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COASTAL WETLANDS

The Evolution of Blue Carbon Science

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Abstract
'Blue carbon' was coined over a decade ago to describe the contribution of mangroves, seagrasses, and tidal marshes to carbon drawdown in coasts and oceans, concomitantly attracting attention of policy-makers and resource managers to their potential as a natural climate solution. Here, we explore the emergence and evolution of this relatively new research field through bibliometrics approaches to investigate patterns and trends in scientific publications through time. Our aim was to understand the evolution of blue carbon science, from where we came from and where we are now. We analysed 1,729 papers from 5,763 authors. Overall, the carbon-sink capacity of these ecosystems has been recognised long before the term 'blue carbon' was coined; with an annual percentage growth rate of 20% y^{-1}. Research attention was highest for mangroves (~38% of publications), followed by saltmarshes (~22%), and seagrasses (~18%); while ~16% of the studies included two or more blue carbon ecosystems and 5% of the studies focused on other ecosystems. The citation burst analysis showed that, in the 1990s, the hot topic (i.e., fast-growing topic) was related to the overall flux and dynamics of carbon, with a recent transition to the role of coastal vegetation to climate change mitigation from 2009. The term 'blue carbon' became a hot topic in 2017, with the strongest citation burst between 2017 and 2020. This bibliometric study draws the patterns and trends of blue carbon science and indicate that this field is evolving through time to focus more on the blue carbon role as nature climate solutions.

Keywords Blue carbon · Coastal wetlands · Bibliometric survey · Mangroves · Tidal marshes · Seagrasses

Introduction

Blue carbon ecosystems are broadly defined as environments that capture and store ('sequester') organic carbon, and include mangrove forests, tidal marshes and seagrass meadows as main players (Mcleod et al. 2011; Nellemann et al. 2009). There are still uncertainties about the role of macroalgae (seaweeds), but their indirect contribution as 'carbon donors' is likely to be globally-significant (Filbee-Dexter and Wernberg 2020; Hill et al. 2015; Krause-Jensen and Duarte 2016; Trevathan-Tackett et al. 2015). Overall, net carbon sequestration in blue carbon ecosystems can be 10–100 times that of terrestrial forests per unit area, while accounting for around half of the carbon stored in marine sediments globally (Duarte et al. 2013; Mcleod et al. 2011). Thus, blue carbon ecosystems have a key role in climate change mitigation and adaptation (Macreadie et al. 2021). In addition to carbon sinks, these ecosystems provide several other co-benefits such as improving water quality (Adame et al. 2021), acting as a buffer against flooding and extreme events (Arkema et al. 2013, 2015; Menéndez et al. 2020), serving as nursery ground for species target by fisheries (Jänes et al. 2020a, b), and preventing coastal erosion (Kazemi et al. 2021).

The ability of these ecosystems to act as major carbon sinks has been known for decades (Fig. 1), yet the term 'blue carbon' is quite recent, being first introduced in the literature in 2009 (Nellemann et al. 2009). Blue carbon was initially framed as the 'carbon sink role of marine vegetation', with two major reports published before 1980 discussing the role of seagrasses as carbon sinks in Denmark (Boysen-Jensen 1914) and recognising a substantial global carbon cycling in the oceans via phytoplankton (Riley 1944). In the early 1980s, a key study was published on the role of marine macrophytes as a carbon sink (Smith 1981; Fig. 1). Since

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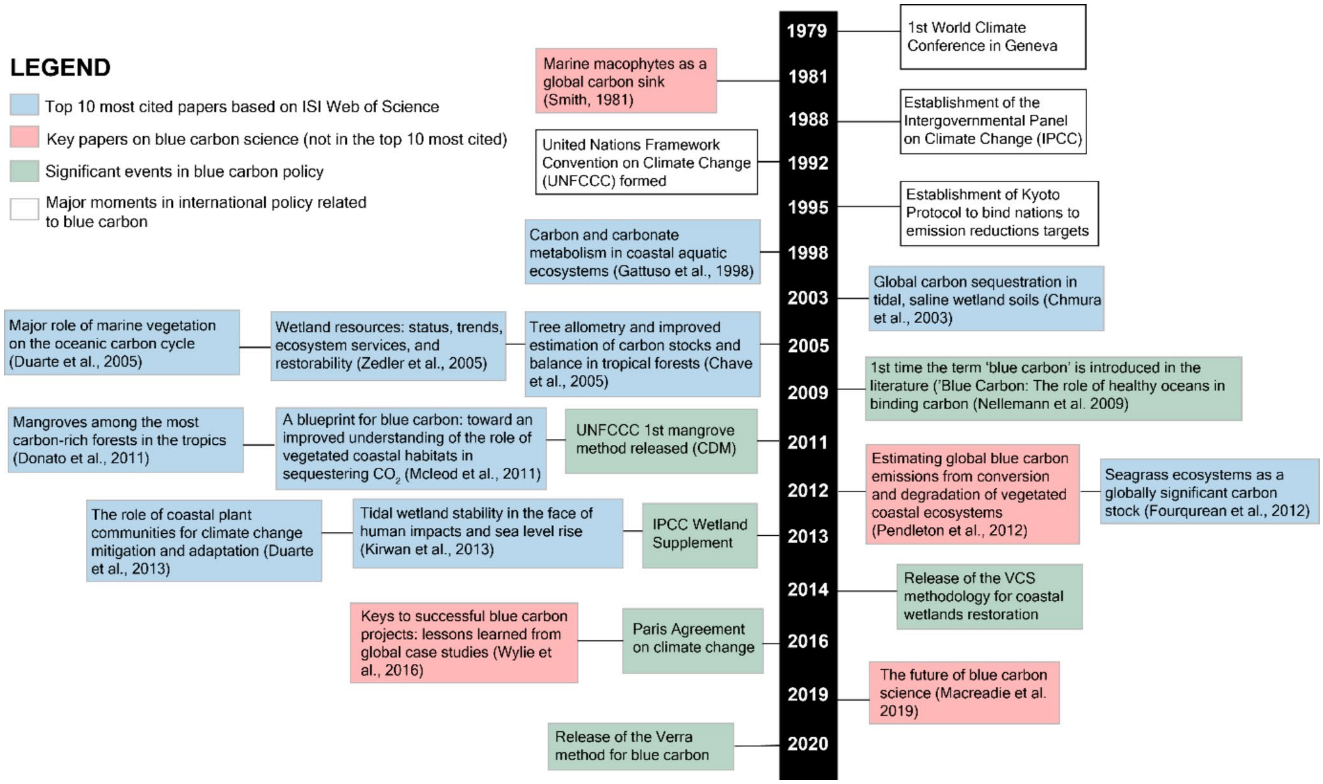

Fig. 1 Timeline showing: (1) top 10 most cited papers based on ISI Wed of Science, (2) key papers on blue carbon science [i.e., important papers in the blue carbon science that are not in the top 10 most cited papers. The four papers in this category include the first paper noting the contribution of coastal vegetation as a carbon sink (Smith 1981), the first paper estimating global potential emissions from the conversion of blue carbon ecosystems (Pendleton et al. 2012), the first paper summarising lessons learnt from blue carbon restoration projects (Wylie et al. 2016) and the recent roadmap summarising the main open questions in blue carbon science (Macreadie et al. 2019)], (3) significant events in blue carbon policy and (4) major moments in international policy related to blue carbon (Chave et al. 2005; Chmura et al. 2003; Donato et al. 2011; Duarte et al. 2005, 2013; Fourqurean et al. 2012; Gattuso et al. 1998; Kirwan and Megonigal 2013; Macreadie et al. 2019; Mcleod et al. 2011; Nellemann et al. 2009; Pendleton et al. 2012; Smith 1981; Wylie et al. 2016; Zedler and Kercher 2005).

2009, the term 'blue carbon' has expanded by improving the estimates of the contribution of mangroves, seagrasses, and tidal marshes as carbon sinks, providing a practical approach to implementing these ecosystems in strategies for climate change mitigation and adaptation. Furthermore, the growing interest for blue carbon is also reinforced by their inclusion in international climate agreements and policies (Fig. 1), such as in Nationally Determined Contributions (Herr et al. 2017; Herr and Landis 2016; Macreadie et al. 2021; World Bank 2021).

The growing expansion of blue carbon science in the past twenty years is supported by increasing research efforts to address uncertainties and open questions on the role of conservation and restoration of these ecosystems to climate change mitigation and adaptation (Macreadie et al. 2019). Despite recent efforts to understand the development of blue carbon research globally (Jiang et al. 2022; Lai et al. 2022), we still lack a comprehensive assessment (including macroalgae) of the development and growth of blue carbon science as a research field. Here, our aim is to explore the global scientific literature on blue carbon over time, considering mangroves, tidal marshes, seagrasses and macroalgae. For this, we performed a bibliometric analysis on blue carbon research with the aim to identify current trends for leading papers, authors, keywords, and geographical spread of contributions. Bibliometric analysis is an efficient tool to map and identify publication records and trends of specific topics, with our results providing valuable insight into the evolution of blue carbon science and helping strategize the future of blue carbon research.

Methods

In January 2021, we conducted a literature search, which included peer-reviewed studies identified within the general database of the ISI Web of Science (Clarivate™; webofknowledge.com), including search in the title, abstract, author keyword, and keyword plus fields of SCI-SCI Expanded database. We used a timeframe between 1900 and 2020 and incorporated a Boolean logic (i.e., AND, OR, *, $) to combine terms related to the ecosystem (i.e., mangrove, seagrass, saltmarsh) and dataset (i.e., carbon sequestration, stocks) (Table S1). The main objective of the search was to target publications focusing on the ability of coastal wetlands to sequester and store carbon. Our searches were only in English, which may partially overlook research published in other languages (Amano et al. 2021; Christie et al. 2021). Another limitation of this approach is that our analysis does not include grey literature (e.g., thesis and dissertations) or reports.

The original search resulted in 2,035 bibliographic records. This database was screened to double check the search criteria, the relevance to the study and to extract information on habitat type (i.e., mangroves, tidal marshes, seagrasses, macroalgae, other), and methodological approach (i.e., qualitative methods and review, quantitative and/or modelling). Furthermore, the database was carefully scrutinised to eliminate records for duplicate references, missing information, and papers that did not focus on blue carbon science. This process resulted in 1,729 relevant publications in total. The final dataset was then used to evaluate: (1) publication patterns, (2) trends in authors and keyword networks, and (3) evolution of the scientific literature on blue carbon.

Data Analyses

We used the bibliometrix R package (Aria and Cuccurullo 2017) to develop a quantitative analysis and statistics of blue carbon publications. For that, we evaluated the overall annual production between 1900 and 2020, top manuscripts per number of citations, most productive countries and most relevant journals. Then, we used VOSviewer software (version 1.6.16; www.vosviewer.com) to perform the co-occurrence and co-authorship analysis to understand the trends among authors and keywords in blue carbon science. VOSviewer uses clustering algorithms that helps to identify connections in the bibliometric dataset, and also allows for the creation, visualisation and exploration of maps based on bibliometric network data (van Eck and Waltman 2017). To identify collaboration patterns on blue carbon science, we created a co-authorship network based on the number of publications that researchers have jointly authored. For that, we restricted the analysis to publications with a maximum of 25 authors per document and a minimum threshold of 5 documents per author to show the top 50 most well-connected authors in blue carbon science. Table S2 provides a detailed information for each term used in the bibliometric analysis included in this study.

To investigate the most active area of blue carbon science, we used the CiteSpace software version 5.8.2 (Chen 2006, 2017) to perform a citation burst history analysis for keywords and references. This analysis provides an indication of publications and/or keywords that attracted a high degree of attention from its scientific community based on the Kleinberg's algorithm (Chen 2006, 2017). In this study, we used this analysis to identify the publications that are associated with a surge of citations (lasting from a single to multiple years) and which are the fast-growing topics in the field based on our database. This analysis was performed to identify the hot topic across the evolution of the scientific literature on blue carbon.

Results & Discussion

The bibliometric database compiled 1,729 records: 1475 articles, 38 book chapters, 2 data papers, 88 proceeding papers, 105 reviews and 21 publications of other type (i.e., corrections, notes, editorial notes and letters) according to the classification of the WoS database (Fig. 2). We found 5,763 authors, with 65 authors of single authored documents and 5,698 authors of multi-authored documents. From this total, approximately 38% of the studies focused on mangroves, 22% on saltmarshes, and 18% on seagrasses (Fig. 2). Recent bibliometric research on blue carbon ecosystems have found a similar pattern, with mangroves being the most studied ecosystem (Jiang et al. 2022). While these ecosystems have been considered the main players in blue carbon science (Duarte et al. 2013; Mcleod et al. 2011), there has been increasing evidence of the contribution of macroalgal ecosystems to carbon sequestration (Krause-Jensen and Duarte 2016; Ortega et al. 2019). Macroalgae are an important component of the ocean's carbon cycle, with an estimated global area in the range of 6.06 to 7.22 million km^2 (Duarte et al. 2022). Despite recent estimates showing that these ecosystems could potentially sequester a range of 61 to 268 Tg C per year globally (Krause-Jensen and Duarte 2016), there are still large uncertainties on including this ecosystem into future blue carbon assessments. Here, we found that ~16% of the studies included two or more blue carbon ecosystems, while 5% of the studies focused on other ecosystems such as oyster reefs and macroalgae, representing the growing interest in the macroalgae role in blue carbon science in the most recent years.

The first scientific publication highlighting the importance of vegetated coastal ecosystems was published in 1981 (Smith 1981), yet blue carbon is still a recent terminology for the capacity of vegetated coastal ecosystems to capture and store carbon in their biomass and soil (Fig. 2). It is also important to note that it is difficult to define a 'blue carbon publication' prior to 2009 when the term was first published (Nellemann et al. 2009), with searching power decreasing prior to this date. Overall, we found that the scientific literature in blue carbon science substantially increased since

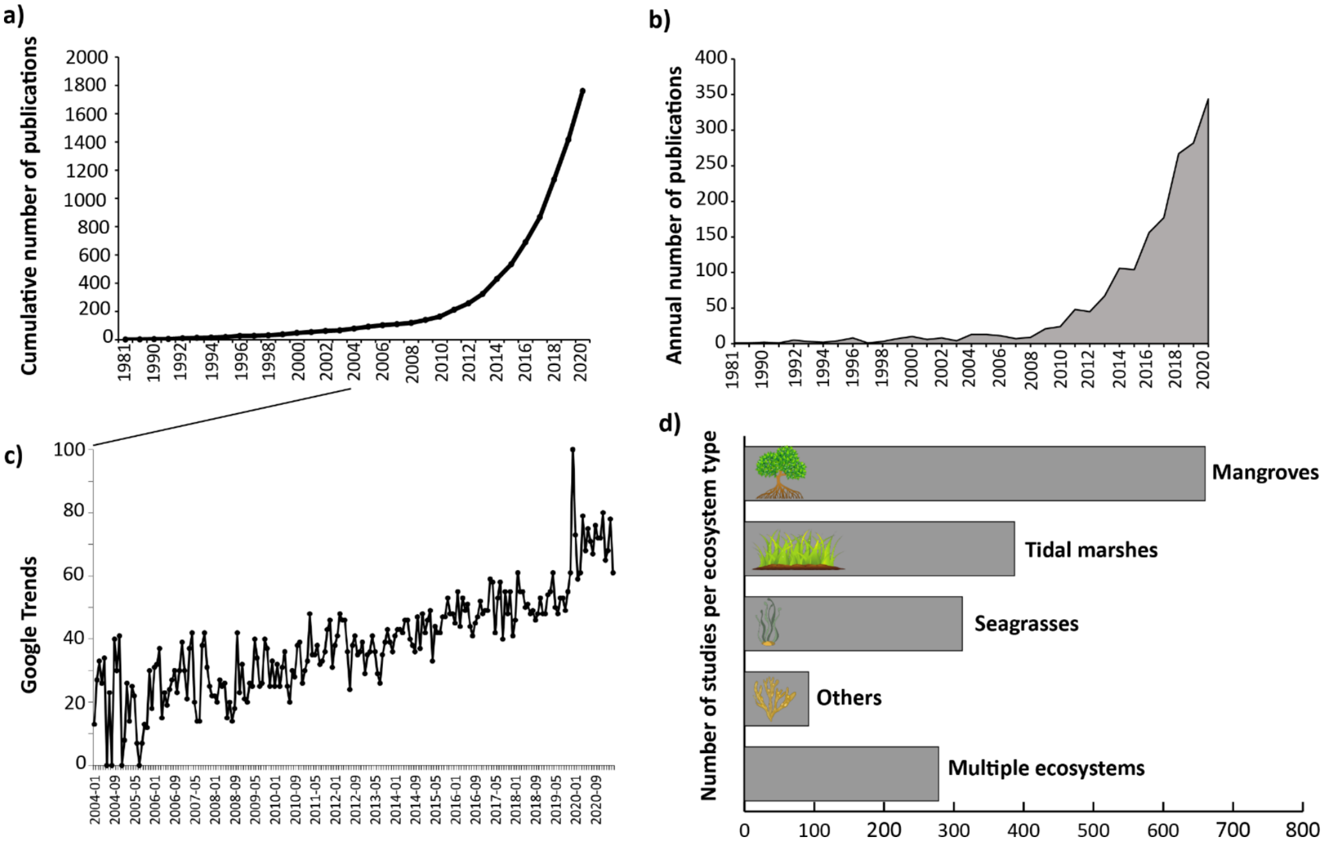

Fig. 2 Distribution of (a) cumulative number of publications; (b) annual number of publications on blue carbon science between 1981 and 2020; (c) worldwide interest on the topic 'blue carbon' over time in the Google Trends, from 2004 to the present; and (d) number of published papers from our dataset per ecosystem type. In the Google Trends, a value of 100 is the peak popularity for the term, and 0 means that was not enough data for the term.

2005 (cumulative number and annual number of publications), which is also followed by worldwide interest on the topic (Fig. 2). Our bibliometric analysis showed an annual percentage growth rate of 20.02% y^{-1}.

The top 10 journals publishing blue carbon science, each publishing between 1.9–5% of the total number of publications in the database, included around 26% of the articles (Figure S1). These 10 journals correspond to 2.28% of the total amount of journals included in the database (n = 439). The journal 'Estuarine, Coastal and Shelf Science' is the leading journal on blue carbon publications (5%), with a smaller and sparse number of publications since early 1990's, but with a greater peak since 2017. 'Science of the Total Environment', 'Wetlands', 'Marine Ecology Progress Series', 'Frontiers in Marine Science' and 'Global Change Biology' followed in the rank and showed fluctuations over time in the annual publication patterns (Figure S1). Despite these finding, none of the most cited papers (Table 1) were published by the top ten journals publishing blue carbon science (Figure S1). Overall, five out of the top 10 mostly cited papers in blue carbon science were published before the term 'blue carbon' was introduced for the first time in the literature in 2009, and were mostly related to the capacity of coastal wetlands to sequester and store carbon. After 2009, the remaining top 10 mostly cited papers focused not only on the storage capacity, but also in the ecosystem contribution towards climate change mitigation and adaptation.

The keyword co-occurrence (N = 252 individual keywords) identified contextual links among publications (Fig. 3), with the 10 most abundant keyword displayed in Table 2. As expected, the term 'blue carbon' was the most frequent term, followed by 'carbon sequestration' and 'mangrove' as the 2nd and 3rd most used terms; while 'ecosystem services' and 'sea level rise' were the 9th and 10th most used keywords, respectively (Table 2). The results of our keyword co-occurrence network showed that 'blue carbon' is closely related to 'sediments' and 'carbon', with the proximity of the nodes indicating how the keywords are related to each other (Fig. 3). Visually, all clusters show a high degree of overlapping as some keywords are placed in between other cluster areas. Furthermore, the size of the nodes indicates how frequent these keywords usually occur in the blue carbon science literature (Fig. 3). In this case, the top 5 keywords based on their total link strength were 'blue

Table 1 The 10 most cited papers in blue carbon science based on the database extracted from the ISI Web of Science. Here, we have also included the number of citations for each paper found in Google Scholar and Scopus by July 2021.

Ranking	WoS	Scopus	Google Scholar	Reference
1	1,586	1,713	3,213	Chave, J., C. Andalo, S. Brown, M. (A) Cairns, J. Q. Chambers, D. Eamus, H. Folster, F. Fromard, N. Higuchi, T. Kira, J. P. Lescure, (B) W. Nelson, H. Ogawa, H. Puig, B. Riera, and T. Yamakura. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99.
2	1,194	1,255	1,905	Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger, and B. R. Silliman. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Frontiers in Ecology and the Environment 9:552–560.
3	1,021	1,130	1,929	Donato, D. C., J. B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kanninen. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience 4:293–297.
4	984	1,059	1,791	Zedler, J. B., and S. Kercher. 2005. Wetland resources: Status, trends, ecosystem services, and restorability. Annual Review of Environment and Resources 30:39–74.
5	782	873	1,417	Chmura, G. L., S. C. Anisfeld, D. R. Cahoon, and J. C. Lynch. 2003. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochemical Cycles 17: 1111
6	743	758	1,212	Fourqurean, J. W., C. M. Duarte, H. Kennedy, N. Marbà, M. Holmer, M. A. Mateo, E. T. Apostolaki, G. A. Kendrick, D. Krause-Jensen, K. J. McGlathery, and O. Serrano. 2012. Seagrass ecosystems as a globally significant carbon stock. Nature Geoscience 5:505–509.
7	697	722	1,000	Kirwan, M. L., and J. P. Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53–60.
8	651	682	1,025	Gattuso, J. P., M. Frankignoulle, and R. Wollast. 1998. Carbon and carbonate metabolism in coastal aquatic ecosystems. Annual Review of Ecology and Systematics 29:405–434
9	645	659	1,168	Duarte, C. M., J. J. Middelburg, and N. Caraco. 2005. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2:1–8
10	621	653	923	Duarte, C. M., I. J. Losada, I. E. Hendriks, I. Mazarrasa, and N. Marbà. 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change 3:961–968.

carbon', 'carbon sequestration', 'mangrove', 'salt marsh' and 'climate change' (Table 2).

As shown in Fig. 3, the central keywords 'blue carbon' and 'carbon sequestration' are strongly related, considering both the closeness of their locations in the network map and the thickness of their connection (which represents higher number of co-occurrences). However, the overlay map (Figure S2) shows a temporal mismatch in their co-occurrence. While 'blue carbon' is placed in the temporal spectrum of more recent publications, the average occurrences of the keywork 'carbon sequestration' is more related to the middle of the temporal spectrum (Figure S2). Overall, the left part of the overlay map in Figure S2 show research topics that were more related to past investigations in blue carbon science, such as 'estuary', 'carbonate', 'and carbon flux', while the right part of the figure show research topics ('restoration', 'carbon credits', 'machine learning', 'global warming', 'Paris Agreement') more associated with the recent trends in the field. Overall, our results highlight the future trends of understanding how carbon sequestration can change through restoration or influenced by future climate conditions. However, despite the growing interest in blue carbon ecosystems and the temporal change in the main topics targeted in the field, there are still many unanswered questions – with a recent study developing a roadmap to help guide the future of blue carbon science, in which 10 fundamental questions highlight the gaps in the

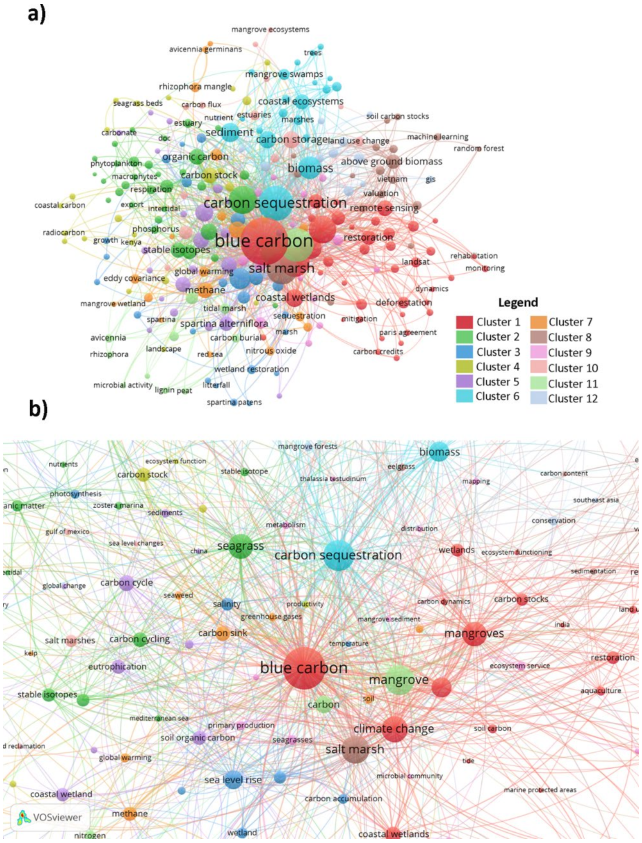

Fig. 3 Network map of 252 keywords showing the results of the (a) co-occurrence network analysis and (b) a zoom of the network in an area close to the most searched term 'blue carbon'. The size of the nodes represents their "total link strength" indicating that these keywords occur frequently in the literature regarding blue carbon. Lines are connecting the nodes with thickness based on "link strength" (i.e., the magnitude of their co-relation).

Table 2 Top 10 keywords ranked according to the total link strength.

Ranking	Keyword	Total link strength	Occurrences
1	Blue carbon	914	325
2	Carbon sequestration	487	178
3	Mangrove	471	166
4	Salt marsh	416	144
5	Climate change	386	124
6	Seagrass	330	119
7	Mangroves	276	115
8	Biomass	232	71
9	Ecosystem services	197	72
10	Sea level rise	193	66

field, ranging from carbon fluxes to restoration (Macreadie et al. 2019).

The citation burst analysis (Fig. 4) was used to identify the publications in our database that are associated with a surge of citations, and therefore, could be identified as hot topics in blue carbon science.. Here, we found that the publication with the strongest burst strength was 'The management of natural coastal carbon sinks' (Laffoley and Grimsditch, 2009) with the surge in citation starting between 2011 and 2015 (Fig. 4). Overall, the temporal distribution across the years shows a pattern of increasing interest towards blue carbon publications by ~2010 (Fig. 4). The publications listed in Fig. 4 had a key role to set the scene for the development of blue carbon science and were essential to move it forward. Interestingly, only three publications (Chmura et al., 2003; Duarte et al., 2005; Gattuso et al., 1998) identified in the citation burst analysis are also within the top 10 most cited papers in blue carbon science (Table 1). Furthermore, if considering the duration of the burst, Gattuso et al. (1998) is the publication with the longest citation burst (2004–2015) despite not having the strongest burst (Fig. 4).

If we consider the keywords, we can observe that, in the 1990s, the hot topic was related to the overall flux and dynamics of carbon with a transition to the role of coastal vegetations to mitigate climate change from 2009, which also confirms the pattern found in our overlay map (Figure S2). The term 'blue carbon, despite being coined for the first time in 2009 (Fig. 1), became a hot topic only in 2017, having the strongest citation burst found in our analysis (Fig. 4). This pattern could be explained by the lag between the time when researchers start to conduct blue carbon research and when their publications start to emerge. Furthermore, it could also be related to the higher evidence of the role that blue carbon plays in climate change mitigation and adaptation and their inclusion in policy (e.g., Paris Agreement, IPCC Wetland Supplement in 2013). After the 2015 United Nations Climate Change Conference (COP 21), the key role played by the oceans, and especially blue carbon ecosystems, in the carbon storage and sequestration have been officially recognised for the first time. This led to further efforts globally to conserve and restore mangroves, tidal marshes and seagrasses. Considering the citation bursts in the past 10 years (since 2015), our results showed that the focus of blue carbon research has been on productivity in different ecosystems, flux dynamics, policy and restoration. With the increasing interest on blue carbon as a nature climate solution at local and national scales, we expect that these topics will continue to be within the hot topics in blue carbon science.

Overall, we found a total of 5,191 authors contributing to blue carbon publications during 1981–2020 within 69 countries. If we consider the affiliation of first authors, about 26% of the publication had authors affiliated in the United States, followed by 13.4% in China and 13.3% in Australia institutions (Fig. 5). Furthermore, United Kingdom (4.97%), India (4.27%), Spain (3.3%), Indonesia (2.89%), Japan (2.89%), Brazil (2.83%) and Germany (2.83%) compose the top 10 countries with higher number of authors in blue carbon science (Fig. 5). Interestingly, Australia, United States,

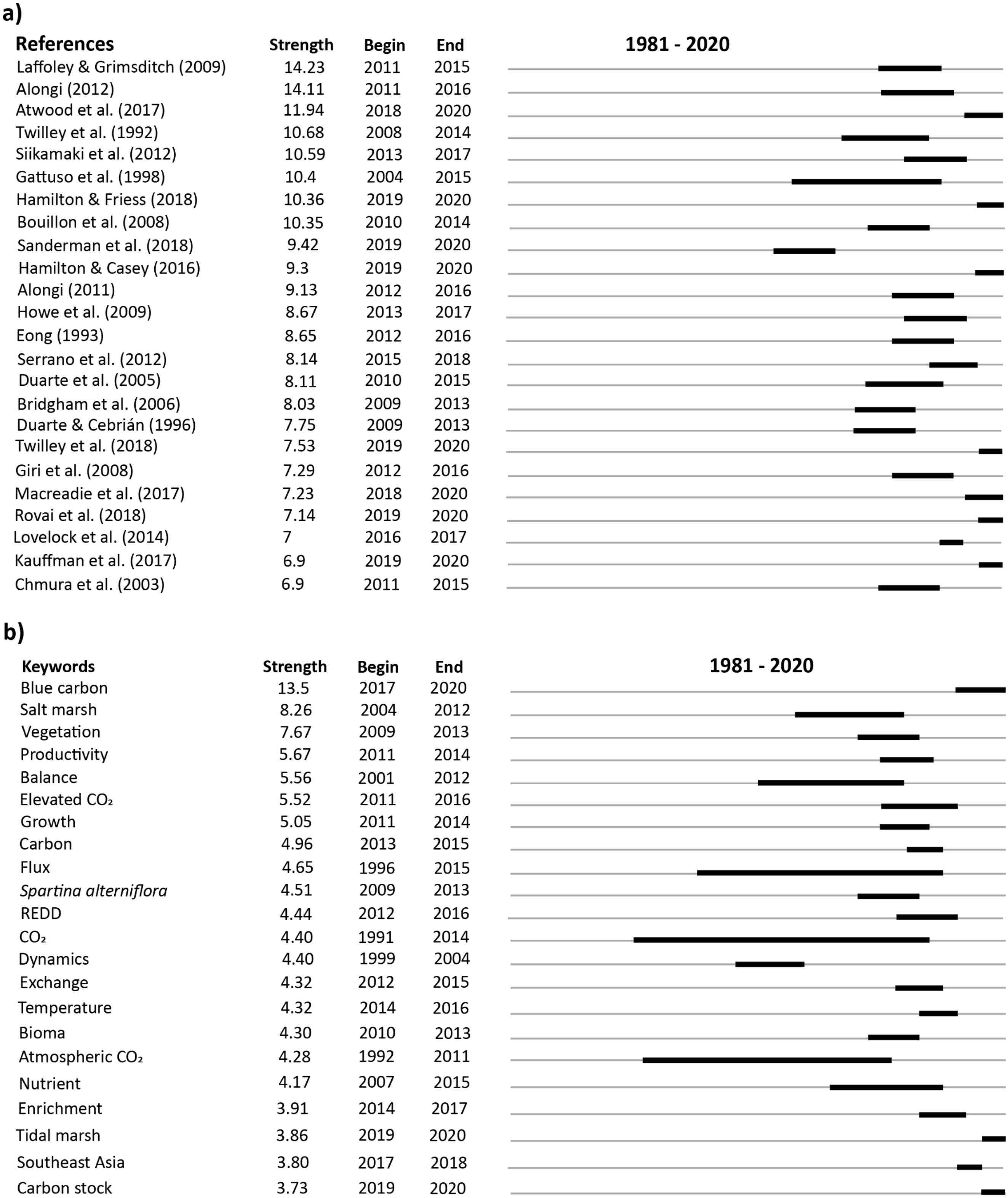

Fig. 4 Citation burst analysis of (a) references (Alongi 2011, 2012; Atwood et al. 2017; Bouillon et al. 2008; Bridgham et al. 2006; Chmura et al. 2003; Duarte et al. 2005; Duarte and Cebrian 1996; Eong 1993; Gattuso et al. 1998; Giri et al. 2008; Hamilton and Casey 2016; Hamilton and Friess 2018; Howe et al. 2009; Kauffman and Bhomia 2017; Laffoley and Grimsditch 2009; Lovelock et al. 2014; Macreadie et al. 2017; Rovai et al. 2018; Sanderman et al. 2018; Serrano et al. 2012; Siikamäki et al. 2012; Twilley et al. 1992, 2018) and (b) keywords based on the literature review on blue carbon research from 1981 to 2020. For each reference and keyword, the burst strength and timespan are shown. Black lines indicate the time period with the strongest citation burst.

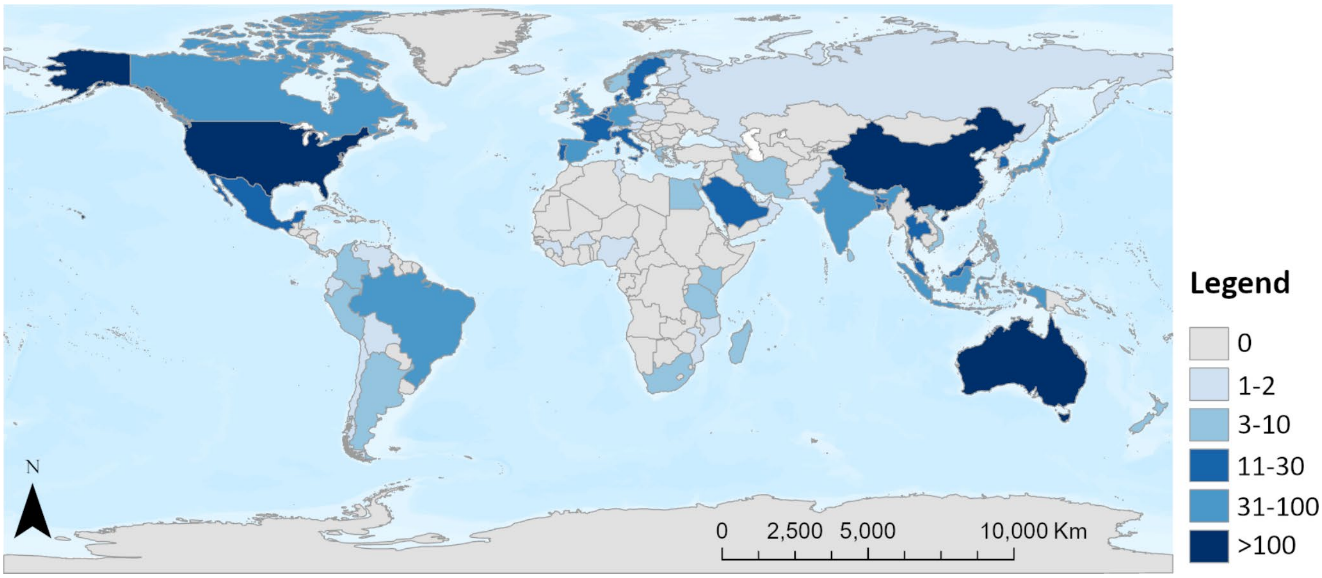

Fig. 5 Geographical distribution of first authors based on their affiliation. In total, 69 countries were recorded in our database.

Indonesia and Brazil are also amongst the countries with higher distribution of blue carbon ecosystems and potential carbon stocks (Macreadie et al. 2021). However, it is important to highlight that one major limitation of our study is that only publications in English were considered in our search, and that grey literature and reports were excluded from the analysis. Therefore, the contribution of countries such as Brazil, Mexico, Chile are likely to have been underestimated (Amano et al. 2021; Christie et al. 2021).

Our co-authorship network analysis revealed 9 clusters, which were formed by a combination of country of affiliation and research topic. Cluster 8 and 9 are the most well-connected clusters consisting of authors related to geochemistry studies based in Australia and Brazil, respectively (Fig. 6). Clusters 3 and 5 are composed by Chinese authors working on different topics in blue carbon science, with the major difference based on who they collaborate in the network map. Cluster 5 is connected with Cluster 4, while Cluster 3 is connected with Cluster 6. Clusters 1, 2 and 4 are the largest and strong connected clusters and consist of authors who are widely known to have a long-term collaboration network, with the majority of them based in Australia. In this case, habitat type is likely acting as a divider between these clusters, with authors included in Cluster 1 being more active in mangrove research, while those in Cluster 2 are known experts on seagrass ecosystems. Cluster 4 is composed by authors that usually focus on saltmarshes and mangroves (Fig. 6). Cluster 6 combines Australian authors that are more related to coastal and geomorphology in blue carbon ecosystems. Finally, Cluster 7 is composed by authors working on blue carbon ecosystems based in UK and Kenya. This Cluster is connected with Cluster 2 through a node representing H. Kennedy (Fig. 6).

Overall, C. M. Duarte, P. I. Macreadie, O. Serrano, P. S. Lavery and C. E. Lovelock have the strongest total link strength, which indicate the strength of their co-authorship to others (Fig. 6). However, the overlay map shows a temporal mismatch, with C. M. Duarte and C. E. Lovelock contributing to blue carbon science since the earliest temporal spectrum, while other authors are more related to the middle of the temporal spectrum (Figure S3). In general, the bottom part of the overlay map in Figure S3 show authors that have an average publication year of ≤2015. Our findings in the collaboration analysis also aligns with the most productive countries in blue carbon science (Fig. 5), with these authors playing an important role in building capacity of younger researchers and other countries lacking blue carbon experts.

Overall, we included a sufficiently wide range of blue carbon publications in this study to identify patterns and trends over time. Nevertheless, our study demonstrates that blue carbon science is a rapidly growing field and is still in a strong growth phase (as indicated by its exponential publication trajectory). Our bibliometric study showed that while past trends in the blue carbon science were more related to understanding the carbon cycling in these ecosystems, the research is transitioning to understanding the opportunity for new technologies to help estimate carbon stocks (i.e., remote sensing, machine learning models; (Costa et al. 2021; Ewers Lewis et al. 2020; Pham et al. 2020; Sanderman et al. 2018; Simard et al. 2019; Young et al. 2021), the role of these ecosystems as nature climate solutions through their restoration and conservation (Costa et al. 2022; Hagger et al. 2022; Macreadie et al. 2021; Moritsch et al. 2021;

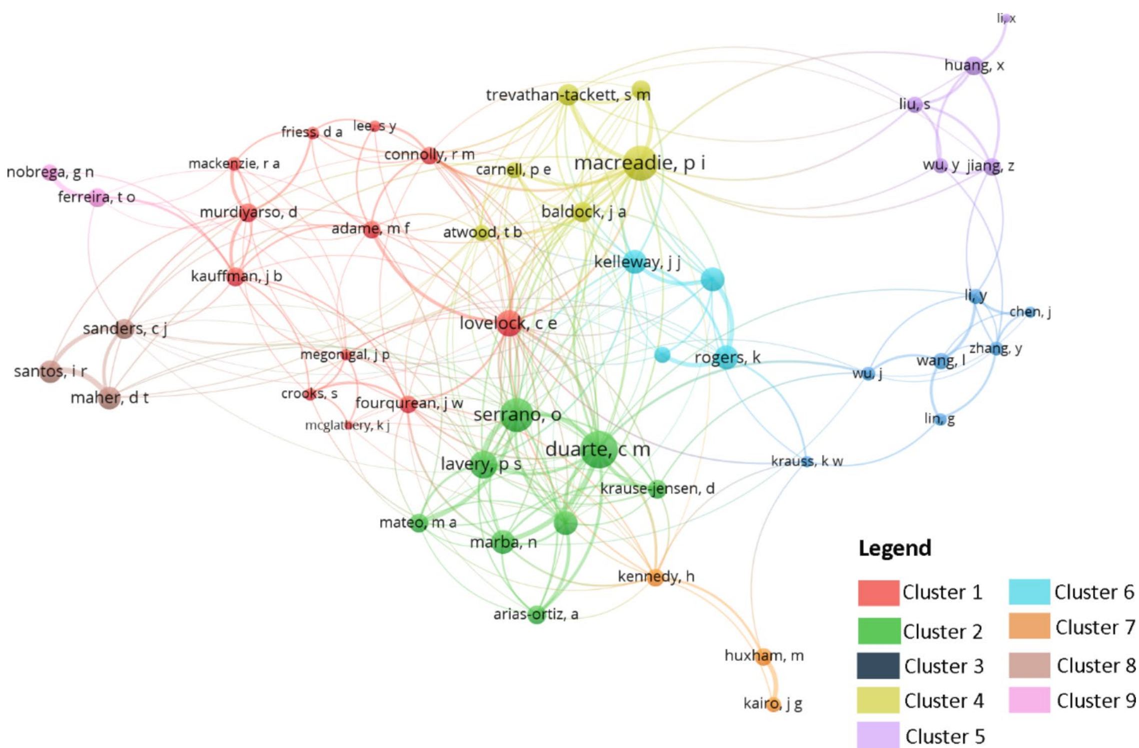

Fig. 6 Co-authorship network map of top 50 most well-connected authors based on their total link strength. In this analysis, the minimum number of documents of an author was set to 5 and the maximum number of authors per document was set to 25. We used the fractional counting method, which reduces the influence of documents with many authors.

Wedding et al. 2021), and finally, the potential changes in their distribution and carbon sequestration due to future climate conditions.

With more countries adopting legislation to conserve and restore blue carbon ecosystems to help adapt and mitigate climate change, there is growing demand from government and private sector to operationalise blue carbon projects. However, we still need to overcome several barriers to overcome uncertainties in social, governance, financial and technological dimensions (Macreadie et al. 2022). For that, we recognise that the translation of blue carbon science into policy and practice will increasingly require transdisciplinary collaborations involving policy experts, environmental economists, biogeochemists, spatial modelers, ecologists, social scientists, among others. Fortunately, the blue carbon science has already proven to be a collaborative field with 99% of papers involving multiple authors and long-term, multi-country collaborative networks (Fig. 6). The challenge will be to expand these networks to include all actors who can help break through barriers to develop on-ground blue carbon restoration projects (Friess et al. 2022; Macreadie et al. 2022) and their potential value (Carnell et al. 2022).

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Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Micheli Duarte de Paula Costa. The first draft of the manuscript was written by Micheli Duarte de Paula Costa and Peter I. Macreadie, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The publication list collated and used in this study is available in the Supplementary Material.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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