Linking Inland Waters and Mangrove Carbon: A Bibliometric Analysis of Global Research Trends (2000–2024)

Veince Benjamin Silahooy [1,4], *Tri* Retnaningsih Soeprobowati [1,2*], *Mussadun* [1,3], *Sri* Puryono [1]

[1] Doctor of Environmental Science Program, School of Postgraduate, Diponegoro University, Semarang, Indonesia
[2] Department of Biology, Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia
[3] Department of Urban and Regional Planning, Faculty of Engineering, Diponegoro University, Indonesia
[4] Biology Study Program, Faculty of Science and Technology, Pattimura University, Ambon, Indonesia

Abstract. This study provides a comprehensive bibliometric analysis of global research on the linkage between inland waters and mangrove carbon, aiming to identify conceptual bridges within the emerging blue carbon continuum. Using data from Scopus and visualized through VOSviewer, co-occurrence and co-authorship network analyses revealed four major thematic clusters—mangrove–sediment processes, land use–soil carbon, global carbon sequestration, and ecosystem services—along with one bridging cluster connecting rivers, wetlands, estuaries, and organic carbon. These results highlight the ecological and scientific continuum from terrestrial to coastal systems, emphasizing the underexplored role of estuaries and deltas as transitional carbon sinks. Collaboration mapping shows that research remains concentrated in developed countries, while tropical regions, particularly Southeast Asia, are emerging as new research hubs. The study identifies major knowledge gaps, including the limited integration of carbon fluxes across ecosystems, insufficient modeling and remote-sensing synthesis, and weak socio-economic linkage in policy frameworks. Overall, this research contributes to advancing an integrative understanding of inland–coastal carbon dynamics, offering both a scientific foundation and a methodological roadmap for ecosystem-based climate mitigation aligned with the SDGs and national climate commitments.

1 Introduction

Climate change represents the most significant environmental challenge of the 21st century, primarily driven by the increasing concentration of greenhouse gases (GHGs) in the atmosphere. In mitigation efforts, natural ecosystems play a vital role as carbon sinks. While terrestrial forests have traditionally received the greatest attention, growing recognition is now being given to aquatic ecosystems for their contribution to the global carbon cycle.

*Corresponding email: trsoeprobowati@live.undip.ac.id

In this context, blue carbon ecosystems—such as mangroves, seagrass meadows, and salt marshes— are acknowledged as critical reservoirs of carbon that help maintain global climate balance [1].

Inland waters—including rivers, lakes, reservoirs, and freshwater wetlands—serve not only as conduits for water transport but also as significant components of the carbon cycle. These ecosystems transport both organic and inorganic carbon from terrestrial areas toward coastal and marine zones. Beyond their role as pathways for carbon transfer, inland waters also act as sites of carbon storage through sedimentation, as well as sources of greenhouse gas emissions resulting from decomposition processes [2]. This dual function positions inland waters as crucial hotspots in the global carbon budget.

Mangroves are widely recognized as one of the most efficient coastal ecosystems for carbon storage. More than half of their carbon reserves are stored within anaerobic sediments capable of retaining carbon over extremely long timescales. However, this storage capacity does not operate in isolation—it is strongly influenced by hydrological conditions. Nutrient supply, sediment input, and the quality of freshwater inflows from terrestrial and inland sources directly affect the productivity and carbon accumulation within mangrove ecosystems.

The linkage between inland waters and mangrove carbon is particularly evident in transitional zones such as deltas, estuaries, and tidal wetlands [3]. Freshwater flows carrying sediments and nutrients play a vital role in accelerating sediment accretion processes, which are essential for the persistence of mangroves amid rising sea levels [4]. Moreover, the quality of riverine inputs influences carbon decomposition dynamics, either enhancing or diminishing mangroves' carbon storage capacity. Thus, this interconnection represents a key mechanism for understanding carbon cycling across ecosystems [4-5].

Although both systems play crucial roles in the global carbon cycle, studies on inland waters and mangrove carbon have largely been conducted in isolation. Research on inland waters has predominantly focused on carbon transport and greenhouse gas emissions, while mangrove studies have emphasized carbon storage capacity and coastal ecosystem functions. Only a few studies have attempted to integrate these domains, leaving the hydrological and ecological linkages between them poorly mapped and understood.

In a context where existing literature remains fragmented, a bibliometric approach offers a comprehensive means of exploring the relationship between inland waters and mangrove carbon. This method allows for tracing global publication trends, identifying key authors, journals, and contributing countries, and mapping major research themes and keywords. Consequently, bibliometric analysis not only provides an overview of research evolution but also reveals knowledge gaps that can inform future scientific inquiries.

This bibliometric study holds broad significance—both scientifically and practically. From a scientific standpoint, it contributes by systematically mapping recent interconnections between inland waters and mangrove carbon. From a policy perspective, the findings support climate mitigation strategies through the conservation of interconnected aquatic ecosystems, aligning with the commitments of the Nationally Determined Contributions (NDCs) and Sustainable Development Goals (SDGs) 13, 14, and 15. Practically, the study advocates for integrated management approaches that account for the ecological connectivity between freshwater and coastal ecosystems.

Based on the above rationale, this study aims to fill the existing gap by exploring recent scientific developments and collaboration patterns linking inland waters and mangrove carbon within the context of blue carbon research. Specifically, it examines global publication dynamics over the last four years, identifies the most influential contributors—authors, journals, and countries—and maps the thematic structure that connects studies across freshwater and coastal ecosystems. Furthermore, this research seeks to highlight the underlying conceptual bridges and to reveal where knowledge gaps remain, providing a

foundation for future investigations on cross-ecosystem carbon cycling and its implications for integrated blue carbon management.

2 Method

This study employs the Scopus database as the primary data source, given its extensive coverage, high indexing quality, and consistency in providing the metadata required for bibliometric analysis.

The search process was conducted using a Boolean string that combined two main groups of keywords—inland waters and mangrove carbon. The search query employed was as follows:: (TITLE-ABS-KEY (inland water* OR river* OR lake* OR reservoir* OR freshwater wetland* OR pond*) AND (mangrove* OR blue carbon OR carbon stock OR carbon sequestration)). The search results were exported in comma-separated values (CSV) format to facilitate further data processing. Document extraction was performed on August 1, 2025, at 23:17 GMT+07.

For data analysis, VOSviewer was utilized as the primary tool to perform bibliometric network mapping, including keyword co-occurrence, co-authorship, bibliographic coupling, and citation analysis, providing a comprehensive visualization of thematic and collaborative structures within the dataset.

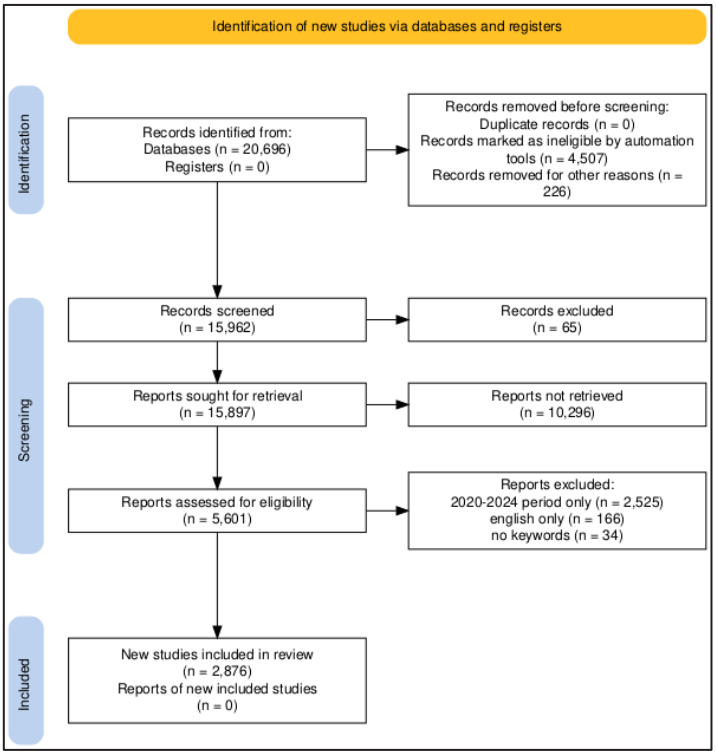

Fig. 1 Data collection stages

The literature selection process adhered to a modified PRISMA framework [7] adapted to the specific needs of this study (Fig 1). In the identification phase, an initial screening restricted the dataset to documents categorized as journal articles, resulting in 4,507 records.

Subsequent filtering ensured that only articles published in peer-reviewed scientific journals were retained, leading to the removal of 226 records.

During the screening stage, three sequential steps were undertaken. First, 65 documents that were not yet in their final publication status were excluded. Second, 10,296 non–open-access articles were removed from the dataset. The selection of Open Access (OA) publications in this study was guided by principles of scientific transparency and analytical reproducibility. OA articles allow other researchers to freely access, verify, and replicate the findings without publisher-imposed restrictions. Moreover, using OA materials ensures the availability of full-text content necessary for thematic validation and advanced text analysis, while maintaining compliance with ethical standards and publication copyright regulations. Thus, filtering based on OA status was not intended to limit the study's scope, but rather to uphold the integrity, accessibility, and sustainability of the data used in this bibliometric analysis. Third, an additional screening was conducted using specific criteria, including the publication period (2020–2024)—which excluded 2,525 documents—non-English language publications (166 documents), and records lacking keyword metadata (34 documents). Focusing on publications from 2020–2024 allows the dataset to represent the latest scientific insights, technological progress, and policy-oriented studies.

After completing all stages of the selection process, a total of 2,876 articles met the inclusion criteria and were analyzed in this study. These articles served as the foundation for bibliometric mapping, thematic analysis, and the identification of research gaps within the field of inland waters and mangrove carbon.

3 Result

3.1 Publication Trends

An analysis of publication trends during the 2020–2024 period reveals a substantial and steadily increasing number of articles related to inland waters and mangrove carbon (Fig 2). This upward trajectory reflects the growing global attention toward the roles of inland and coastal aquatic ecosystems in the carbon cycle and in climate change mitigation. The surge in publication volume is also influenced by stronger international policy frameworks—such as the implementation of the Paris Agreement and the pursuit of Sustainable Development Goals (SDGs)—which have spurred research on ecosystem-based mitigation strategies.

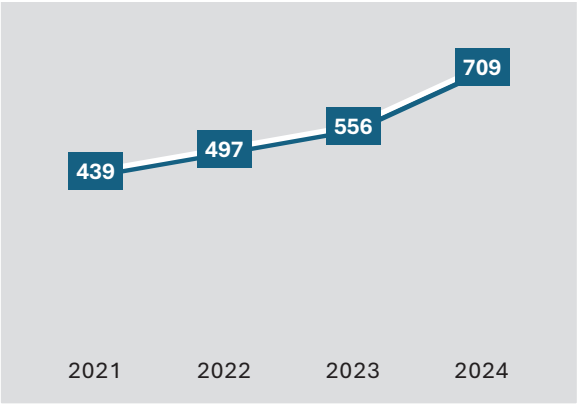

Fig. 2 Trend in the Number of Publications Over Time

Although the literature in both domains has expanded rapidly, bibliometric mapping indicates that studies on inland waters and mangrove carbon have largely evolved independently. This pattern highlights a critical need for integrative research that emphasizes the ecological and biogeochemical linkages between freshwater systems and mangrove carbon storage capacity.

3.2 Journal and Author Distribution

Bibliometric analysis identified the ten leading journals that dominated publications in the field of inland waters and mangrove carbon during the 2020–2024 period. Sustainability (Switzerland) ranked first with 79 articles, followed by Ecological Indicators with 72 articles, and Science of the Total Environment with 67 articles. In addition, Forests and the International Journal of Greenhouse Gas Control contributed 65 and 64 articles, respectively, reflecting a strong research emphasis on ecosystem conservation and climate change mitigation (Fig 3).

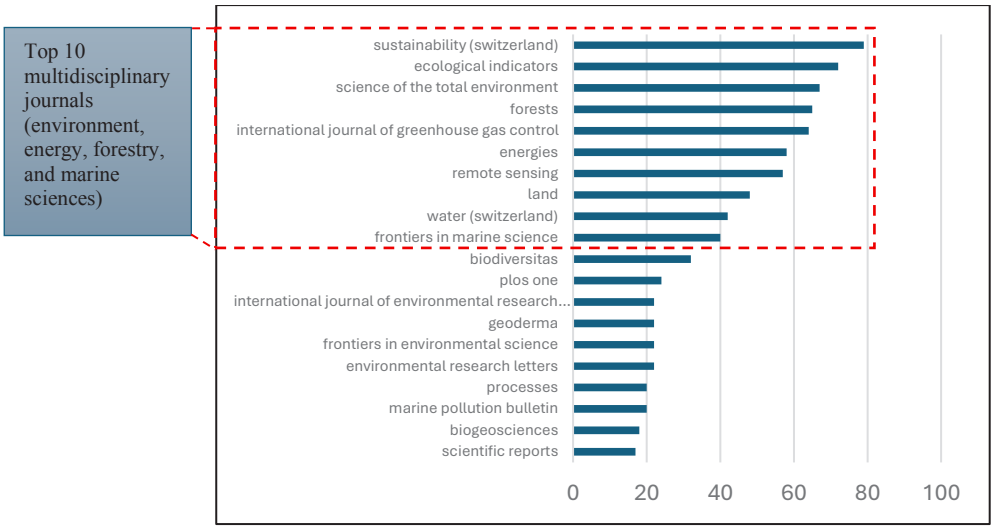

Fig. 3 Top 10 multidisciplinary on inland waters and mangrove carbon.

Other journals that also played a significant role include Energies (58 articles) and Remote Sensing (57 articles), reflecting the growing integration of technological approaches in ecosystem carbon research. Meanwhile, Land (48 articles), Water (Switzerland) (42 articles), and Frontiers in Marine Science (40 articles) complete the list of the top ten journals, reinforcing the notion that this research topic is highly multidisciplinary, spanning the fields of environmental science, energy, forestry, and marine studies. The prominence of these journals indicates that the interconnectedness between inland waters and mangrove carbon has garnered wide attention—not only within ecological research but also in the broader contexts of applied science and sustainability policy (Fig 4).

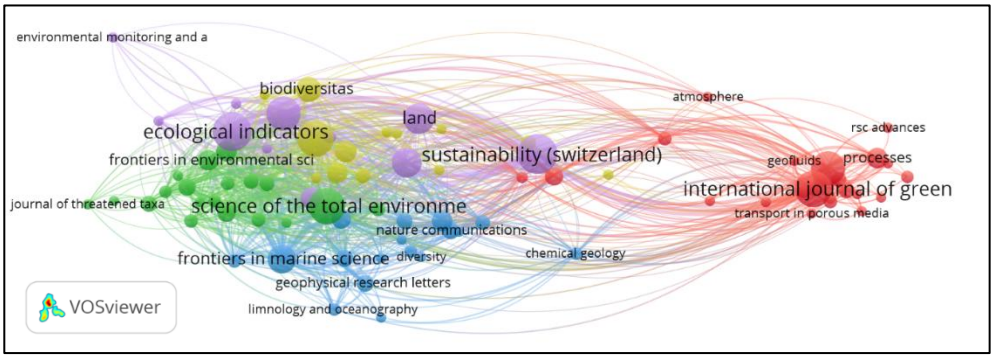

Fig. 4 Journal co-citation network showing linkages among major publication outlets in inland water and mangrove carbon research.

The analysis of author productivity and influence (Fig 5) reveals an interesting dynamic within the research landscape addressing the interlinkages between inland waters and mangrove carbon. Several authors, such as Mohammad Basyuni and Qiang Yu (purple cluster), stand out for successfully combining high productivity with substantial academic impact. Basyuni, with nine publications and 148 citations, and Yu, with seven publications and 176 citations, occupy strategic positions as consistent contributors whose work is frequently referenced in the field. Conversely, although William Ampomah (red cluster) ranks among the most prolific authors, his relatively lower citation count suggests that publication quantity does not necessarily equate to scientific influence.

On the other hand, some authors with fewer publications have demonstrated remarkably high impact (green cluster), such as Zhenghua Rui (292 citations from 5 publications) and Philippe Ciais (262 citations from 6 publications). This finding underscores that research quality, thematic relevance, and methodological innovation are key factors driving academic visibility. Overall, this pattern indicates that studies on the interconnections between inland waters and mangrove carbon are shaped both by sustained productivity and by innovative contributions that resonate strongly within the global scientific community—together forming a core group of authors who steer the intellectual development of this emerging field.

3.3 Contributions by country/region

The analysis of international scientific collaboration networks reveals that research on inland waters, mangrove carbon, and broader blue carbon dynamics exhibits a wide but uneven global distribution (Fig 6). Based on bibliometric visualization and dataset metrics, China and the United States emerge as the two most productive and collaborative countries, representing the primary research hubs in Asia and North America, respectively. These are followed by Australia, the United Kingdom, India, and the Netherlands, together forming the core axis of the global blue carbon research network.

Western Europe—particularly the Netherlands, Germany, the United Kingdom, and France—shows strong inter-country linkages, indicating that cross-institutional integration within this region is well established and primarily oriented toward carbon modeling and climate policy development. Meanwhile, Southeast Asia and the South Pacific—notably Indonesia, Malaysia, the Philippines, and Australia—have demonstrated a significant increase in publication output over the past three years, with research focusing more on carbon dynamics in tropical ecosystems such as mangroves, wetlands, and deltas.

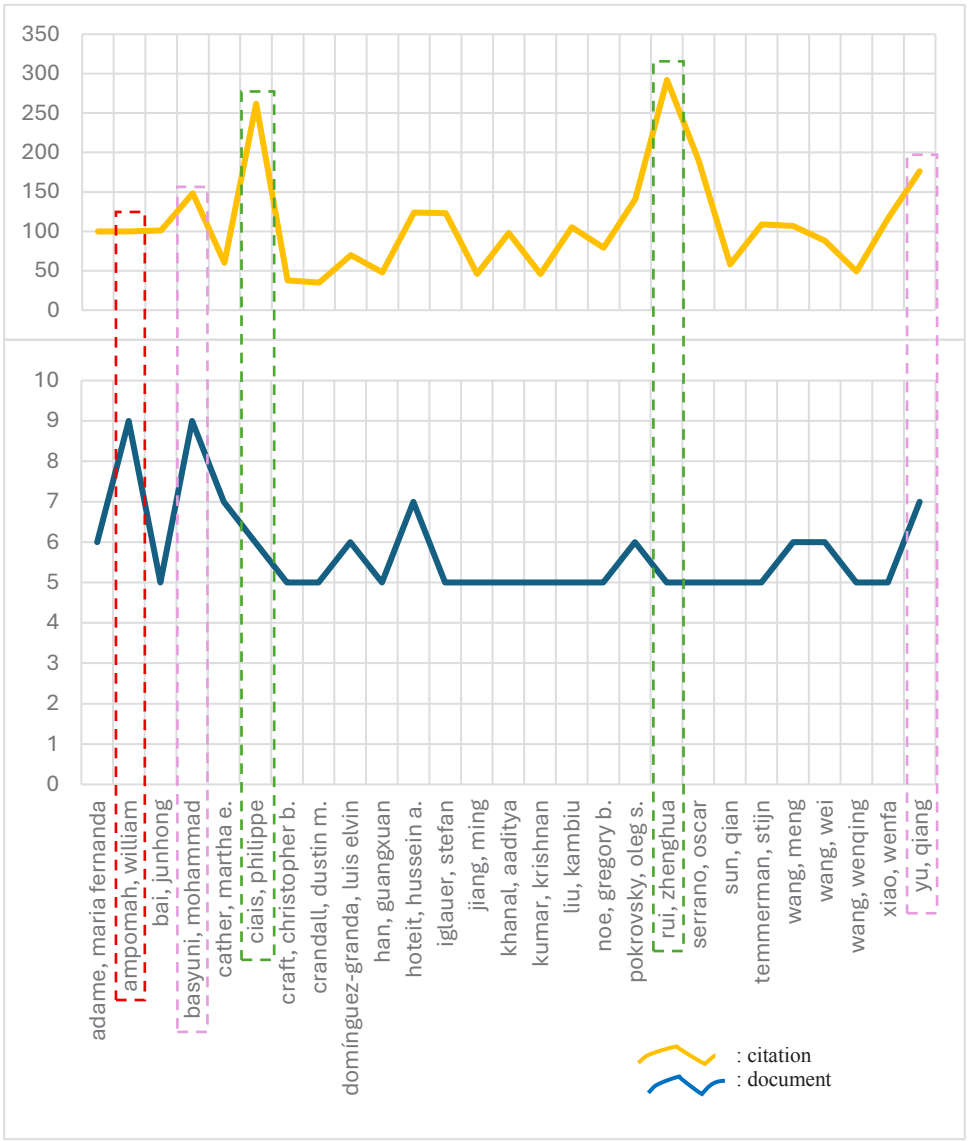

Fig. 5 Top authors ranked by number of publications and citations in inland water and mangrove carbon research, illustrating the leading contributors and their influence within the field.

In terms of total link strength, China, the United States, and Australia occupy the top positions as countries with the strongest collaboration networks, followed by several Western European nations that, while moderately productive, maintain broad international partnerships. This pattern also highlights a North–South collaboration dynamic, where developed countries primarily contribute expertise in technology, modeling, and data synthesis, while tropical nations provide field data and rich natural ecosystem contexts.

Furthermore, the average publication year analysis reveals an emerging wave of research contributions from developing countries such as Bangladesh, Indonesia, Malaysia, and

Vietnam, with most of their publications appearing between 2022 and 2024. This trend indicates the rise of new research hubs in the tropical regions of Asia. The global map illustrates that, although the highest collaboration intensity remains concentrated in the Northern Hemisphere, there is a clear expansion toward tropical and subtropical regions, signifying a gradual shift in research focus toward coastal systems and blue carbon ecosystems in these areas.

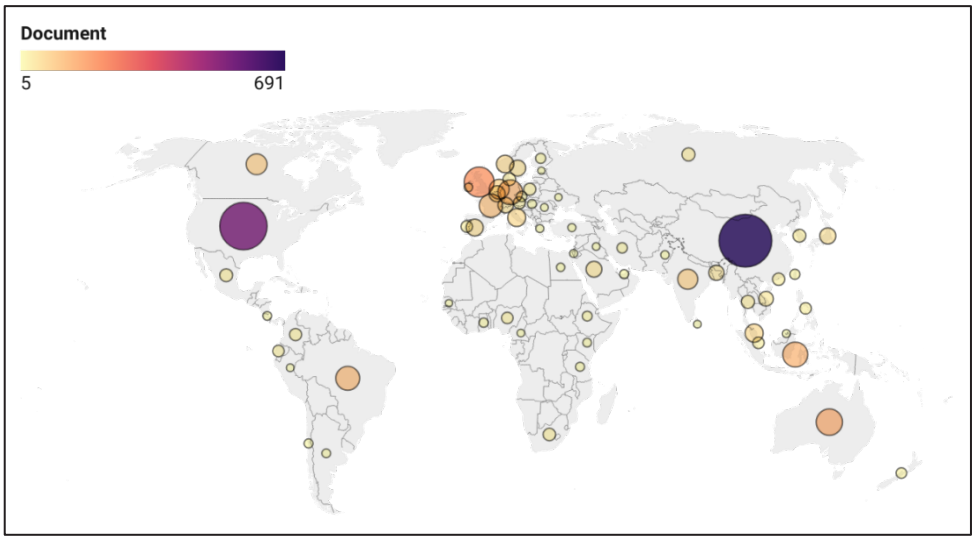

Fig. 6 Map of International Scientific Collaboration (Co-authorship by Country) on publications related to inland waters–mangrove carbon during the period 2000–2024.

3.4 Co-Occurrence Analysis of Keywords

The co-occurrence keyword analysis revealed four main clusters, each representing the thematic structure of global research related to the interconnections among inland waters, mangrove ecosystems, and carbon dynamics. These clusters capture distinct yet interrelated research focuses that collectively explain the processes, functions, and governance of carbon across interconnected ecosystems (Fig 7).

The first cluster (red) reveals strong associations among the keywords mangrove, wetlands, sediment, estuary, organic matter, and water quality. This cluster reflects research focusing on the ecological functions of mangroves in carbon storage and accumulation, water quality regulation, and their role as natural traps for sediments and pollutants in coastal regions. The density map shows high concentrations around terms related to sediments and organic matter, indicating that this topic serves as a central focus within coastal ecology research in the context of carbon storage.

The second cluster (green) includes keywords such as ecosystems, land use, soil carbon, biodiversity, reforestation, and rivers. This cluster represents studies exploring the effects of land-use and vegetation change on soil carbon stocks and carbon fluxes across inland water systems. The presence of terms like wetlands and rivers within this cluster indicates that many studies have examined the spatial connectivity between terrestrial landscapes and river systems, which function as the main pathways for carbon transport toward coastal zones [8].

The third cluster (blue) comprises keywords such as carbon sequestration, carbon dioxide, organic carbon, carbon emission, methane, and aquifers. Its main focus lies on long-term carbon storage mechanisms and carbon emission mitigation, encompassing both natural

processes (e.g., sedimentation and biomass accumulation) and engineering approaches (e.g., carbon capture and storage). Visualization results reveal a strong linkage between carbon dioxide and sequestration, emphasizing the global research focus on carbon uptake strategies as a key component of climate change mitigation.

The fourth cluster (yellow) contains keywords such as ecosystem service, decision making, habitat quality, soil conservation, and optimization. This cluster highlights the policy, governance, and environmental planning dimensions that underpin ecosystem-based carbon management. The inclusion of geographical terms such as China and Yangtze River suggests that significant research contributions originate from East Asia, particularly in the context of policy implementation and land-use optimization to support carbon balance and ecosystem sustainability.

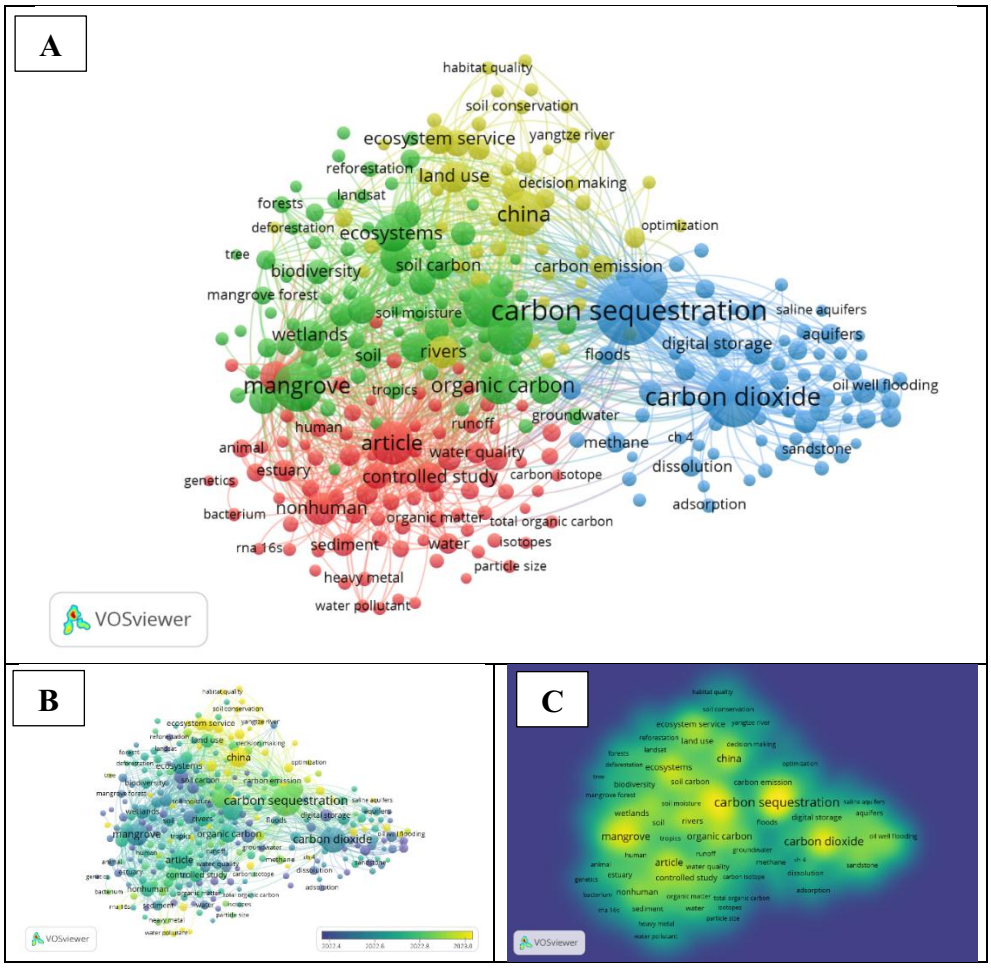

Fig. 7 Keyword Distribution Map: A) Four major clusters; B) Temporal evolution of research themes; C) Keyword density visualization.

The co-occurrence keyword analysis not only identified four primary thematic clusters but also revealed the presence of a bridging cluster that connects research themes between inland water systems and mangrove ecosystems. This cluster is composed of key nodes such as rivers, wetlands, organic carbon, sediment, and estuaries, all of which exhibit high total

link strength and function as pivotal connectors between two major domains—the terrestrial–soil ecosystem cluster (land use–soil carbon) and the coastal ecosystem cluster (mangrove–sediment).

The network visualization shows that these nodes occupy transitional positions between the green and red regions, signifying their role as ecological mediators linking upstream and downstream systems. Meanwhile, the overlay visualization reveals that nodes such as rivers, organic carbon, and sediment appear in green–yellow hues, representing more recent publication periods (2022–2024). This pattern indicates that research on cross-ecosystem carbon connectivity is an emerging global theme, reflecting a growing scientific focus on the integration of inland and coastal carbon dynamics.

4 Discussion

4.1 Patterns of Scientific Leadership and Global Collaboration

The findings reveal a hierarchical structure of global scientific leadership within blue carbon research. The dominance of China and the United States reflects not only their strong research capacity but also a geographical shift in the environmental science epicenter—from Europe toward Asia. In particular, China has made substantial investments in cross-ecosystem research, exemplified by initiatives such as the Yangtze River Basin studies and the South China Sea Blue Carbon Program, which expand understanding of the carbon linkages between inland and coastal systems. Nevertheless, bibliometric analysis also indicates that China's average citation rate remains lower than that of several European countries, suggesting that publication quantity does not always correlate with scientific impact.

Emerging patterns of international collaboration highlight a significant South–North partnership trend. Tropical countries such as Indonesia, Malaysia, India, and Brazil are increasingly becoming key collaborators with Australia, the United Kingdom, and the United States in blue carbon research. Such collaborations not only enhance research capacity in developing nations but also enrich the global empirical database by combining field observations from tropical ecosystems with modeling and analytical expertise from developed countries. In this context, intercontinental collaboration serves as a cornerstone for advancing the understanding of the blue carbon continuum, which connects carbon flows across rivers, wetlands, estuaries, and mangroves.

Several intriguing anomalies also emerge from the analysis. Japan, for instance, occupies a moderate position in terms of productivity but demonstrates a high average citation rate, indicating high-quality research output despite a relatively small publication volume. In contrast, India shows high productivity yet a low normalized citation impact, suggesting that much of its research remains fragmented and weakly connected within the global scientific network. Indonesia stands out as a developing country with substantial potential, characterized by the most recent average publication year (post-2023) and an increasing total link strength, signaling its growing role as an emerging research hub for blue carbon studies in Southeast Asia.

The scientific implications of these patterns are highly significant. The emergence of new collaboration centers in tropical Asia reflects a democratization of scientific knowledge in the field of blue carbon, which was previously dominated by Europe and North America. These results reinforce the urgency of establishing cross-tropical collaborative platforms to accelerate innovation in cross-ecosystem carbon research and management. By expanding collaboration networks and sharing analytical capacities, tropical nations such as Indonesia, Malaysia, the Philippines, and Brazil can serve not only as data providers but also as co-leaders in shaping the global research and policy agenda on carbon governance [9].

Overall, this pattern of scientific collaboration demonstrates that the understanding of the blue carbon continuum is inherently global and transcontinental, relying on the synergy between tropical regions (natural carbon providers) and temperate regions (model and policy developers). This dynamic signifies a new trajectory in blue carbon research—shifting from isolated local studies toward a globally collaborative research network that integrates data, technology, and policy as key pillars for sustaining cross-ecosystem carbon systems [9].

4.2 Thematic Clusters

The thematic mapping results indicate that the four clusters collectively explain the ecological and scientific continuum of carbon from terrestrial to coastal systems. Rather than existing in isolation, each cluster forms part of an integrated framework that defines the blue carbon continuum, emphasizing the interconnectivity among habitats across ecosystems.

Cluster 1 strengthens the understanding that mangroves function as terminal carbon sinks within the cross-ecosystem carbon cycle. Processes of sedimentation and organic matter accumulation in mangrove soils not only stabilize coastlines but also serve as crucial mechanisms for long-term carbon burial. Research within this cluster highlights biotic–abiotic interactions, particularly the relationships among biodiversity, sediment microorganisms, and carbon storage capacity [10]. Thus, mangroves play a dual role—as both carbon reservoirs and natural buffers protecting coastal environments from degradation and pollution.

Cluster 2 reveals that land-use changes in upstream regions directly influence carbon balance in inland and coastal systems. Activities such as deforestation, urbanization, and agricultural intensification accelerate soil carbon loss and increase the nutrient and sediment loads transported downstream [11]. Conversely, reforestation and land conservation practices strengthen the function of watersheds as sources of stable carbon that sustain coastal carbon stocks. Consequently, carbon management must be viewed as a land–sea linked system, rather than as separate terrestrial and marine entities.

Cluster 3 represents a broader dimension of carbon dynamics, where natural biogeochemical processes intersect with technological innovations for climate mitigation. Studies on carbon sequestration and storage [1] suggest a global shift toward integrating ecosystem-based approaches (e.g., mangroves and wetlands) with engineered subsurface carbon storage technologies. This reflects a transition from purely ecological studies toward integrated carbon management, encompassing scientific, technical, and policy dimensions. Within this framework, blue carbon becomes a critical component of global mitigation strategies that merge nature-based and technological solutions.

Cluster 4 marks a paradigm shift in carbon research—from quantifying carbon stocks to integrating social, economic, and policy dimensions into carbon management. Research in this cluster demonstrates that the success of emission reduction and carbon enhancement efforts depends heavily on evidence-based governance and decision-making [12]. The concepts of ecosystem services and nature-based solutions serve as key frameworks supporting conservation policy and land-use planning. Accordingly, this cluster expands the scientific focus from biophysical processes to the implementation of equitable and sustainable carbon policies, particularly in coastal zones that serve as vital buffers against climate change.

4.3 Bridging Cluster and Conceptual Integration

Conceptually, the existence of the bridging cluster indicates that research on coastal carbon dynamics cannot be separated from the carbon processes occurring within inland water systems. Rivers and wetlands act as biophysical conduits, transporting both dissolved and

particulate organic carbon toward estuarine and mangrove zones, where long-term carbon burial takes place [3, 8]. This connectivity underscores the cross-ecosystem nature of the carbon cycle, suggesting that the understanding of blue carbon should expand into a broader "blue carbon continuum" framework encompassing upstream carbon sources, transformational processes in estuaries, and final storage in mangrove sediments.

This finding forms the basis of the study's core novelty—an effort to formalize the functional relationship between inland water carbon and mangrove carbon within a single, interconnected ecological and biogeochemical system. This approach not only provides a theoretical contribution to understanding cross-ecosystem carbon cycling but also offers practical implications for spatially integrated carbon management from upstream to coastal regions within the framework of climate change mitigation.

The integration of all four thematic clusters demonstrates that global carbon dynamics operate not within isolated ecosystem boundaries but as an ecological continuum linking inland waters, estuaries, and coastal mangrove ecosystems. The land use–soil carbon cluster (Cluster 2) represents upstream carbon sources, driven by organic weathering, surface runoff, and riverine transport of dissolved and particulate organic matter [13]. These processes transition into estuarine and deltaic zones, reflected in the mangrove–sediment cluster (Cluster 1), where nutrients and sediments from upstream are trapped and deposited, forming the foundation for long-term carbon burial [14]. Meanwhile, the carbon sequestration–storage cluster (Cluster 3) highlights the global climate significance of these mechanisms, emphasizing both biomass and sedimentary carbon storage. Finally, the ecosystem service–policy cluster (Cluster 4) introduces a social–ecological dimension, underscoring the need for science-based, cross-regional governance to maintain the continuity of the carbon cycle from headwaters to coasts.

Collectively, these clusters conceptualize a model of cross-ecosystem carbon connectivity, illustrating the flow, transformation, and storage of carbon from terrestrial to coastal environments [15]. This conceptualization reinforces the "blue carbon continuum" paradigm, wherein rivers, wetlands, and estuaries serve as biogeochemical bridges transferring carbon from land-based ecosystems to mangrove carbon burial zones. Understanding this continuum is essential for developing integrated carbon management approaches that move beyond ecosystem-specific strategies to encompass ecological, hydrological, and policy linkages across landscapes. Overall, this synthesis affirms that the sustainability of blue carbon stocks can only be achieved through systemic management that integrates ecological processes, technological innovation, and governance frameworks—establishing this study as a significant conceptual contribution to the global discourse on carbon connectivity from upstream to coastal ecosystems.

4.4 Research Gaps and Recommendations

Overall, the analysis indicates that blue carbon research remains fragmented and insufficiently integrated across ecosystems. Most studies on inland waters continue to focus on internal processes within rivers, wetlands, or reservoirs—such as organic carbon dissolution and greenhouse gas emissions—without examining their linkages to carbon storage in coastal zones. Conversely, mangrove research has largely concentrated on carbon stocks and sediment burial, often overlooking the carbon inputs originating from upstream catchment areas. As a result, the connections between carbon transport in inland waters and carbon burial in mangroves are still rarely explored comprehensively, and there is limited application of isotopic tracers or organic biomarkers to trace carbon transfer across ecosystems.

In addition, the roles of estuaries and deltas as ecotones or transitional zones—which function as critical sediment and carbon deposition areas—remain understudied. Many

investigations treat estuaries merely as mixing zones between freshwater and seawater rather than as active carbon sinks supporting the stability of mangrove carbon stocks. In tropical regions such as Southeast Asia, however, estuaries and deltas are essential in channeling organic matter and sediments that form the foundation of coastal carbon layers. On the methodological side, cross-ecosystem modeling and remote-sensing applications are also still limited. Current carbon models are typically developed separately for terrestrial, freshwater, and coastal systems, preventing a holistic understanding of carbon transport and storage processes from upstream to downstream. Integrating remote sensing and spatial modeling across ecosystems could provide a powerful approach to better represent carbon connectivity.

Furthermore, the socioeconomic and policy dimensions of blue carbon research remain relatively underexplored. Most studies have prioritized biophysical and technical aspects, such as carbon stock measurements and ecosystem mapping, while economic valuation, community livelihoods, and incentive mechanisms—including carbon credits and payments for ecosystem services—are seldom addressed. This gap often results in scientific findings that are disconnected from policy needs and local sustainable development priorities.

Based on these findings, future research should adopt a more integrated, cross-ecosystem approach. Key recommended directions include:

1. Tracing carbon pathways from rivers to mangroves using natural isotopic or molecular markers to determine source-to-sink linkages.
2. Examining the role of estuaries and deltas more deeply as active carbon storage zones within tropical coastal systems.
3. Developing integrated carbon models that combine terrestrial-to-coastal remote-sensing data for spatially continuous carbon flow representation.
4. Incorporating socioeconomic and policy dimensions into blue carbon research to enhance its applicability for communities and decision-makers.

By addressing these research gaps, blue carbon studies can evolve into a comprehensive, applicable, and policy-relevant discipline, supporting climate change mitigation efforts and promoting equitable and sustainable coastal management.

4.5 Research Contributions

This study provides significant contributions across three key dimensions—scientific, methodological, and policy—which collectively strengthen the understanding of cross-ecosystem carbon linkages from terrestrial to coastal systems.

Scientifically, this research identifies and formalizes the conceptual intersection between two previously parallel fields: studies on inland water carbon fluxes and mangrove carbon burial. Over the past two decades, these domains have evolved within separate disciplines—limnology and coastal ecology—each employing distinct approaches, parameters, and observational scales. Through bibliometric analysis, thematic mapping, and network visualization, this study uncovers a bridging cluster that conceptually and empirically connects the two research areas, particularly through the theme rivers–wetlands–estuaries–organic carbon. In doing so, it broadens the scientific understanding of the carbon continuum and emphasizes the importance of viewing land–water–coastal systems as an integrated ecological unit within the global carbon cycle.

Methodologically, the study provides a roadmap for future blue carbon research by promoting a transition from isolated, ecosystem-specific investigations toward an integrated cross-ecosystem approach. By employing co-occurrence keyword analysis, co-authorship networks, and overlay visualizations, the study demonstrates how global research is gradually shifting from localized foci to systemic interconnections among terrestrial, freshwater, and coastal systems. This insight lays the foundation for developing new methodological frameworks that combine biogeochemical measurements, spatial modeling, and multispectral

remote sensing to trace carbon flows from upstream sources to downstream sinks. Consequently, this study contributes not only by mapping the current scientific landscape but also by offering a conceptual and technical framework for future interdisciplinary and cross-ecosystem research.

From a policy perspective, this research underscores the importance of adopting a freshwater–coastal continuum framework as the scientific basis for ecosystem-based climate mitigation. The findings demonstrate that maintaining a continuous carbon cycle from headwaters to coasts plays a strategic role in emission reduction, long-term carbon storage, and enhancing coastal ecosystem resilience to climate change. These insights provide direct inputs for national and regional policy development, particularly in advancing commitments to the Nationally Determined Contributions (NDCs) and the Sustainable Development Goals (SDGs)—notably SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). By emphasizing the integration of upstream–downstream systems in blue carbon management, this study supports a paradigm shift from sectoral conservation to integrated carbon governance across ecosystems, offering valuable implications for spatial planning, coastal rehabilitation, and the development of carbon-based economies in Indonesia and other tropical regions.

5 Conclusion

The findings of this study confirm that research on blue carbon, particularly the interlinkages between inland waters and mangrove carbon, remains largely sectoral and has yet to achieve full cross-ecosystem integration. Through bibliometric analysis and network visualization, this study identified four major clusters and one bridging cluster that together illustrate the carbon continuum extending from terrestrial to coastal ecosystems. Patterns of international collaboration reveal that global research hubs remain concentrated in developed countries; however, a new trend has emerged with increasing contributions from tropical regions, including Southeast Asia. These results underscore the urgent need to develop integrative scientific and policy approaches that combine biophysical, spatial, and socioeconomic dimensions in understanding the carbon cycle across ecosystems. In doing so, this study not only broadens the scientific frontier of global blue carbon systems but also provides a conceptual foundation for the formulation of climate mitigation policies and sustainable coastal management strategies.

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Author contributions

The study design was conducted by VBS, TRS, M. Material preparation and data collection were conducted by VBS and SP. All authors conducted data analysis, text composition, and revisions. Each author reviewed and confirmed the final manuscript.

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