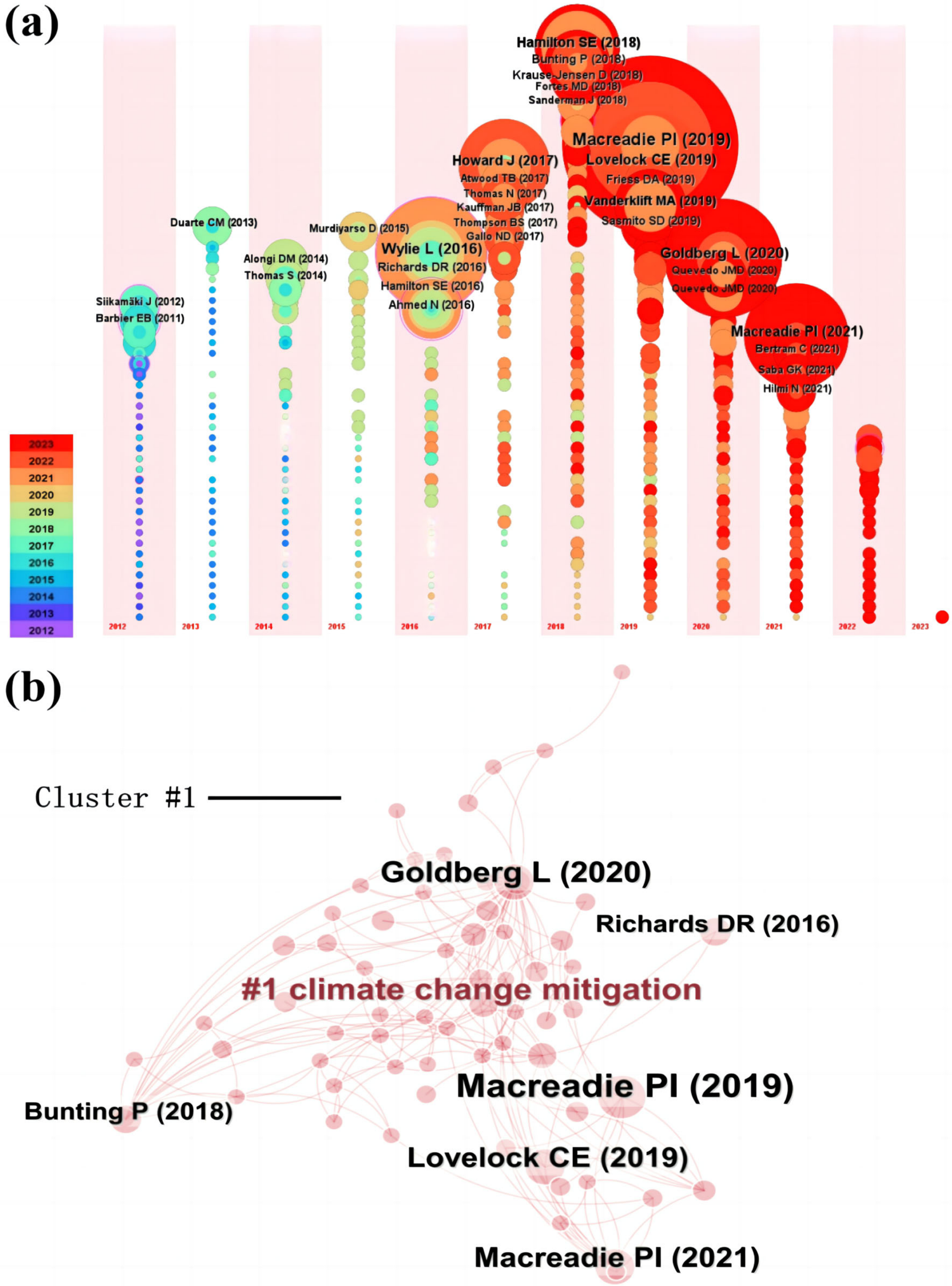

Figure 6. Reference co–citation timezone view (**a**) and Clustergram #1 (**b**). (**a**) The timezone intervals represent the time when the nodes first appeared, the size of the nodes indicates the duration, while the color indicates the time when they were last cited. When the threshold is set to 6, 33 references are displayed. (**b**) Labels for Cluster #1 and the members within that cluster. Clustering information: climate change mitigation (5.93, 0.05); anthropogenic threats (5.93, 0.05); mangrove cover change (5.93, 0.05); remote sensing (3.2, 0.1); redd (3.12, 0.1) (Source: CiteSpace and the authors' research).

Table 3. The top 10 highly co–cited articles (Source: analysis and summary by the authors).

Rank	Document	Source	Citations	Year	Cluster ID
1	Richards DR and Friess DA. (2016) Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012	Proceedings of the National Academy of the United States of America	613	2016	1
2	Macreadie et al. (2019) The future of Blue Carbon science	Nature Communications	461	2019	1
3	Bunting P et al. (2018) The Global Mangrove Watch–A New 2010 Global Baseline of Mangrove Extent	Remote Sensing	359	2018	1
4	Goldberg et al. (2020) Global declines in human–driven mangrove loss	Global Change Biology	346	2020	1
5	Howard J et al. (2017) Clarifying the role of coastal and marine systems in climate mitigation	Frontiers in Ecology and the Environment	300	2017	4
6	Lovelock and Duarte. (2019) Dimensions of Blue Carbon and emerging perspectives	Biology Letters	208	2019	1
7	Hamilton SE and Friess DA. (2018) Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012	Nature Climate Change	202	2018	10
8	Macreadie et al. (2021) Blue carbon as a natural climate solution	Nature Reviews Earth & Environment	201	2012	1
9	Wylie L et al. (2016) Keys to successful blue carbon projects: Lessons learned from global case studies	Marine Policy	183	2016	5
10	Vanderklift MA et al. (2019) Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems	Marine Policy	82	2019	6

Table 3 indicates that five articles have citation frequencies exceeding 300. The paper finished by Richards DR and Friess DA (2016) has a citation count of 613, examining the rates and drivers of mangrove deforestation in Southeast Asia between 2000 and 2012 and providing significant insight into the loss of these vital ecosystems and the factors contributing to their decline [90]. Based on Figure 6a, Macreadie et al. have made another significant contribution to the field of research in 2019, receiving widespread attention and citations, which indicates its enduring impact. In the article, the authors discuss blue carbon ecosystems' significant contribution to global carbon storage and suggest that blue carbon can play a key role in mitigating and adapting to climate change [91]. In another article published in 2021, Macreadie et al. evaluated the carbon storage and restoration potential of blue carbon ecosystems at the global scale as well as their potential to reduce global carbon emissions [92]. Figure 6b shows that 6 of the 10 most cited references belong to Cluster #1. Cluster #1's representative labels indicate that its members are concerned with the critical issues of climate change mitigation, human activities' threats to mangrove ecosystems, and changes in mangrove coverage, all of which are crucial to preserving and managing blue carbon.

3.3.2. Author Co–Citation Analysis: Unraveling Their Impact

The "Cited Author" node type is selected based on the basic settings of the original software, which generates the co–citation network of authors in a given field of study (see Figure 7). In light of the fact that the H–index is an important indicator of the impact and productivity of researchers, we analyzed the top 10 authors with the highest co–citation frequency and ranked them in descending order according to their H–index [93].

Table 4 presents the top 10 authors with the highest co–citation frequency with their associated metrics, including the number of articles, the number of citations, and the H–index. Among the top–ranked authors, Duarte CM is also ranked first in the H–index, with approximately four times as many articles as the second–ranked author. A wide range of his widely cited research results demonstrates the impact of his work on marine science, ecology, and environmental protection. As a result, he has provided key insights and solutions to global ocean issues [94]. With similar research outputs and impacts, Lovelock CE and Barbier EB rank second and third, respectively. Lovelock CE is one of the leading researchers in the field of blue carbon ecosystems with 304 publications and an H–index of 69 [95]. With 276 publications and an H–index of 61, Barbier EB is a prominent figure in environmental economics and sustainable development [96]. Furthermore, other distinguished authors, including Alongi DM, Macreadie PI, and Donato DC, have also made notable contributions to the field through their publications and H–index.

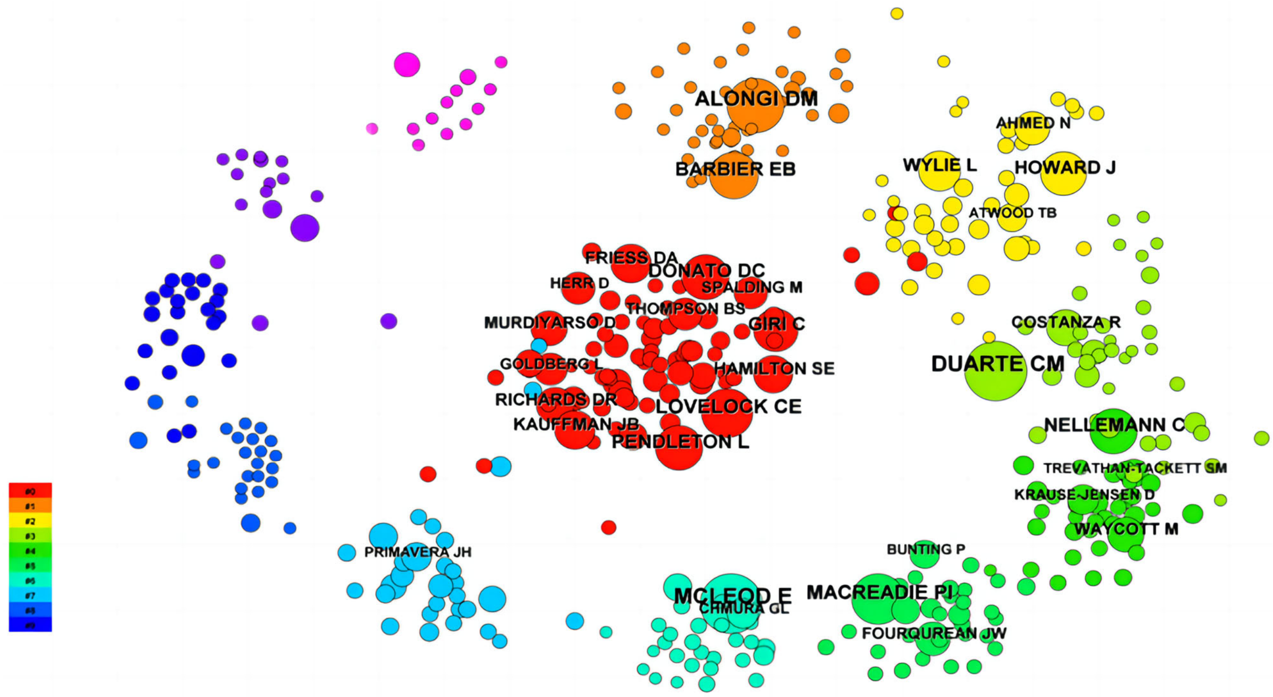

Figure 7. Author co–citation map. Co–citations between authors are displayed in a circular view, with each color representing a cluster. When the threshold is set to 14, a total of 31 authors are displayed (Source: CiteSpace and the authors' research).

Table 4. The top 10 highly co–cited authors (Source: analysis and summary by the authors).

Rank	Author	Publications in WoS	Number of Citations	H–index	Cluster ID
1	Duarte, C.M.	1072	84,822	133	3
2	Lovelock, C.E.	304	17,718	69	0
3	Barbier, E.B.	276	20,179	61	1
4	Alongi, D.M.	133	9635	51	1
5	Macreadie, P.I.	140	4534	35	5
6	Donato, D.C.	65	6753	33	0
7	Nellemann, C.	60	2895	27	4
8	Mcleod, E.	76	4571	26	6
9	Pendleton, L.	65	2640	23	0
10	Howard, J.	23	550	6	2

The depth and breadth of the field could be further explored. Figure 7 shows that cluster #0 has attracted a significant number of prominent authors, including Conato DC, Lovelock CE, Pendleton L, Giri C, Friess DA, and Richards DR. A representative label of Cluster #0 is "restoration", which indicates that these authors are engaged in research and scholarly contributions related to ecosystem restoration, particularly with regard to the rehabilitation and recovery of natural environments.

3.3.3. Journal Co–Citation Analysis: Investigating Their Influence

Researchers can gain insight into the influence and status of journals in a field by analyzing journal co–citations. Due to the creation of a journal co–citation network, the ability to study and explore the impact of these journals within particular disciplines is possible. As instructed by the basic settings of the original software, the co–citation network of journals in this field was successfully generated when the node type was set to "Cited Journal" (see Figure 8). In order to assess their influence and status more comprehensively, the top 10 active journals based on the number of citations are filtered, and their key indicators are listed in Table 5. These journals are categorized into clusters #2 and #3, with cluster 2's representative label being "social–ecological systems" in Figure 8b. In other words, these journals tend to examine the dynamics and governance of coupled human–natural systems. The representative label of cluster #3 is "ecosystem services", suggesting that these journals emphasize the benefits ecosystems provide to human well–being, as well as the mechanisms by which these services are sustained and valued.

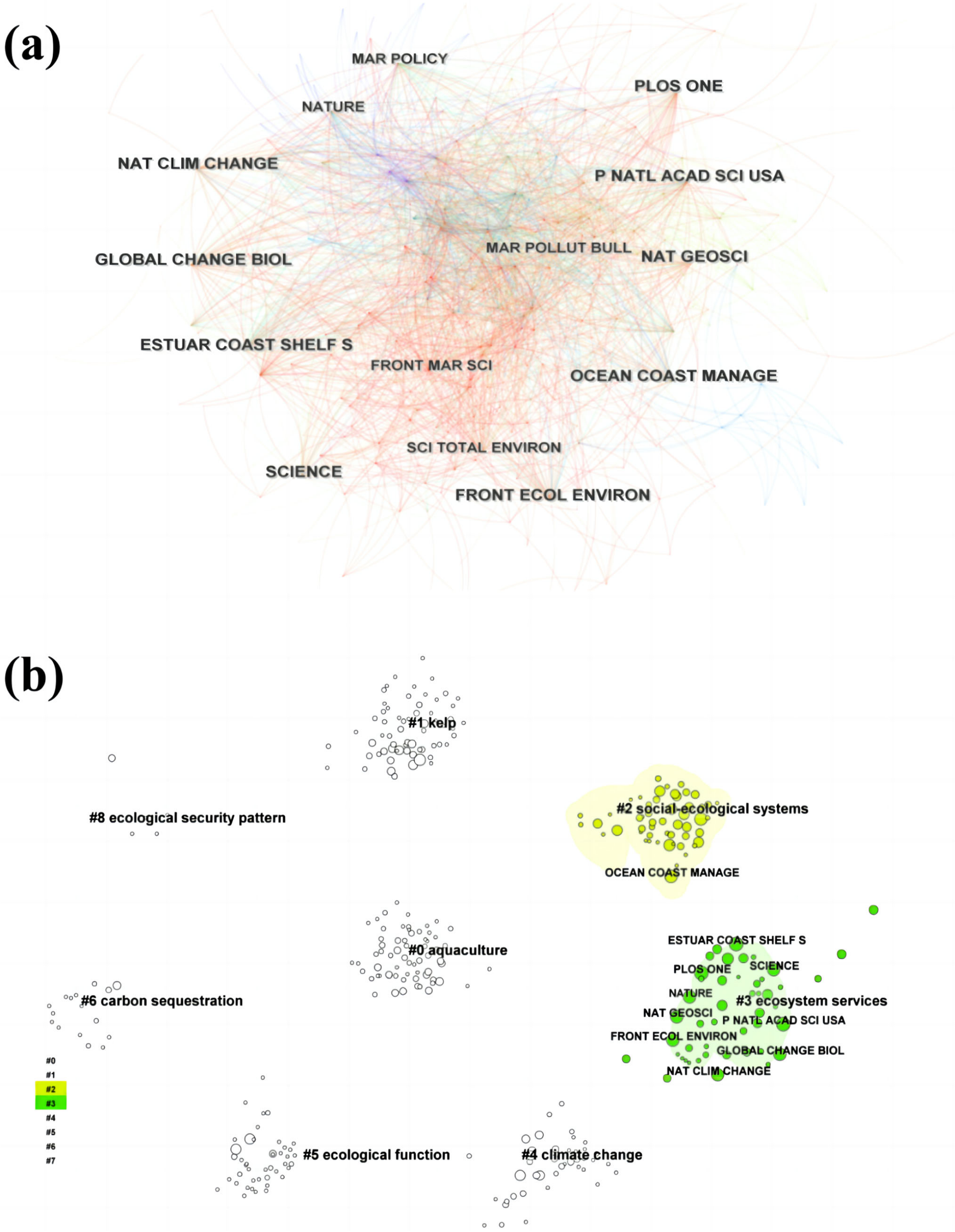

Figure 8. Journal co–citation network map (**a**,**b**). (**a**) Tree–ring nodes. A total of 14 journals are displayed when the threshold is set to 89. (**b**) Cluster nodes. Cluster #2 and Cluster #3 are highlighted based on (**a**) as 10 journals can be found in them (Source: CiteSpace and the authors' research).

Table 5. The top 10 most active journals (Source: analysis and summary by the authors).

Count	Journal	Articles	Categories	Impact Factor
107	PLoS ONE	2	Multidisciplinary Sciences	3.7
107	Proceedings of the National Academy of Sciences of the United States of America	1	Multidisciplinary Sciences	11.1
103	Estuarine Coastal and Shelf Science	7	Marine & Freshwater Biology	2.8
97	Frontiers in Marine Science	13	Marine & Freshwater Biology	3.7
96	Ocean & Coastal Management	7	Oceanography	4.6
94	Nature Climage Change	1	Environmental Studies	30.7
93	Science	1	Multidisciplinary Sciences	56.9
91	Nature Geoscience	1	Geosciences; Multidisciplinary	18.3
91	Global Change Biology	3	Environmental Sciences; Ecology	11.6
89	Nature	1	Multidisciplinary Sciences	64.8

Among these journals, *Nature* has the highest impact factor (64.8, 2022) among the top 10 journals [97], illustrating the journal's importance and broad influence in the academic community [98]. Rogers et al.'s article "Wetland Carbon Storage Controlled by Millennial–Scale Variation in Relative Sea–Level Rise" was published in 2019 and had an important impact on blue carbon research [99]. *Frontiers in Marine Science* (FMS) has published the most articles in this research field, 13 in total, despite having a relatively low impact factor of 3.7. It is one of the leading journals in the field of marine science, making it an ideal forum for blue carbon researchers to present their findings. A wide range of topics are discussed in these articles, ranging from ocean carbon cycles to ecosystem health. One article was published in 2015 [69], another in 2016 [100], one in 2019 [101], one in 2021 [102], one in 2023 [103] and the remaining eight in 2022 [104–111]. *Frontiers in Marine Science* has contributed to the field at various times, which is essential to its continued growth. Additionally, it is important to mention that seven articles were published in two journals, *Estuarine Coastal and Shelf Science* and *Ocean & Coast Management*, which are devoted to the management and protection of marine and coastal ecosystems as well as providing a research platform for blue carbon. *Estuarine Coastal and Shelf Science* mainly published articles between 2019 and 2022 [112–118], while *Ocean & Coast Management* published one article in 2018 [119] and some other articles between 2020 and 2022 [120–125].

The distribution of these journals in terms of subject areas are examined, and the findings covered a wide range of fields, such as environmental sciences, marine and freshwater biology, ecology, oceanography, etc. This diversity of disciplines reflects the wide range of interests of academics and the high priority given to environmental and biological studies. While natural science plays an important role in this field, collaboration and integration between disciplines still need to be strengthened. Particularly in the social sciences, policy research and socio–economic impact assessments have not yet received sufficient attention.

4. Findings, Conclusions, and Future Research

4.1. Main Findings

As a result of the analysis of the selected sample of literature related to blue carbon and sustainable development, a more comprehensive understanding of the perspectives expressed by experts and scientists from across the globe, the following main findings can be drawn.

4.1.1. Has Potential but Need for Filling the Field

As a result of using blue carbon to promote the achievement of SDGs, a certain consensus has been reached within the research community. In 2023, 49 research papers were published, a record high; this trend suggests that there will be more research conducted on this topic in the future. There is a strong possibility that research regarding blue carbon and sustainable development will continue to grow as climate change and sustainable development continue to gain attention [126–133]. In spite of this, academic research in this area is in its infancy, with the amount of research being relatively small and confined to a few specific areas of study. There are relatively few researchers in this field, and most of them reside in a small number of regions or countries. Research participation rates are low in regions with great maritime interests, such as Africa and South America. While the Alliance of Small Island States (AOSIS) has actively promoted the inclusion of blue carbon on the global climate agenda [134], it has not been an active participant in the study.

4.1.2. Currently Researched Topics

The issue of blue carbon and sustainable development is a comprehensive issue that spans multiple disciplines and fields, including the sciences (e.g., ecology, climate science, biology, oceanography), technology and engineering, and social sciences (e.g., policy, management, and economics). As a result of its analysis, it can be roughly divided into four research topics, which are as follows:

Topic I: Blue carbon plays a prominent role in ocean and climate change issues

Inextricably linked to climate, the oceans play a key role in climate change mitigation and adaptation [135–140], and blue carbon plays a potential contributing or even the predominant role [11,55,140–151]. As part of the ongoing discussions regarding the ocean–climate nexus and blue carbon, more attention is being paid to carbon cycling and storage processes in the open ocean as a potential solution to climate change [107]. Maintaining and increasing blue carbon such as *Caulerpa* farming is one of the most basic strategies for combating global warming [152–154]. Due to regional warming, the northern Antarctic Peninsula is likely to experience macroalgal expansion and blue carbon gains as a result of glacial retreat [155]. Meanwhile, a natural methane (CH_4) emission from blue carbon ecosystems may counteract atmospheric CO_2 uptake [156]. A seagrass–colonized coastline is a net source of CH_4 to the atmosphere; CH_4 production is sustained by methylated compounds created by the plant, as opposed to the fermentation of buried organic carbon [157]. In contrast to the short lifetime of CH_4 in the atmosphere, undisturbed coastal wetlands produce limited quantities of CH_4 emissions [153,158,159]. As natural carbon storage hotspots, blue carbon ecosystems are also at risk from global change [159–165]. As an example, the typical blue carbon ecosystem exhibits a high level of heavy metal accumulation capacity; however, extreme rainfall can lead to a change in sediment particle size, thereby causing heavier metal concentrations to increase towards the sea [166].

In many international organizations and countries such as Fiji, blue carbon as a carbon mitigation strategy is incorporated into National Development Contributions (NDCs), national management plans, etc. [11,107,167,168]. Community participation is essential in the implementation process as the blue carbon ecosystem is deeply woven into the need for NDCs [169]. In fact, key issues involved the reliance of blue carbon measures on slowing sea level rise as well as restoration efforts [11]. In particular, coastal wetlands are dependent on the interaction between human impacts and sea–level rise to survive [158]. In addition to providing climate change mitigation benefits, MPAs in different places can also contribute to the preservation and enhancement of blue carbon pools [170].

Topic II: Blue carbon ecosystem assessment and sustainable management

Seagrasses (dead seagrass, seagrass beds, seagrass meadows), mangroves, coral reefs, kelps, saltmarshes, macroalgae (or seaweeds), benthic microalgae, etc., constitute the blue carbon ecosystem, whose comprehensive benefit is also determined by the size, quality, and extent of the ecosystem [69,71,76,104,110,124,135,136,161,164,165,168,170–184]. Due to the structural complexity of coastal vegetation ecosystems (root systems, dense vegetation, and leafy canopy in seagrass systems), salt marshes, mangroves, and seagrass beds are capable of efficiently capturing sediment and associated organic carbon from both riverine and oceanic sources [164]. Among these, coastal wetlands (mangrove, tidal marsh and seagrass) sustain the highest rates of carbon sequestration per unit area of all natural systems, primarily because of their comparatively high productivity and preservation of organic carbon within sedimentary substrates [99,158,159]. However, blue carbon ecosystems have been severely depleted in the last 50 years, primarily as a result of human activities [72,78,101,162]. Of course, human activities like human–made structures can also enhance the biogeochemical sink capacity [185]. Consequently, it is necessary to conduct qualitative and quantitative assessments of the blue carbon ecosystem's components, carbon storage, carbon cycling, carbon sequestration, monitoring, and potential risks under different conditions [10,72,100,110,112,114,116–119,123,141,145,146,149,151,160,164,167,172,174,175,186–228].

Generally, the capacity of coastal ecosystems to sequester blue carbon per unit area is greater than that of terrestrial and ocean ecosystems [13]. A mangrove ecosystem with a low freshwater demand, for example, is recognized for providing valuable ecosystem services as well as having the highest carbon content of any forest ecosystem [74,229]. The ecosystem functions of restored mangroves are higher than unrestored degraded mangroves, but are lower than that of natural mangrove groves [113,188,230].

Carbon sinks can be increased through the efficient carbon sequestration of blue carbon ecosystems [231]. A main benefit of microalgae is their ability to sequester carbon and produce biomass without the need for arable land [152]. It may be possible to increase blue carbon by reducing the use of chemical fertilizers on land in order to promote microbial carbon sequestration in marine ecosystems [232]. Although invasive species (*Phragmites australis*, *Sporobolus alterniflora*) are probably harmful, soils provide an effective carbon sink [233–235]. Furthermore, the Abu Dhabi Blue Carbon Demonstration Project indicates that coastal ecosystems provide numerous additional environmental benefits, including habitat for sea turtles and dugongs, stabilization of shorelines, fish production, and water quality maintenance [236].

As a result of technological advancements, we discovered that blue carbon consists not only of shellfish and macroalgae but also the carbon transformed by microbes, dissolved organic carbon, and sedimentary particulate carbon [164,237]. Habitat (distribution) maps are increasingly being created to account for blue carbon using remote sensing data, acoustic methods, species distribution models (SDMs), and machine learning algorithms [74,104,142,151,164,175,179,187,238–244]. By using satellite images and biological data, we are mapping the percent seagrass cover (SPC), the above–ground biomass (AGB) and the below-ground biomass (BGB) on islands to monitor temporal changes in the distribution of seagrass meadows [245]. It is possible to trace the carbon flows in blue carbon ecosystems using ecological network analysis (ENA) as total coastal carbon flows were many times greater than terrestrial ones [164,246,247]. In order to support coastal and small island zonation planning, conservation prioritization, and marine fisheries enhancement, multi-source spatial datasets can be used to map the climatic and human pressures on blue carbon ecosystems [205]. In order to improve soil health in blue carbon ecosystems, biochar–based technologies must be developed [242].

In order to protect the blue carbon pool and formulate a sustainable management plan, incorporating REDD+ (Reducing Emissions from Deforestation and Forest Degradation Plus) will play an important role and is the ultimate objective of developing blue carbon policies [71,140,248]. The ability to quantify carbon accumulation in sediments is a useful tool for estimating the amount of carbon stored in mangrove ecosystems, which is a precondition for the implementation of REDD+ programs [117,164,228].

In Vietnam, the benefits of mangrove-aquaculture systems (MAS) are a possible triple–win approach for communities towards sustainable development [120]. The Blue Carbon Strategy Framework (including coordination, policy, and funding) is imperative for Indonesia [249,250]. Local cases in the Philippines indicate that the concept of "blue carbon" has not yet been fully integrated into management plans [251]. Despite the fact that the drivers were not ranked based on the assessment, key respondents cited 'institutional capacities' as a major factor hindering the management of blue carbon ecosystems [252]. A crucial component of the improvement of blue carbon sinks in China's reclamation history districts was coastal management practices (the size of industry and population control, balanced fertilization techniques in reclamation areas, and maintaining adequate vegetation cover in reserves) [147]. The fundamental drivers for reducing the total blue carbon stock of the Sundarban, the world's largest contiguous mangrove forest, are recurrent tropical cyclones, soil erosion, anthropogenic pollution, and so on [253]. Plantations of iteroparous mangrove species may provide an effective solution to these challenges [254]. Furthermore, it is proposed that living shorelines that incorporate blue carbon ecosystems into their design could sustain and/or increase carbon stocks and carbon sequestration capacity in Australia [150].

Increasing the blue carbon potential of marine protected areas (MPAs) may be a key contributor to carbon emissions reduction [139]. It will be possible to achieve substantial gains with a small amount of coverage with MPAs on specific carbon pools [170]. The design, location, and management of MPAs could be utilized to protect and enhance carbon sequestration, and to ensure the integrity of carbon storage through conservation and restoration practices [78,138]. The overall positive result may be diminished if MPAs were established solely based on biodiversity considerations such as coral reefs [170].

Blue carbon as a new funding mechanism can be applied and developed to the sustained funding for marine protected areas (MPAs); implementing many of these potential solutions (blue bonds, debt–for–nature swaps) have some capacity requirements [111].

Topic III: Integrating sustainability into economic development

Based on an uncertainty propagation approach, 0.15–1.02 billion tons of carbon dioxide are released globally annually, causing economic damages of US $6–42 billion [73]. Furthermore, large marine ecosystems have the potential to contribute to the harnessing and growth of the blue economy [145]. A carbon finance program can help to protect 20% of the world's mangrove forests (2.6 million hectares) [255]. By utilizing and investing blue carbon as a source of climate finance, we are able to fill the finance gap associated with ocean sustainability [102,140]. The sequestration of blue carbon must be quantitatively evaluated and exchanged in order to become an economically viable product [256].

In terms of evaluation, mangrove restoration has positive benefit–cost ratios ranging from 10.50 to 6.83 under variable discount rates [188]. The plural valuation of mangroves may therefore be applied to sustainability initiatives [257]. The benefit transfer method is one of the most common valuation methods, but it risks recycling old estimates without advancing our understanding. In spite of continued use of replacement costs and improper use of carbon prices, estimating the economic value of carbon storage and sequestration remains a challenge [184]. In order to fund large-scale blue carbon restoration needs, tools such as payment for ecosystem service (PES) schemes and common asset trusts (CATs) can be used together [258]. First, we must estimate the carbon price, and then we must address economic, social, and governance issues [142,259]. Despite increasing promotion of PES to protect blue carbon ecosystems, biophysical stressors external to the PES site (pollution, etc.) will affect the potential contribution of PES sites [75,260]. One of the few positive stories for ocean acidification is that if ocean acidification results in a significant increase in above– and below–ground biomass, this increase in sequestration capacity will be worth between £500 and 600 billion between 2010 and 2100 [70].

At the implementation level, increasing economic sustainability can also be achieved by applying the ecosystem services concept and framework to aquaculture, etc. [261]. The potential for return (ROI) is a key factor in attracting more investment in rehabilitation-oriented blue carbon [262]. Voluntary carbon markets (VCMs) are more attractive to smaller projects due to their lower transaction costs using the blockchain technology, etc. [69,76,79,263]. Local communities may benefit from coastal carbon offset projects, and carbon credits can be traded on carbon markets [236]. Using the blue carbon economic model, fuel and food may be produced from marine ecosystems by sequestering, storing, and harvesting carbon [264]. The farming and industry of macroalgae, seaweed, etc., can provide future energy, economic growth, and sustainable livelihoods if the interactions between these operations and the surrounding marine ecosystems are taken into consideration [264–266]. Phytomariculture of seagrass offers the advantage of producing a seedbed and nursery for the development of blue carbon projects, such as the restoration of seagrass habitats [267]. In order to achieve the green and sustainable development of the carbon industry system, the maximum removal of black carbon impact, the maximum increase of gray carbon scale, and the maximum development of the blue carbon economy must be the main goals [268].

However, there are a number of challenges to overcome. In spite of the fact that ecosystems are excellent carbon reservoirs, blue carbon is marginalized on global markets for several reasons [80]. Very few operational blue carbon sites have been identified [121]. In Vietnam, financial incentives have contributed to the planting of more mangroves, but their effectiveness has been limited by conflicting national policies (such as the expansion of aquaculture in mangrove areas) [269]. Few blue carbon credit projects are operational due to low credit–buyer incentives, uncertainty regarding the amount of emissions reductions that can be credited, and high project costs [262]. Local residents have not combined their perceptions of tourism and blue carbon ecosystems [270].

Topic IV: Blue carbon policy and international cooperation

Blue carbon policies are continuously evolving in related countries. Blue carbon policies in China have shifted from protecting ecosystems to increasing stocks, and the policy approach has evolved from simple protection to a comprehensive approach [271]. Due to the government's revocation of the mangrove protection act, Brazil's mangroves are no longer protected permanently, which will likely result in increased loss rates in the future [272]. It is possible for policy subsidies from the government to encourage the carbon trading platform to cooperate and improve their carbon sequestration capacity; however, if the subsidies are too high, the system will not have an evolutionarily stable strategy [273]. The balance is constantly shifting in policy. Coastal ecosystems are managed by policies and decision–makers that integrate physical, ecological, and social factors; natural threats and lack of law enforcement were the primary factors contributing to mangrove forest degradation in the Philippines, posing a fundamental disadvantage for local people [274–276]. It is essential to investigate stakeholder preferences, especially those related to livelihoods, in order to ensure the sustainable development and conservation of blue carbon ecosystems [79,277]. As a result of various environmental and social constraints, the effective implementation of regulations and guidelines regarding sustainable aquaculture practices in Indonesia remains a challenge [122]. For the fisheries policy to be a more effective one, the maximum carbon sequestration must be incorporated into fisheries management, rather than only focusing on Maximum Sustainable Yield (MSY) [109]. By conserving large fish species preferentially, fisheries management can increase overall carbon storage in the fish community while balancing several SDGs [278].

To determine the best eco–site, a spatially explicit, integrative, and culturally relevant site selection process is necessary, with blue carbon storage value being assigned the greatest weight [108]. Natural–based solutions and ecosystem–based approaches are good policy options [279,280]. In detail, blue carbon can be integrated into national Marine Spatial Planning (MSP) as a conservation management tool in the proposed spatial planning laws [106,163]. MSPs that address ocean climate change ('climate-smart MSPs') may find that ocean climate change modelling is a key decision–support tool [281]. The primary proximate drivers of coastal aquaculture expansion were identified as aquaculture development and economic opportunities, whereas factors relating to institutional policies played a lesser role [125]. Government policy interventions should be prioritized to increase the expansion of sustainable coastal aquaculture and mangrove conservation [125].

As most places where blue carbon occurs are managed under common–property or open–access regimes, the impacts of blue carbon projects will be highly dependent on how they address property rights [76]. Furthermore, as part of the UNFCCC process, blue carbon sequestration may serve as a governance niche [139]. Conserving and restoring blue carbon ecosystems overlap with protected area management, which are overseen through the Convention on Biological Diversity and the Antarctic regime complex for the Southern Ocean [140]. However, there is a limited number of empirical values generated by these studies [183], especially in terms of policy perspectives.

In light of the evaluation of the blue carbon development index (BCDI), global cooperation could contribute to improving the global average BCDI score and sequestering carbon dioxide [282]. The establishment of a blue carbon co–operation and trading mechanism with other countries would enhance the implementation of global fishery resources and extend the industrial chain [283]. A source of future international support for blue carbon–rich countries is institutional recognition [140]. The Australian Government announced the establishment of an international partnership for blue carbon in 2015 [77]. Despite the lack of formal recognition within the climate process, communities of practitioners have served as networked constituencies (such as the Blue Carbon Partnership) [140]. An economic model of blue carbon international cooperation proves the economic feasibility of blue carbon cooperation [256]. There is a high likelihood that not all countries will participate in blue carbon international cooperation, but sub–alliance groups of multiple countries should be considered [256].

4.2. Conclusions and Future Research

4.2.1. Conclusions

According to the IPCC report, the global carbon footprint is increasing [14]. Oceans are estimated to remove 30% of atmospheric CO_2 emissions every year, and their potential to increase sinks is significant [284–286], contributing to the achievement of the SDGs. This research provides a comprehensive overview of blue carbon and sustainable development. The study explored an extensive and broad array of literature from the WoS database. It is likely that research on blue carbon and sustainable development will continue to grow. The key components of blue carbon and sustainable development were "counts" and discussed [140]. The issue of blue carbon plays a significant role in oceans and climate change. In addition to the size, quality, and extent of the blue carbon ecosystem, its comprehensive benefit is also determined by its composition. Many studies have been conducted on the qualitative and quantitative assessment of the blue carbon ecosystem. Many places have attempted to manage blue carbon in a sustainable manner using a variety of technologies. Investing in blue carbon as a source of climate finance enables us to bridge the funding gap associated with ocean sustainability and meet stakeholder needs [107]. It is essential to estimate the correct carbon price in order to integrate sustainability into economic development, followed by addressing social, policy, and governance concerns. There is a continuous evolution of blue carbon policies in related countries, and international cooperation is in the process of being implemented. In this review, it was discovered that there is no coordinated, systemic approach to assessment, blue carbon sink capacity remains limited, and insufficient policy support hinders the development of blue carbon and sustainable development [287].

4.2.2. Future Research

There is a need for future research on blue carbon and sustainable development to focus on the following areas: (1) Blue carbon research should be balanced among different types. The current push to measure and offset blue carbon has focused on coastal regions to date [107,232]. Different types of blue carbon have different potentials. In addition to coastal blue carbon, other types of blue carbon should receive more attention, particularly from a scientific perspective [101]; (2) A greater emphasis should be placed on distributional equity. Rather than considering distributional equity, blue carbon currently focuses more on technological innovation, ecological sustainability, and economic viability [121]. A great deal of potential exists for blue carbon, but there are very few specific sites, and the majority are based on protected blue carbon ecosystems, such as mangroves. The policies and regulations that address the needs of coastal communities and advance social equity are far from what is expected [121]; (3) Incorporating blue carbon into the marine industries by developing a blue carbon strategy. If future oceans are to contribute more widely to human well–being [121], further research is required in order to bring blue carbon resources into carbon markets [232,248,288]. The coastal blue carbon projects around the world serve as a testing ground for new ideas, methodologies, and funding mechanisms [79]. When blue carbon is incorporated into the process of developing the marine industry [136,166,289], it can provide solutions to some of the current challenges, such as a lack of carbon sites and a lack of funds. By developing the mariculture industry, for example, increasing the application scenarios for blue carbon, we can achieve the goal of increasing carbon sinks; (4) Blue carbon policies should be developed and coordinated at the regional level. Despite the fact that blue carbon policies are in place in many countries, cooperation and interaction among countries are very limited. However, if it is agreed that blue carbon is the key to achieving carbon neutrality in the future, regional coordination through sub–alliances of multiple nations is an important initiative. Standards, regional planning, and other forms can be used to promote regional blue carbon policies that integrate science, practice, and policy around the world. As a result, a new conceptual model for blue carbon is likely to be created [290].

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