RESEARCH ARTICLE

A bibliometric survey on global strategies for blue carbon ecosystems management: Current status and future priorities

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As the problem of climate change becomes increasingly serious, blue carbon sinks represented by mangroves and seagrass meadows have attracted much public attention due to their outstanding carbon storage capacity and ecosystem services. This research systematically reviewed 3,045 documents related to the theme of blue carbon sinks from 1974 to 2023 in the Web of Science database using the bibliometric tool 'bibliometrix' and the Python programming language. The results found that these documents were mainly divided into three thematic clusters including the ocean cluster, the blue carbon cluster, and the dynamic cluster. In addition, China and the United States were focusing on the application of new materials and methods in the research, presenting a research landscape that was both competitive and cooperative. Further, technological innovation, policy optimization, and socio-economic impact assessment were likely to become future research hotspots. The results suggested that policies for the utilization and protection of blue carbon sinks should be formulated at the national level, and climate cooperation under multilateral frameworks with the participation of developing countries should be strengthened to contribute to global strategies for carbon emission reduction and climate change response.

Keywords: blue carbon; climate change; ecosystem services; bibliometrics.

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Introduction

Blue carbon is defined as the capacity of nearshore marine vegetation ecosystems including mangroves, salt marshes, and seagrass beds to absorb and sequester carbon through primary production and sedimentation processes over extended periods. These ecosystems play a pivotal role in the global carbon cycle and are estimated to sequester approximately 25% of global carbon dioxide emissions annually with variations depending on measurement criteria. Concurrently, they provide multiple ecosystem services including coastal protection, water purification, and fisheries enhancement, which significantly enhance biodiversity by providing critical habitats. While coral reefs primarily participate in carbonate cycling, they exhibit synergistic effects with blue carbon governance in terms of habitat provision and coastal protection. In the context of global climate governance and the advancement of national "dual carbon goals," the conservation and restoration of blue carbon sinks have been shown to play a crucial role in mitigating and adapting to climate change. These efforts have also been demonstrated to stimulate employment and blue economic development, while enhancing tourism quality and community well-being. The increasing frequency of extreme climate events further underscores the practical necessity and urgency of strengthening blue carbon research and management practices.

Considering these developments, recent research has been primarily concentrated on three areas, which includes: (1) The scope and definition of blue carbon ecosystems have been gradually standardized in the accounting field. Key parameters such as soil organic carbon (SOC) and spatial base maps have been continuously improved [1]. Methane (CH_4) and nitrous oxide (N_2O) have been included in the comprehensive greenhouse gas balance, and repeatable methane and nitrous oxide removal (MRV) standards have been established, enhancing comparability across regions and projects [2]; (2) management effectiveness that practices characterized by “protection first + restoration in parallel” have progressed from the proof-of-concept stage to the scale-up stage. Various co-benefits have been incorporated into the measurement framework to assess co-benefits and uncertainty ranges. These benefits include carbon sequestration benefits as well as coastal protection, biodiversity conservation, and fishery resource enhancement [3]; (3) risk assessments show that the combined pressures of sea level rise, extreme events, and human disturbances significantly increase the probability of degradation and loss, which highlights the urgency of identifying high-risk/high-opportunity areas and promoting nature-based adaptation and resilience governance [4]. Notwithstanding the considerable progress that has been made in blue carbon research in recent years, there are still critical gaps in the scope of evidence, the spatiotemporal scales, the identification of mechanisms, and the implementation of governance. It should be noted that data and accounting continue to rely on early remote sensing and traditional methods to a certain extent [5]. Inconsistent resolution and scope, insufficient ground verification, and the lack of global long-term, comparable time series weaken precise assessments of scale and trends [6]. In addition, insufficient attention has been paid to biogeochemical coupling and disturbance effects among ecosystems such as mangroves, salt marshes, and seagrass beds. The mechanisms underlying their impact on carbon pool stability and flux remain inadequately elucidated, limiting the explanatory power regarding the "ecological function-carbon cycle" relationship [7]. Further, the compound pressures of sea-level rise, ocean acidification, and extreme climate events continue to intensify [8], yet systematic assessments of their impact pathways and thresholds remain inadequate, leaving management and adaptation strategies lacking actionable evidence [9]. Policy research has been found to insufficiently consider regional heterogeneity and implementation constraints. This is evidenced by the lack of testable performance evaluation frameworks, which hinders the effective translation of research findings into executable governance solutions [10].

In light of these considerations, the objectives of this study were to clarify conceptual boundaries and accounting methodologies by systematically tracing the thematic evolution and knowledge structure of blue carbon research using core literature from Web of Science from 1974 to 2023, characterize the spatial distribution of research capacity and collaboration patterns through national-scale cooperative network analysis to identify the key factors and influence networks, synthesize the evidence base of the blue carbon ecosystem across scenarios including carbon sequestration, biodiversity conservation, and coastal protection to propose adaptive governance pathways oriented toward risk prevention and control, along with a future research agenda to clarify directions for subsequent studies. Bibliometrix in R was employed in this study for the organization and analysis of literature data supplemented by Python visualization to enhance readability and insights. This research focused on multiple ecosystem services including biodiversity conservation, water purification, and disaster mitigation. Through an analysis of extant evidence, the study extracted insights into synergies and trade-offs, which advanced from a singular carbon sink perspective toward an integrated evaluation paradigm encompassing diverse services to propose a problem-oriented adaptive governance agenda and analytical framework, establishing a reusable methodology pathway of "bibliometric analysis—theme identification—evidence synthesis" that enhanced the explanatory power and extensibility of blue carbon research in theoretical integration and knowledge accumulation.

Materials and methods

Data collection

The prevailing consensus in extant research recognizes mangroves, seagrass beds, and salt marshes as the predominant blue carbon sinks. This study used "Mangrove carbon," "Seagrass carbon," and "Salt marsh carbon" as core keywords for topic screening in the literature [11]. Concurrently, the terms "Blue carbon" and its synonymous concepts including "Coastal carbon," "Marine carbon," and "Oceanic carbon," were incorporated into the keyword list. The search terms "marine carbon" and "oceanic carbon" were used as supplementary keywords. Moreover, the search scope was constrained into two primary databases within Web of Science (https://www.webofscience.com/) including SCI-EXPANDED and SSCI. According to the established criteria, a comprehensive search was conducted and yielded a total of 3,045 articles pertaining to blue carbon from the years 1974 to 2023. These publications along with their citation information were imported into the Bibliometrix tool (https://www.bibliometrix.org/) in BibTeX format for bibliometric analysis under R (https://mirrors.tuna.tsinghua.edu.cn/CRAN/).

Data analysis

Subsequent analysis primarily utilized Bibliometrix supplemented by Python (https://www.python.org/) for reanalysis and visualization. The research trajectory of blue carbon was mapped through the analysis of annual publication volumes, while segmentation of developmental stages was conducted based on key policy milestones. Python language was employed to construct international collaboration networks, wherein node size was indicative of total collaboration volume, while link color and width were associated with developmental stage and collaboration intensity, respectively, to explore research partnerships among key nations. A "density-centrality" two-dimensional coordinate system was then constructed. The thematic clustering analysis was performed using Keyword Plus, and the top 50 most-cited papers (NTC) from each cluster were selected for analysis to dissect the core content of thematic clusters. The research also focused on revealing the differing research priorities among major countries in the blue carbon sink field by examining the top ten publishing nations within each thematic cluster. The Trend Topics module was utilized for the visualization of keyword frequency and temporal trends, which facilitated the identification of shifts in research focus and the emergence of topics.

Results and discussion

Literature time trend analysis

The research on blue carbon can be divided into initial emergence phase from 1974 to 2008, rapid growth phase from 2009 to 2014, and explosive expansion phase from 2015 to 2023. The first related paper was published in 1974 followed by a period of limited output that persisted for many years. In the 1980s, research gradually shifted its focus to the study of carbon cycling within mangrove ecosystems. Representative studies demonstrated that mangrove organic carbon was transported to nearshore areas *via* detrital pathways. However, nearshore animals exhibited no evidence of isotopic assimilation. The nascent phase exhibited minimal publication volume and impact. From 2009 to 2014, there was a marked increase in annual output, reaching 40 papers in 2009 with an approximate 33% year-on-year increase and subsequently maintaining elevated

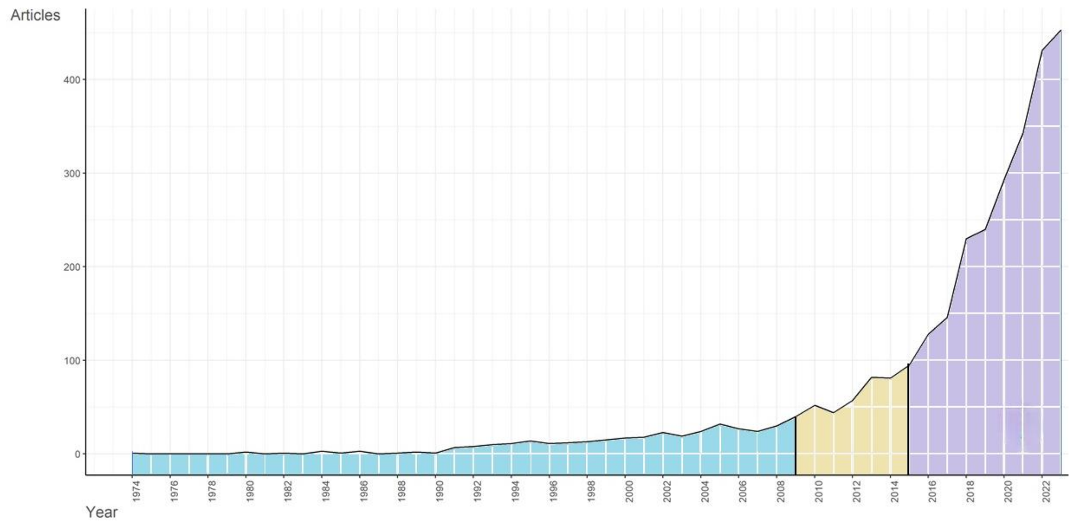

Figure 1. Annual production on blue carbon sinks.

levels. The number of publications increased exponentially, reaching 95 in 2015 and surpassing 100 for the first time in 2016 with 128 articles. This figure continued to increase, reaching 230 in 2018 and 453 in 2023 (Figure 1). The scope of research themes has evolved from early studies on mangrove carbon cycling to encompass carbon stock assessments, ecological functions, and management strategies. The years 2009 and 2015 represented pivotal turning points, primarily driven by significant advancements in the field. In 2009, the United Nations Environment Programme and other institutions formally introduced the "blue carbon" concept, thereby providing a systematic definition of the role of coastal and marine ecosystems in carbon sequestration. Concurrently, researchers observed accelerating degradation of these ecosystems' long-term carbon sequestration capacity, which highlighted the urgency of the issue and directly spurred subsequent thematic research. In the aftermath of the establishment of the Nationally Determined Contributions (NDCs) framework within the 2015 Paris Agreement, national climate strategies commenced the incorporation of blue carbon into mitigation and adaptation toolkits, thereby encouraging its integration into NDCs and policy design at the operational level. This development has led to a further expansion in research demand and collaborative networks. Consequently, the topic has evolved from a "single ecosystem process" toward an interdisciplinary trajectory encompassing "multi-ecosystem, multi-method, multi-sector governance." The initial accumulation of knowledge and methodologies regarding mangrove carbon cycles has established a substantial foundation for subsequent expansions into seagrass beds, salt marshes, and more extensive coastal carbon management. This transition has led to an augmentation in the scope of research and the magnitude of research outputs.

International collaboration network

The collaborative network for global blue carbon research has undergone significant expansion and increased interconnectedness over time (Figure 2). During its nascent phase from 1974 to 2008, collaboration was primarily concentrated between Europe and the United States with the most prevalent collaborative engagement being observed between the United States and Germany with 20 documented instances followed by Germany and the United Kingdom with 11 instances, and the United States and the United Kingdom with 9 instances. Other collaborative efforts encompassed the United States and Canada with eight documented

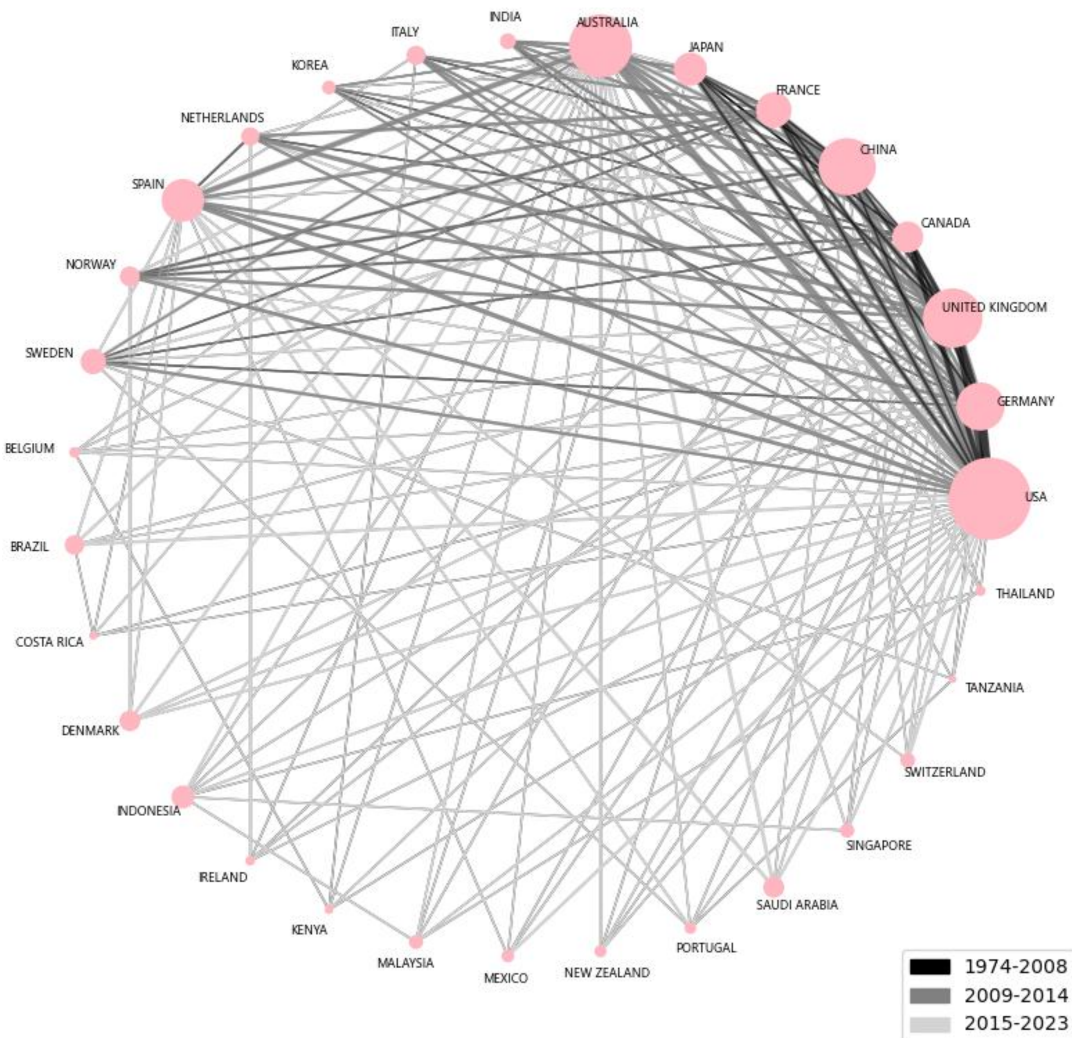

Figure 2. International collaboration network of blue carbon sinks.

instances, and the United Kingdom and Canada with six recorded instances. Except for sporadic collaborative endeavors involving Japan, New Zealand, and the United States, the network's core was predominantly situated in Europe and North America. During the period of rapid growth from 2009 to 2014, cooperation with Asia and Oceania underwent significant intensification, resulting in the formation of emerging hubs. China engaged in 18, 9, 8, 7 collaborative endeavors with the United States, the United Kingdom, France, and Japan, respectively. Japan, in turn, collaborated 11, 7, 6 times with the United States, the United Kingdom, and Germany, respectively. Additionally, South Korea, India, and other nations participated in the network. A review of international relations revealed that Australia had collaborated on 14 occasions with both the United States and Canada, 11 times with the United Kingdom, 8 times with Spain, and 4 times each with India and Malaysia. Recent studies have revealed a series of emerging connections between the continents of South America and Africa. Brazil has collaborated with Germany, United States, and France on 3, 3, and 2 occasions, respectively. In contrast, South Africa has cooperated with Canada, Ireland, and other nations. The period between 2015 and 2023 was characterized by a substantial surge in cooperation intensity, resulting in the formation of a tripolar pattern. The frequency of interactions between China and the United States reached 140 instances, while those between the United States and Australia reached 123 instances. Furthermore, there was a notable escalation in activity within Europe and between American nations. The frequencies of these interactions included UK – Germany 46 times, UK – France 29 times, UK – Spain 27 times, UK – Norway 21 times, UK – Canada 20 times, Germany – France 28 times. There was an increase in the participation of the Netherlands, Switzerland, Sweden, and other countries. The correlation between South America and the Middle East was minimal, yet Brazil recorded 29 interactions with the US and 17 with Spain, while Saudi Arabia had 39 with Australia, 38 with Spain, and 27 with the US, suggesting an accelerated integration of peripheral regions. As time passed, the collaborative network underwent a shift in its structure, transitioning from an initial "Atlantic core" phase that was predominantly characterized by the influence of Europe and the United States to a more multi-polar configuration. This new structure was marked by the coexistence of the "Pacific Rim" and the "Europe-US" regions. In the aftermath of 2015, a tripolar pattern emerged and anchored by the United States, China, and Australia. This pattern was characterized by a significant increase in cross-regional connections and a more decentralized structure. The rise of Asia and Oceania led to an expansion in the coverage of diverse coastal ecosystem scenarios, resulting in a convergence of disciplines on data, methodologies, and governance issues. Europe's high-density internal connections served to maintain its leadership in methodological and assessment frameworks. Although there was an increase in the participation of emerging nodes such as those located in South America and the Middle East, these regions continued to occupy secondary positions. This finding suggested the presence of enduring interregional imbalances and capacity deficiencies in global collaboration. The network's expansion and multipolarization were indicative of enhanced channels for knowledge and technology diffusion, thereby facilitating evidence accumulation and comparability across disparate ecological zones. However, to continuously narrow the "core-periphery" gap, mechanisms such as open data, joint projects, and talent mobility should be strengthened to enhance the depth and resilience of cross-regional and interdisciplinary collaboration.

Conceptual structure of blue carbon sinks

1. Cluster analysis of the blue carbon sinks

Cluster analysis results suggested that blue carbon research could be categorized into three primary clusters of Ocean, Dynamic, and Blue carbon, which encompassed 2,737 publications, accounting for 89.9% of the total dataset. A notable distinction emerged among these groups with respect to developmental stage and academic standing (Figure 3). The Ocean cluster demonstrated high network density of 5.954, signifying an extensive research scope, while its low centrality of 1.278 placed it peripherally, predominantly in the second quadrant. This finding suggested relative maturity within the field, but an insufficient core status within the academic network. Many related studies concentrated on marine carbon cycling and biogeochemical processes, as well as the impacts of climate change on marine ecosystems, which placed particular emphasis on the roles of phytoplankton, calcifying plankton, and sediments in carbon storage and transport mechanisms [12]. Conversely, the blue carbon cluster demonstrated balanced centrality of 1.361 and density of 5.367, situated at the core of the quadrant diagram, which suggested that the field possessed both academic significance and research depth, thereby establishing itself as a core and steadily developing direction. The primary focus of this research was the carbon sink function of blue carbon ecosystems and their role in mitigating climate change [13, 14]. Dynamic clustering occupied the fourth quadrant, where its high centrality of 1.910 highlighted its core position within the academic network, though low density of 4.906 indicated that it remained in an early developmental stage. This cluster examined the dynamic evolution of

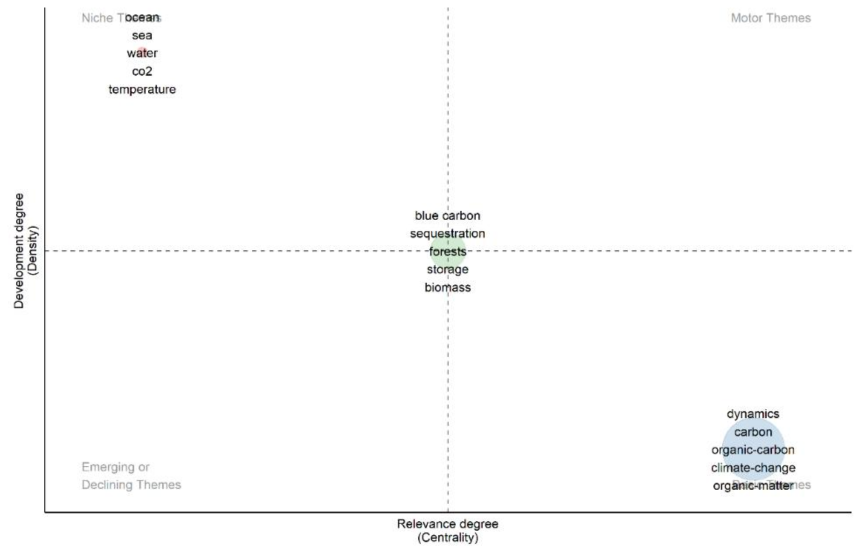

Figure 3. Thematic clustering of blue carbon sinks.

the global carbon cycle and its mechanisms influenced by climate and human activities. Key discussions included land-ocean carbon fluxes [15], changes in marine biogeochemical processes, and the macro-level impacts of climate change on global carbon stocks [16]. All three clusters addressed carbon sequestration and climate change effects in aquatic environments, though each adopted a distinct research perspective. The Ocean cluster placed emphasis on microscopic biological and process mechanisms, while the Blue carbon cluster highlighted ecosystem conservation and its economic and climate governance significance, and the Dynamics cluster focused more on macroscale carbon cycle patterns and the impact of human activity policies (Figure 4). With respect to the dissemination of research findings, the Ocean and Dynamic clusters had been predominantly published in prominent high-impact journals such as Nature and Nature Climate Change, suggesting their interdisciplinary influence and high recognition within their respective fields. Conversely, research on Blue carbon clusters was more frequently published in specialized journals such as Estuarine, Coastal and Shelf Science, which underscored its in-depth exploration of regional and specific environmental conditions.

2. Cluster content analysis of blue carbon sinks

(1) Ocean cluster

A total of 952 papers in the research dataset were assigned to this cluster, accounting for 34.8% of the total articles. The research agenda of the institute was primarily oriented around two research foci with the first focus on the carbon cycle and geochemical cycles between marine organisms and atmospheric carbon dioxide and the second focus on the effects and feedback of climate change on marine ecosystems. With respect to the carbon cycle, research was mainly concentrated on the role of the ocean as a pivotal component of the global carbon cycle and its regulatory mechanisms. Through processes such as calcification, organic matter burial, and microbial activity, the ocean continuously exchanged with atmospheric carbon dioxide, playing a crucial role in regulating atmospheric CO_2 concentrations [17]. The extant research suggested that elevated levels of carbon dioxide (CO_2) in the atmosphere resulted in diminished rates of oceanic calcification [18]. This phenomenon was further substantiated by the findings of ice core evidence, which elucidated a historical correlation between atmospheric CO_2 levels and the sensitivity of the carbonate system [19]. As CO_2 concentrations continued to rise, changes in the ocean's chemical environment

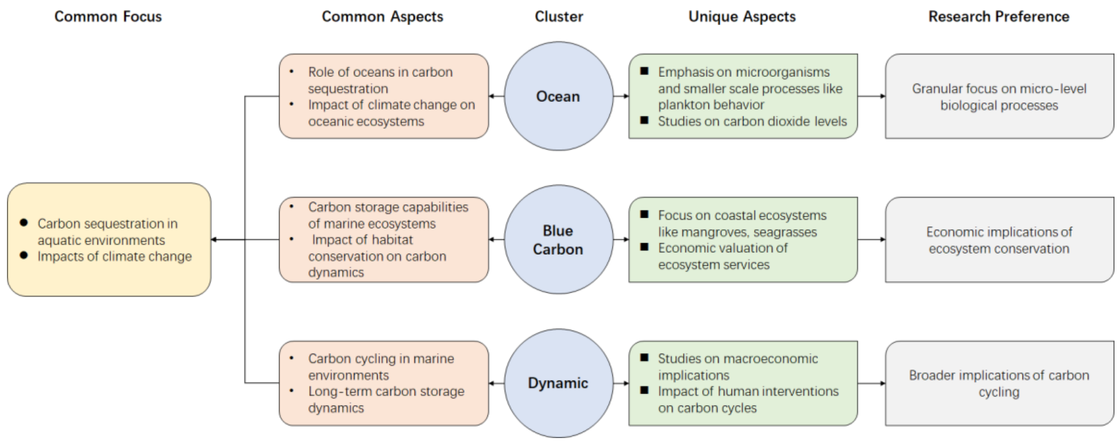

Figure 4. Comparison of clustering research directions in blue carbon sinks.

might diminish its carbon sequestration capacity [20]. Furthermore, interactions between organic matter deposition and mineral ballast significantly influenced deep-sea carbon storage efficiency. In addition, microbial communities served as micro-scale drivers, constituting crucial links in regulating biogeochemical feedback mechanisms. With respect to the ramifications of climate change, research endeavors had mainly focused on the repercussions of environmental transformations including, but not limited to, ocean acidification, rising sea surface temperatures, and upper-layer circulation on ocean carbon sink functionality and ecosystem stability. Advancements in observational techniques such as lidar enhanced the accuracy of carbon dioxide flux assessments. Changes in upper-ocean circulation directly affected phytoplankton diversity and its carbon sequestration potential [21]. Concurrently, acidification demonstrated to have deleterious effects on calcareous organisms, thereby disrupting the carbon cycle [22]. In addition to natural climatic factors, human activities exerted a significant impact on marine ecosystems. Microplastics had been shown to disrupt marine organisms, while semi-volatile aromatic hydrocarbons entering the ocean *via* atmospheric deposition had been found to affect biogeochemical processes and potentially weaken ocean carbon sink functions [23], thereby posing a threat to the global carbon cycle.

(2) Blue carbon cluster

Within the dataset, 820 publications were assigned to this cluster, accounting for 29.9%. The primary focus of the research was on the interactions between blue carbon ecosystems and climate change, as well as the ecosystem services they provided. Typical ecosystems such as mangroves, seagrass beds, and salt marshes were recognized as vital components and key reservoirs in the global carbon cycle [24]. In comparison to terrestrial ecosystems such as forests, coastal and marine ecosystems had been found to possess a substantial carbon storage capacity, which was not only present in living organisms but also in sediments and soils. However, processes driven by climate change such as sea level rise and increasing sea surface temperatures adversely impacted these carbon reservoirs, potentially triggering the release of stored carbon [25]. Consequently, precise estimation of the carbon storage capacity of blue carbon ecosystems was imperative [26]. The preservation and rehabilitation of these ecosystems had been identified as a pivotal strategy for curbing climate change [27]. Building upon this foundation, economic valuation could further underscore the potential role of blue carbon ecosystems within climate finance and carbon market mechanisms [14], thereby supporting the advancement of economically incentivized international cooperation [28]. Beyond the scope of carbon sequestration, blue carbon ecosystems provided a diverse array of ecosystem services that bore significant implications for ecological stability and societal well-being [29]. Complex ecosystems such as mangroves not only maintained their own health but also provided critical habitats for numerous marine and terrestrial species, thereby enhancing regional biodiversity [30]. However, these ecosystems were subject to accelerated degradation risks due to dual impacts from human activities and natural disturbances [31]. Consequently, the integration of ecological benefits with economic value had emerged as a pivotal direction for research and policy practice, aiming to facilitate comprehensive assessments of conservation and restoration. Meanwhile, enhancing public awareness of blue carbon's value helped strengthen policy frameworks and management measures, further unlocking the potential of blue carbon ecosystems in global climate governance.

(3) Dynamic cluster

A total of 965 papers were assigned to this cluster, accounting for 35.2% of the total. The research in this cluster was oriented towards investigating the carbon sequestration benefits of marine protected areas (MPAs) and the impacts of human activities on blue carbon ecosystems. Substantial studies indicated that the establishment of MPAs not only aided in biodiversity conservation but also enhanced fishery productivity and boosted the carbon storage capacity of marine sediments [16]. Consequently, the promotion of synergistic conservation of marine ecosystems from a global perspective was recognized as a crucial pathway to maintain their efficient carbon capture and storage functions [15]. Furthermore, macroalgae sequestered approximately 173 TgC annually, underscoring the urgent need for greater recognition of their role in global carbon sink assessments. The integration of marine protected areas and related ecosystems into the global climate governance framework had emerged as a critical issue in international environmental policy [32], which facilitated a more systematic utilization of their carbon sequestration potential in policymaking, thereby enabling the effective counteraction of the adverse impacts of climate change [33]. However, the impact of human activity on blue carbon ecosystems could not be disregarded. The accelerated degradation of mangrove carbon pools consequent to coastal development portended a further threat to regional biodiversity [34]. To a greater extent, methane emissions from certain mangrove ecosystems showed to partially offset their carbon sequestration benefits, which prompted researchers to consider the dynamic balance between greenhouse gas emissions and carbon storage when evaluating the climate contributions of blue carbon ecosystems. Furthermore, the implementation of seaweed farming activities had the potential to modify dissolved organic carbon levels in water bodies, thereby exerting an influence on the broader carbon cycling processes within these ecosystems [35]. It was imperative to incorporate the long-term environmental ramifications of human activities into the global carbon management agenda to achieve sustainable regulation of the carbon cycle.

Country contributions analysis in blue carbon sinks clusters

In the clustered samples, single-country authors accounted for 50.8% of publications, indicating that "within-border" collaboration remained a significant productive force (Figure 5). A close examination of the extant literature revealed that the United States (US) and China (CN) were the leading contributors in all three major clustering themes. The US began earlier with a relatively even temporal distribution, while China surged rapidly after 2020, reaching its annual peak in 2023 and securing the top position among all nations in dynamic clustering based solely on 2023 output. With respect to the selection of subjects, the marine cluster encompassed research endeavors focused on the synthesis of carbon dots (CDs) from marine

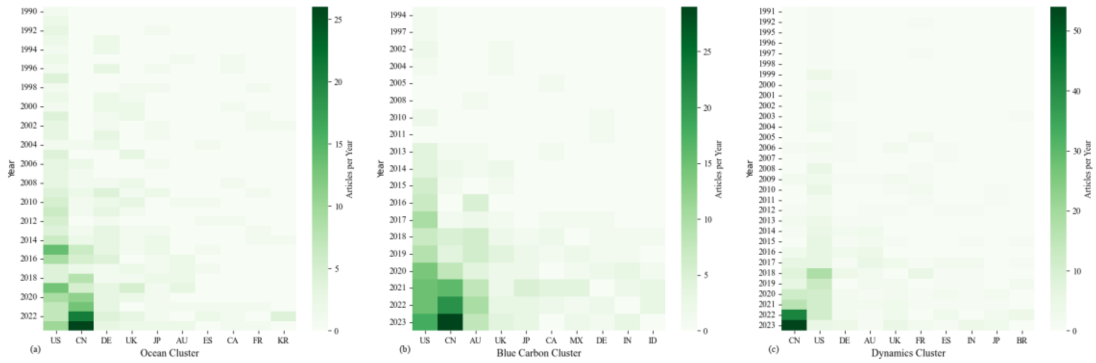

Figure 5. Clustering in blue carbon research: Top 10 countries by publications.

organic matter/waste as a carbon source for antibiotic detection and anti-counterfeiting applications [36]. The blue carbon cluster had placed significant emphasis on spatiotemporal sustainability assessment and global collaboration for blue carbon with a particular focus on remote sensing classification of mangrove and soil carbon influencing factors [37]. Within the Driving Factors cluster, Chinese scholars explored the coupling relationship between soil organic carbon and N/P in BCE, discussed opportunities and challenges of CCUS/CCS systems from an industrial perspective [38], and expanded the multifaceted applications of marine shell resources in remediation and filtration [39]. A study of U.S. researchers revealed that multiscale processes at the ocean-atmosphere-biosphere interface were the focus of analysis, which included associations between volatile organic compounds (VOCs) and plankton communities, gas exchange in seagrass meadows, and the impact of mesoscale eddies on carbon cycling. The analysis of these processes was conducted *via* satellite altimetry and Lagrangian buoys [40]. Regarding blue carbon, studies focused on coastal ecosystem connectivity and carbon storage, mangrove restoration enhancing ocean alkalinity and promoting CO_2 removal, and extreme climate impacts on coastal forests [41]. Dynamic clustering involved technical assessments of electrochemical direct ocean capture (eDOC), climate benefits of Louisiana's Coastal Master Plan, and negative effects of salt marsh pond evolution [42]. Europe (DE/UK) focused on open ocean macroalgae cultivation and CDR potential, proposing a scalable earth observation framework to assess seagrass carbon storage and ecosystem services [43]. Since 2020, Australia (AU) had continued to prioritize the restoration of coastal wetlands, emphasizing the synergistic benefits and mitigation effects of these efforts on biodiversity, fisheries, and water quality [26]. This evidence suggested that substantial single-country representation was indicative of significant shaping effects of domestic research and policy agendas on the blue carbon research landscape. Meanwhile, China and the US exhibited a "dual-peak" progression with distinct pathways with the US leaning toward process analysis, remote sensing-observation, and engineering frontiers and China emphasizing biogeochemical coupling of industrialization technologies (CCUS/CCS) and rapid expansion of material applications (CDs/shell-based) with both converging on coastal ecosystem restoration like mangroves, forming complementary "mechanism-application" chains. Europe, on the other hand, emerged as a leader in the field, offering policy-relevant methodological tools through CDR solutions such as open-ocean macroalgae farming and ocean alkalinity enhancement, along with observable frameworks. In contrast, Australia emphasized the multifaceted co-benefits of restoration engineering through nature-based solutions. The country-led, multi-thematic approach under discussion had been found to accelerate

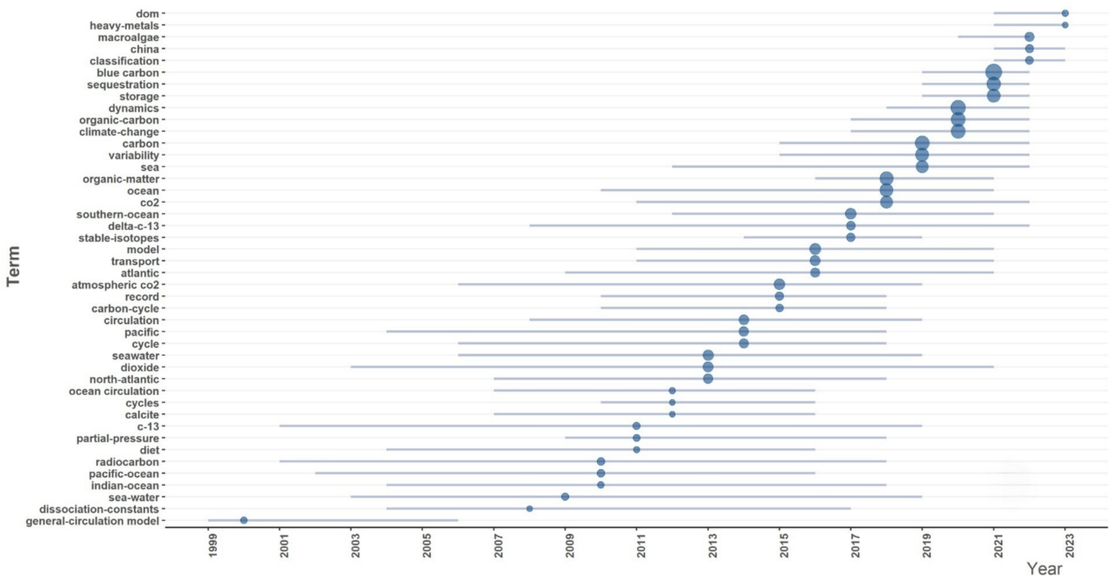

Figure 6. Trends topics of blue carbon sinks.

technological and evidence accumulation. However, this approach had risk as it carried the potential for methodological homogenization and regional bias. The enhancement of transnational replication, data openness, and multi-ecological zone joint assessments had the potential to transform "domestic strengths" into globally comparable, transferable blue carbon governance knowledge.

Trend topics analysis based on hotspot keywords

In terms of keyword frequency analysis, "blue carbon" appeared 398 times, ranking the first followed by "organic matter" (225), "ocean" (200), and "CO_2" (156). Collectively, these findings delineated research landscape centered on marine organic matter and carbon dioxide cycles (Figure 6). In terms of temporal evolution, "blue carbon" reached a cumulative frequency milestone of approximately 25% or around 100 occurrences by 2019. A marked increase in growth was observed after 2020 with an average annual increase of approximately 100 occurrences between 2021 and 2022, which indicated that the topic had maintained its position in terms of prominence. A parallel trajectory was evident in the development of "organic matter," which attained the 25% milestone in 2016 and saw over half of its associated publications emerge by 2018. Its sustained activity through 2021 confirmed the foundational role of organic carbon processes in blue carbon research [16]. Concurrently, keywords "CO_2," "carbon," and "variability" had exhibited upward trends. In the post-2020 era, emerging research trends included "macroalgae", "China", and "classification". Macroalgae emerged as a significant research area in 2020 with the total volume of related literature doubling by 2022, which indicated a rapid escalation in the research community's focus on macroalgae in the context of carbon sinks [44]. The terms "China" and "classification" experienced a surge in prominence during the 2021 – 2022 period, indicative of the concurrent progression of China-specific studies and methodological diversification [45]. Furthermore, the presence of "dissolved organic matter (DOM)" and "heavy metals" had increased significantly since 2021, suggesting a heightened focus on the dynamics of DOC and the interaction between metal-organic and carbonate components within estuarine-coastal systems [46]. The terms "mangroves" and "coastal wetlands" had also gained prominence, reflecting sustained interest in their carbon sequestration capacity, adaptation thresholds, and restoration potential [25]. The blue carbon agenda experienced a notable acceleration following the formalization of the "blue carbon" concept in 2009. The 2015 Paris Agreement, which established the NDC framework, coincided with a series of extreme climate events around 2020 and significant advancements in remote sensing and AI technologies. These factors collectively catalyzed a transition "from mechanism identification to large-scale accounting and governance tools". The significance of coastal wetlands and mangroves in terms of carbon sequestration and adaptation functions had led to an increased focus on policy measures [25]. Meanwhile, the proliferation of macroalgae was indicative of the research community's reevaluation of "underestimated kelp forest carbon sinks" and the demand for enhanced accounting methodologies [44]. The prevalence of "China" and "classification" signified the augmentation of pathways integrating large-scale observation, intelligent classification, and contextualized accounting [45]. The emergence of the emerging hotspots "DOM" and "heavy metals" signified a paradigm shift within the academic community, where there was an increasing integration of carbon cycling, water quality, and pollutant coupling into a unified analytical framework. This approach not only addressed the complex pressures faced by coastal ecosystems but also provided more ecologically comprehensive evidence for blue carbon accounting and management [46]. In essence, the keyword map was expanding from the core triangle of "carbon sink – organic matter – carbon dioxide" toward "multi-ecosystem - multi-stressor - multi-technology pathways". This phenomenon elucidated the recent high research intensity and suggested that future assessments and policy design should prioritize methodological standardization and cross-regional comparability.

Future research outlook in blue carbon

In the future, research on blue carbon must evolve from a "single carbon stock characterization" approach toward a comprehensive paradigm that integrates "multi-dimensional value — multi-scale processes — multi-tool synergy". With respect to the evaluation dimensions, it is imperative to integrate carbon sink functions and ecosystem services such as biodiversity, water purification, disaster mitigation into a unified framework, which will reveal the coupling relationships among different ecological elements and their synergies and trade-offs under climate stress and will provide comparable and actionable value evidence for policy and project decision-making. In methodological approaches, high-resolution remote sensing, long-term *in situ* observations, and machine learning/causal inference models should be integrated to conduct continuous monitoring and forecasting of blue carbon ecosystem structure – function - flux continuums. It is imperative to identify critical thresholds and intervention windows to enhance the accuracy of scenario projections and risk warnings. Under the adaptation - governance path, research on the mechanism chain at the intersection of extreme events and slow-onset warming should be strengthened to formulate nature-based recovery and adaptation strategies that may include the restoration of mangrove, seagrass meadow, and salt marsh ecosystems. Additionally, the implementation of long-term tracking evaluations is necessary to assess the effectiveness of these strategies and to identify spillover effects. At the technology and industry level, the exploration of biotechnologies such as genetics and breeding is necessary to enhance carbon sequestration efficiency in key blue carbon habitats. It is imperative to standardize accounting methods and uncertainty characterization. Additionally, it is essential to align Monitoring – Reporting - Verification (MRV) systems with carbon market mechanisms, which will result in the synergizing of policy tools and market incentives. In the domain of governance and equity, the enhancement of multilateral cooperation and data openness is important. The development of transferable implementation guidelines and financing solutions tailored to diverse ecological zones and varying governance capacities is essential. These guidelines must ensure a genuine balance between research and practice, incorporating scientific rigor, scalability, and accessibility for developing countries.

Conclusions

This research reviewed the literature on blue carbon sinks in Web of Science database from 1974 to 2023 by combining 'bibliometrix' bibliometric tool and Python language. The results found that literature mainly formed three clusters including ocean, blue carbon, and dynamic clusters. Among them, the ocean cluster focused on the carbon storage mechanism of marine ecosystems, the impacts of climate change, the interaction between marine organisms and atmospheric carbon dioxide such as calcification processes and biogeochemical feedback and emphasized the contribution of marine ecosystems to the global carbon cycle. The blue carbon cluster focused on the carbon sink function of coastal ecosystems such as mangrove forests and their mitigation of climate change in addition to the ecological services such as biodiversity conservation and coastline protection, which were of indispensable value. The dynamic cluster focused on the dynamic changes of the global carbon cycle and the impacts of climate and human activities on it. In addition to clarifying the three clustering themes, this study also found that China and the United States had both competition and cooperation in the field of blue carbon sinks with cutting-edge research focusing on the application of new materials and methods. As a result, it is expected that future research hotspots in blue carbon sinks will focus on technological innovation, policy optimization, and socio-economic impact assessment. The study suggested that policies for the utilization and protection of blue carbon sinks should be formulated at the national level, research investment in related fields should be increased, climate cooperation under the multilateral framework should be strengthened, and special attention should be paid to climate change adaptation and response in developing countries, so as to promote the effective implementation of global carbon emission reduction and climate change response strategies and lay a solid foundation for achieving global sustainable development goals.

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