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Publication Performance and Trends in Mangrove Forests: A Bibliometric Analysis

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Abstract: Mangroves are one the most productive ecosystems on Earth, and they are geographically located in the tropics and sub-tropics. Notwithstanding their critical role in providing a large number of environmental services and benefits as well as livelihood provisions, mangrove forests are being lost globally at an alarming rate. At the same time, they are increasingly recognized as a cost-effective nature-based climate solution for their carbon sequestration and storage capacity. Despite their enormous importance to people's lives and the ecosystem, no bibliometric study on this topic has been published to our knowledge. Here, we provide a bibliometric analysis of the research on mangroves with research trends, most influential research based on citation count, and the origins (country and institution) of major research. Using the Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (Clarivate Analytics), we identified 13,918 documents published between 1990 and 2019. Nevertheless, 12,955 articles met our final criteria and were analyzed in detail. Six publications and their citations per publication (CPP_{2019}) were applied to evaluate the publication performance of countries and institutes. When considering the top ten Web of Science subject categories, articles published on the ecology of mangroves had the highest CPP_{2019} of 28. Environmental sciences have been the major category since 2013. The USA dominated the total articles and single-author articles. The USA was also the most frequent partner of international collaborative publications. China published the most single-country articles, first-author articles, and corresponding-author articles. However, articles by the USA and Australia had a higher CPP_{2019}. Sun Yat Sen University in China was the most active university. The Australian Institute of Marine Science dominated all kinds of publications with the top CPP_{2019}. Together with the USA, Australia, China, India, Brazil, and Japan ranked both the top six on total publications and total publications in 2019. Our bibliometric study provides useful visualization of the past and current landscape of research on mangroves and emerging fields, to facilitate future research collaboration and knowledge exchange.

Keywords: mangrove forest; SCI-EXPANDED; scientometrics; TC_{year}; C_{year}; CPP_{year}

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1. Introduction

Mangroves are located in the intertidal zones of coastal tropical and sub-tropical regions of the world (Figure 1) [1]. Globally, they occupy nearly 13.7 million ha of area and are distributed across 118 countries [2]. Mangroves are critical in providing a large number of environmental services and/or benefits, such as buffering coastlines against cyclones, tsunamis, and storm surges [3–5], carbon storage and sequestration [6], water quality regulation [7], provision of breeding habitats for many species of fish and wildlife [8], etc. Mangroves also support local livelihoods through the provision of ecotourism, food, fuel, timber, and construction materials [9,10]. A recent study suggests that the global flood

protection benefits of mangroves are worth nearly USD 65 billion per year [11], while the cyclone protection value of mangroves is worth about USD 1.8 million/km^2 per year [12].

Figure 1. Map showing the global distribution of mangroves (in black). Source: UNEP-WCMC (https://data.unep-wcmc.org; accessed: 15 June 2021).

Since mangroves are a major reservoir of global blue carbon [13] and can sequester carbon from the atmosphere faster than any other terrestrial ecosystems [14], they are increasingly regarded as a cost-effective nature-based climate solution in many parts of the world. In contrast to peatlands (another carbon rich ecosystem), mangroves also release negligible amounts of greenhouse gases per unit area [15]. Notwithstanding their enormous importance to people's lives and their diverse environmental benefits, mangroves are lost globally at a rate faster than the tropical rainforests [16]. Climate change and the resulting sea-level rise, coastal infrastructure development, aquaculture, and conversion to agricultural land are amongst the major threats to this imperiled ecosystem [17,18].

Here, we provide a bibliometric analysis of the publication performance and research trends on mangroves using a systematic survey protocol [19–21]. We identified key areas of research and temporal changes in the research foci on mangroves worldwide. The study also provides critical insight into the impactful research on mangroves and their origin. Our analysis could be useful to design future research on mangroves and recognize the changing value of mangroves to people's lives and nature.

2. Materials and Methods

The data relevant to the present study were derived from the SCI-EXPANDED in Clarivate Analytics Web of Science (updated on 27 January 2021). It was pointed out that the SCI-EXPANDED is designed mainly for researchers to find literature but not used for bibliometric studies [22,23]. Therefore, it is always necessary to have a data treatment but also to have data directly from SCI-EXPANDED for bibliometric studies. Recently, a big difference was found by using 'front page' [24] as filter in widely bibliometric studies [25,26]. *KeyWords Plus* supplied additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI (now Clarivate Analytics) database, and substantially augmented title-word and author-keyword indexing [27]. It was pointed out that the documents, which can only be searched out by *KeyWords Plus*, were irrelevant to the studied topic [20]. Search keywords "mangrove" and "mangroves" were used, which inevitably contain articles related to "mangrove forest" or "mangrove forests". By using advanced search with TI (title), AB (abstract), and AK (author keywords), 13,918 documents, including 12,955 articles having the search keywords in their 'front page' [24] and including document title, abstract, and author keywords from 1990 to 2019, were defined as mangrove-related publications.

In the SCI-EXPANDED, the corresponding author is labelled as reprint author, but in this study, we used the term corresponding author [28]. In multiple corresponding-authors

articles, only the last corresponding author, institute, and country were designated as the corresponding author information [29]. In a single-author article, where authorship is unspecified, the single author is both first and corresponding author [30]. Similarly, in a single institutional article, the institution is classified as the first as well as the corresponding author institution [30].

In order to have accurate analysis results, affiliations originating from England, Scotland, Northern Ireland, Wales, Cayman Islands, and Turks and Caicos (Turks and Caicos Islands) were reclassified as being from the UK (United Kingdom). Affiliations from Hong Kong before 1997 were reclassified as being from China [31]. Affiliations from French Guiana were reclassified as being from France [31]. Affiliations from Bonaire and Neth Antilles (Netherlands Antilles) were reclassified as being from Netherlands [32]. Affiliations from Greenland were reclassified as being from Denmark [33]. Affiliations from Senegambia were checked and reclassified as being from Senegal. Affiliations from USSR were checked and reclassified as being from Russia [34]. Affiliations from Czechoslovakia were checked and reclassified as being from Czech Republic [35]. Similarly, Czechoslovak Acad Sci (Czechoslovak Academy of Sciences) was checked and recorded as Czech Acad Sci (Czech Academy of Sciences).

To examine the citations received by the publications, four citation indicators were applied:

C_0: the total number of citations from the Web of Science Core Collection in publication year [36].

C_{year}: the total number of citations (in a particular year) from the Web of Science Core Collection. C_{2019} means the number of citations in 2019 [28].

TC_{year}: the total number of citations from the Web of Science Core Collection since publication year to the end of the most recent year [37]. In this study, this is 2019 (TC_{2019}).

CPP_{year}: citations per publication ($CPP_{2019} = TC_{2019}/TP$) [28].

When reporting the top ten most frequently cited articles based on total citations (TC_{2019}), we considered the articles containing search keywords in their title or author keywords that are primarily focused on mangroves. Therefore, articles where mangroves were not the main focus or form only a small part within a larger context [38] we purposely excluded after carefully reviewing the abstract. We believed this approach would provide a more relevant and useful scenario of global trends and research on mangroves.

3. Results and discussion

3.1. Document Type and Language of Publication

A relationship between document types and citations per publication has been proposed [39]. In 2015, the citations per publication were improved by using the citation indicator of CPP_{year}, which gives values more accurately [40]. Recently, the number of authors per publication was also applied for the discussion of document types [41]. Table 1 shows the characteristics of 16 document types, including 12,955 articles (93% of the 13,918 documents) with a number of authors per publication (*APP*) of 4.3. It should be noticed that documents can be classified in two document types in the Web of Science Core Collection. For example, 10 documents were classified as book chapters and reviews. Thus, the total percentage was higher than 100% [21]. In addition, 642 proceedings papers were also classified as articles.

Table 1. Citations and authors according to document type.

Document Type	*TP*	%	*AU*	*APP*	TC_{2019}	CPP_{2019}
Article	12,952	93	55,773	4.3	258,555	20
Proceedings paper	642	4.6	2194	3.4	18,655	29
Review	450	3.2	1848	4.1	29,974	67
Meeting abstract	195	1.4	704	3.6	37	0.19
Editorial material	108	0.80	296	2.7	993	8.9
Note	64	0.46	141	2.2	745	12
Correction	62	0.45	319	5.1	49	0.79
Letter	42	0.30	122	2.9	831	20
News item	10	0.20	18	1.8	39	1.4
Book chapter	15	0.11	81	5.4	1264	84
Data paper	4	0.029	28	7.0	11	2.8
Retraction	3	0.022	19	6.3	1	0.33
Addition correction	2	0.014	3	1.5	1	0.50
Book review	2	0.014	2	1.0	2	1.0
Biographical item	1	0.0072	6	6.0	0	0
Discussion	1	0.0072	4	4.0	12	12

TP: number of publications; *AU*: number of authors; *APP*: number of authors per publication; TC_{2019}: the total number of citations from the Web of Science Core Collection since publication year to the end of 2019; CPP_{2019}: number of citations (TC_{2019}) per publication (*TP*).

The book chapters document type had the highest CPP_{2019} of 84, which can be attributed to the five highly cited book chapters with a TC_{2019} of 100 or more [36] by Alongi [13], Balasubramanian et al. [42], Feller et al. [43], Thiel and Haye [44], and Manson et al. [45], with a TC_{2019} of 302, 159, 156, 148, and 124, respectively. The data papers document type had the highest *APP* of 7.0. Furthermore, the average number of authors per mangrove article was 4.3, with the maximum number of authors being 54 by Armisen et al. [46] from France, the USA, Germany, the UK, Canada, New Zealand, Russia, the Netherlands, and Panama.

Of all document types, only 12,955 articles were used for further analysis because they included the whole research, such as introduction, methods, results, discussions, and conclusions. The language of the publication is one of the basic concerns in bibliometric studies as a big data analysis [47]. There were 10 languages in use. English, as the most popular language, comprises 97% of the total articles, followed distantly by Spanish (164 articles; 1.3% of 12,955 articles), Portuguese (95; 0.73%), French (45; 0.35%), Chinese (19; 0.15%), and Japanese (14; 0.11%). Some other languages that were less used were as follows: Russian (9 articles), Malay (3), German (2), and Arabic (1). Articles published in English had a much higher CPP_{2019} of 20 than non-English articles with a CPP_{2019} of 5.5. Articles published in English had a higher *APP* of 4.3 than non-English articles with an *APP* of 3.4.

3.2. Characteristics of Publication Outputs

Ho proposed a relationship between the total annual number of articles (*TP*) and their citations per publication ($CPP_{year} = TC_{year}/TP$) by their years [48] to understand publications and their impact trends in a research topic. Figure 2 presents the distribution of the annual number of articles (*TP*) and their citations per publication (CPP_{2019}) by year, which was expressed as TC_{2019}/TP. The number of articles increased from 92 in 1990 to 309 in 2005, and then it increased sharply to 1050 in 2018 and 1049 in 2019. The year 2000, with 213 articles, had the highest CPP_{2019} of 44, followed by a CPP_{2019} of 41 and 40 in 2005 and 1998, respectively. This could be due to the increasing number of studies in recent years, which the authors cannot cite over time. Based on Figure 2, it takes *CPP*s about a decade to reach a plateau. Similarly, research topics related to the environment, for example environmental monitoring [49], wind tunnels [50], bioaccumulation [51], and Fenton oxidation for soil and water remediation [21], also took about one decade to reach a plateau. It might be concluded that to evaluate the impact of papers, citations

accumulated after at least one decade are needed [52]. A total of 9854 mangrove articles (76% of 12,955 articles) had no citations in the publication year (C_0 = 0). Although, with an increasing number of journals in SCI-EXPANDED, articles have had higher citations in the publication year (C_0) in recent years [53]. Furthermore, among the top 100 C_0 articles, 7.6% and 17% of them were among the top 100 TC_{2019} and C_{2019} articles, respectively.

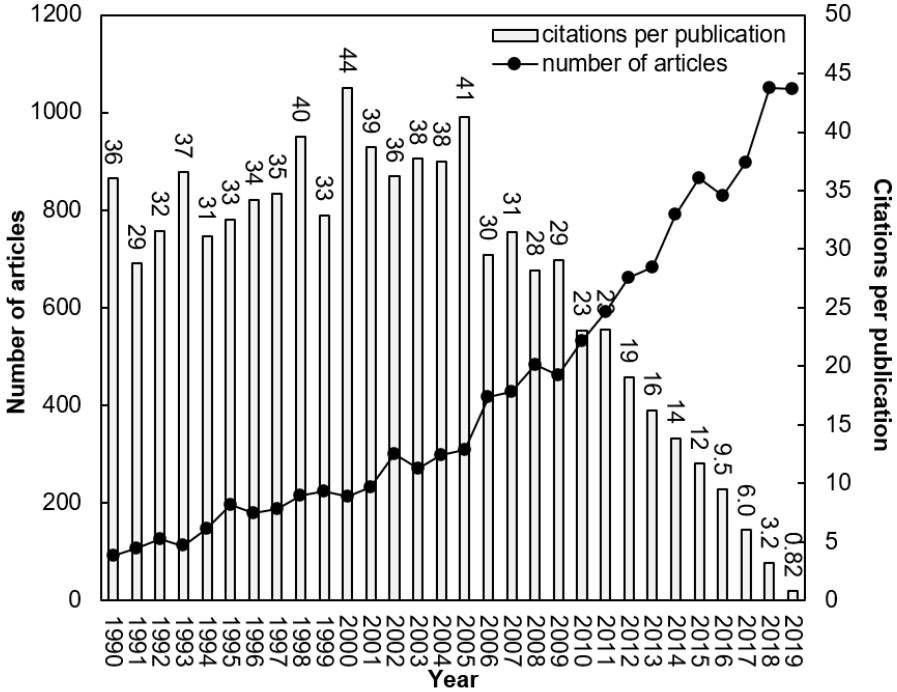

Figure 2. Number of articles and citations per publication by year.

3.3. Web of Science Categories and Journals

Journal Citation Reports (JCR) indexed 9381 journals across 178 Web of Science categories in SCI-EXPANDED in 2019. In order to know development trends among research fields and their interactions, a relationship between the number of articles in categories and publication years was proposed [54]. A total of 12,955 mangrove-related articles were published in 1655 journals, which are classified among the 136 Web of Science categories in SCI-EXPANDED. Altogether, 537 articles were published in 157 journals that were not in SCI-EXPANDED in 2019. Table 2 shows the top ten Web of Science categories with 500 articles or more. In 2019, 106 journals were classified in the category of marine and freshwater biology, which was the leading category with 3140 articles (24% of 12,955 articles). Comparing the top ten categories, mangrove articles published in the category of ecology had the highest CPP_{2019} of 28, followed by oceanography with a CPP_{2019} of 26 (Table 2). The average number of authors in the category of multidisciplinary sciences was 5.2, while in zoology it was 3.1. Figure 3 shows the developments of the top six categories in 2019. Mangrove articles were published mainly in categories of marine and freshwater biology and ecology from 1992 to 2008. The category of marine and freshwater biology was the most popular from 1990 to 2005. Environmental sciences have been the main category since 2013.

Multidisciplinary science is going to be a new category. It has been noticed that journals can be classified in two or more categories in the Web of Science. For instance, Marine Ecology Progress Series was classified in the categories of ecology, marine and freshwater biology, and oceanography, and thus the sum of the percentages was higher than 100% [36].

Table 2. The top ten productive Web of Science categories with *TP* > 500.

Web of Science Category	*TP* (%)	No. *J*	CPP_{2019}	*APP*
Marine and freshwater biology	3140 (24)	106	23	3.8
Environmental sciences	2762 (21)	265	21	4.5
Ecology	1823 (14)	168	28	4.1
Oceanography	1596 (12)	66	26	3.8
Plant sciences	1210 (9.3)	234	20	4.2
Multidisciplinary geosciences	938 (7.2)	200	24	4.3
Zoology	755 (5.8)	168	10	3.1
Water resources	619 (4.8)	94	16	4.1
Physical geography	536 (4.1)	50	24	4.2
Multidisciplinary sciences	534 (4.1)	71	24	5.2

TP: number of publications; No. *J*: number of journals in a Web of Science category; CPP_{2019}: number of citations (CPP_{2019}) per publication (*TP*); *APP*: number of authors per publication.

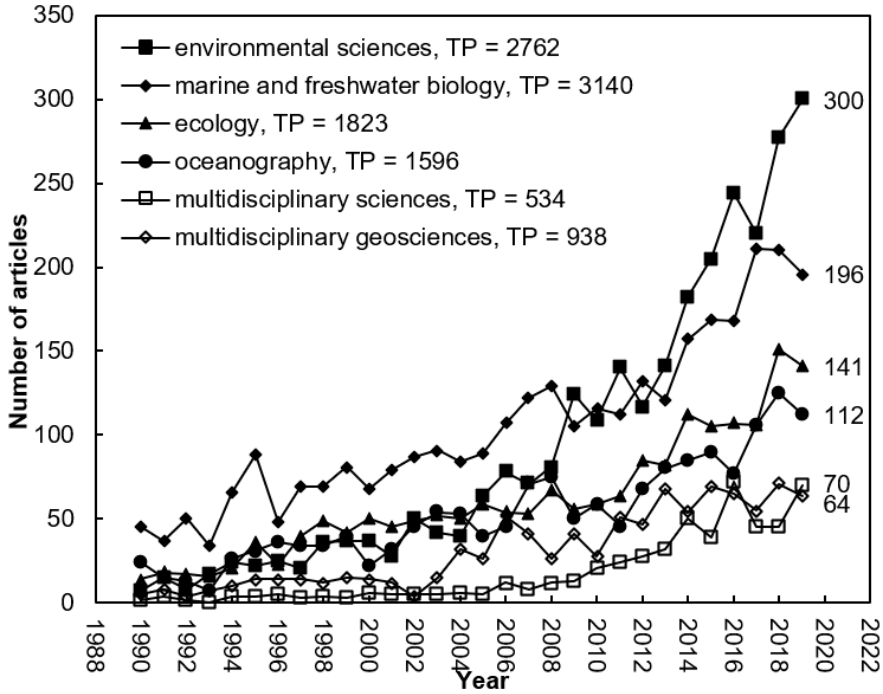

Figure 3. Developments of the top six Web of Science categories in 2019.

The top 15 most productive journals with 100 articles or more are listed in Table 3 with the journal impact factor (IF_{2019}), number of authors per publication (*APP*), number of citations per publication (CPP_{2019}), and Web of Science category. Estuarine Coastal and Shelf Science published the most articles (412 articles; 3.2% of 12,955 articles). Table 3 shows that articles published in *PLoS One* had the highest *APP* of 6.0. Articles published in *Marine Ecology Progress Series* had the highest CPP_{2019} of 41, while articles published in *Indian Journal of Geo-Marine Sciences* had a CPP_{2019} of 1.9. In addition, according to the journal impact factor, *Nature*, with five articles, places first with the highest IF_{2019} of 42.779, followed by *Science* with two articles (IF_{2019} = 41.846), and Nature Climate Change with nine articles (IF_{2019} = 20.893).

Table 3. The top 15 productive journals with *TP* > 100.

Journal	*TP* (%)	IF_{2019}	*APP*	CPP_{2019}	Web of Science Category
Estuarine Coastal and Shelf Science	412 (3.2)	2.333	3.9	32	Marine and freshwater biology Oceanography
Marine Pollution Bulletin	315 (2.4)	4.049	4.8	24	Environmental science sMarine and freshwater biology
Hydrobiologia	276 (2.1)	2.385	3.0	24	Marine and freshwater biology Ecology
Marine Ecology Progress Series	240 (1.9)	2.326	4.0	41	Marine and freshwater biology Oceanography
Journal of Coastal Research	226 (1.7)	0.793	3.7	13	Environmental sciences Physical geography Multidisciplinary geosciences
PLoS One	157 (1.2)	2.740	6.0	24	Multidisciplinary sciences
Revista De Biologia Tropical	153 (1.2)	0.446	3.1	6.2	Biology
Ocean & Coastal Management	148 (1.1)	2.482	3.8	17	Oceanography Water resources
International Journal of Systematic and Evolutionary Microbiology	131 (1.0)	2.415	5.8	12	Microbiology
Journal of Experimental Marine Biology and Ecology	130 (1.0)	2.247	3.1	30	Ecology Marine and freshwater biology
Aquatic Botany	115 (0.89)	1.710	3.8	29	Plant sciences Marine and freshwater biology
Bulletin of Marine Science	115 (0.89)	1.432	3.4	25	Marine and freshwater biology Oceanography
Wetlands Ecology and Management	115 (0.89)	1.221	4.0	17	Environmental sciences Water resources
Estuaries and Coasts	111 (0.86)	2.319	4.0	16	Environmental sciences Marine and freshwater biology
Indian Journal of Geo-Marine Sciences	104 (0.80)	0.328	3.7	1.9	Oceanography

TP: number of publications; IF_{2019}: journal impact factor in 2019; *APP*: number of authors per publication; CPP_{2019}: number of citations (TC_{2019}) per publication (*TP*).

3.4. Publication Performances: Countries and Institutions

Thirty-four articles (0.26% of 12,955 articles) were excluded in the analysis because they did not include any author affiliation information in SCI-EXPANDED. Of the 12,921 mangrove articles from 151 different countries, 8500 articles (66% of the 12,921 articles) were single-country articles across 95 different countries, while 4421 (34%) articles were international collaborations from 147 different countries. Table 4 listed the top ten productive countries with 500 articles or more. Three American countries, three European countries, three Asian countries, and one country from Oceania were ranked in the top ten in terms of publications number. Interestingly, the number of publications was not consistent with the mangrove area coverage of the individual countries. For example, Indonesia has the world's largest mangrove coverage and ranked 11th in publications number (*TP* = 210). Similarly, Australia and Brazil ranked fourth and fifth in terms of publications number, although their mangrove coverage is greater than the USA, China, or India. Outside of the top ten, South Africa, with 174 articles, ranked 22nd and was the top productive country in Africa. Six publication indicators, the total number of articles (*TP*), single-country articles (*IP*), internationally collaborative articles (*CP*), first-author articles (*FP*), corresponding-author articles (*RP*), and single-author articles (*SP*) [55], as well as their citation indicator (CPP_{2019}) [56], were applied to compare publication performance.

Table 4. Top ten productive countries with *TP* > 500.

Country	*TP*	*TP*		*IP*		*CP*		*FP*		*RP*		*SP*	
		***R* (%)**	CPP_{2019}	***R* (%)**	CPP_{2019}	***R* (%)**	CPP_{2019}	***R* (%)**	CPP_{2019}	***R* (%)**	CPP_{2019}	***R* (%)**	CPP_{2019}
USA	2665	1 (21)	31	2 (16)	32	1 (30)	30	2 (14)	32	2 (14)	32	1 (21)	37
China	2118	2 (16)	17	1 (17)	16	3 (15)	18	1 (15)	16	1 (15)	16	7 (2.8)	28
India	1490	3 (12)	14	3 (14)	12	8 (7.2)	20	3 (10)	13	3 (10)	13	3 (6.1)	13
Australia	1466	4 (11)	31	5 (9.1)	30	2 (16)	33	5 (8.3)	31	5 (8.4)	31	2 (16)	40
Brazil	1335	5 (10)	15	4 (10)	11	6 (10)	21	4 (8.9)	12	4 (8.8)	12	8 (2.7)	12
Japan	707	6 (5.5)	19	6 (3.2)	14	7 (10)	22	6 (3.9)	16	6 (3.9)	16	12 (2.2)	13
Germany	698	7 (5.4)	25	10 (1.7)	27	5 (13)	25	8 (2.8)	24	8 (2.9)	24	5 (3.1)	21
UK	696	8 (5.4)	26	11 (1.4)	26	4 (13)	25	9 (2.6)	29	9 (2.6)	28	4 (4.5)	26
Mexico	528	9 (4.1)	16	7 (3.1)	12	13 (6.0)	20	7 (2.9)	14	7 (2.9)	13	19 (1.2)	28
France	502	10 (3.9)	25	9 (2.2)	22	10 (7.1)	27	11 (2.5)	24	10 (2.5)	24	5 (3.1)	10

TP: total number of articles; *TPR* (%): rank of total number of articles and percentage; *IPR* (%): rank of single-country articles and percentage in all single-country articles; *CPR* (%): rank of internationally collaborative articles and percentage in all internationally collaborative articles; *FPR* (%): rank of first-author articles and percentage in all first-author articles; *RPR* (%): rank of corresponding-author articles and percentage in all corresponding-author articles; *SPR* (%): rank of single-author articles and percentage in all single-author articles; CPP_{2019}: number of citations (TC_{2019}) per publication (*TP*); N/A: not available.

The USA dominated among the three publication indicators with a *TP* of 2665 articles (21% of 12,921 articles), a *CP* of 1344 articles (30% of 4421 internationally collaborative articles), and an *SP* with 204 articles (21% of 964 single-author articles). China also ranked top among the three publication indicators with an *IP* of 1475 articles (17% of 8500 single-country articles), an *FP* of 1921 articles (15% of 12,921 first-author articles), and an *RP* of 1863 articles (15% of 12,812 corresponding-author articles). Comparing the top ten countries, the USA had the highest CPP_{2019} for their total articles, single-country articles, first-author articles, and corresponding-author articles with a CPP_{2019} of 31, 32, 32, and 32, respectively. Australia had the highest CPP_{2019} for their total articles, single-country articles, first-author articles, and corresponding-author articles with a CPP_{2019} of 31, 32, 32, and 32, respectively. Australia had the highest CPP_{2019} for their total articles, internationally collaborative articles, and single-author articles with a CPP_{2019} of 31, 33, and 40, respectively. China ranked second in *TP*, first in *FP*, third in *CP*, first in *FP*, first in *RP*, and seventh in *SP*, but in CPP_{2019} ranked seventh in *TP*, sixth in *FP*, 10th in *CP*, sixth in *FP*, sixth in *RP*, and fourth in *SP*. Figure 4 shows a comparison of the development among the top five productive countries in 2019 with 100 articles or more. The USA, China, India, Australia, and Brazil not only ranked the top five on total publications but also on total publications in 2019. The USA ranked top from 1990 to 2009, while China has ranked top since 2013. A sharp increase was found in China, the USA, and Australia in recent years, ranking first, second, and third in 2019, respectively.

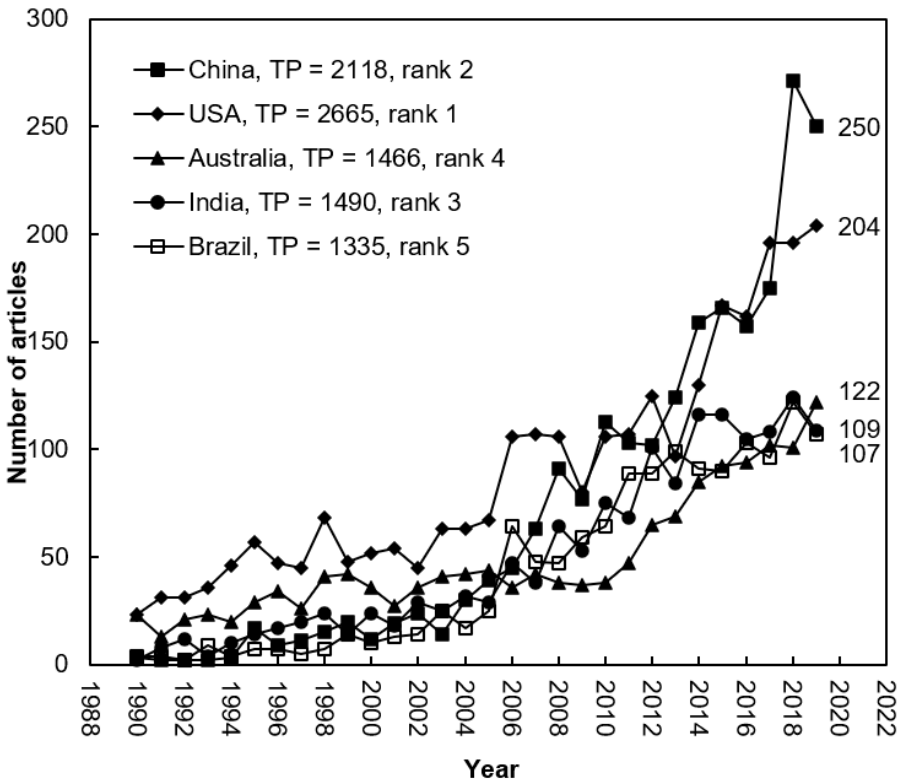

Figure 4. Comparison of development trends among the top five productive countries in 2019.

With regard to institutions, 4273 articles (33% of 12,952 articles) were of a single institution, whereas 8648 articles (67%) were inter-institutionally collaborative. Table 5 demonstrates the characteristics of the top 20 productive institutions with 120 articles or more and six publication indicators [55] and their citation indicator CPP_{2019}. The Chinese Academy of Sciences in China took the leading position for four publication indicators with a *TP* of 473 articles (3.7% of 12,952 articles), a *CP* of 414 articles (4.8% of 8648 inter-institutionally collaborative articles), *FP* with 283 articles (2.2% of 12,952 first-author articles), and an *RP* of 271 articles (2.1% of 12,812 corresponding-author articles).

The Xiamen University in China and the Annamalai University in India took the leading position with an *IP* of 97 articles (2.3% of 4273 single institution articles), respectively. The Australian Institute of Marine Science in Australia ranked top with an *SP* of 18 articles (1.9% of 964 single-author articles). The Australian Institute of Marine Science dominated the CPP_{2019} for their six types of publications: *TP*, *IP*, *CP*, *FP*, *RP*, and *SP*. The National Autonomous University of Mexico had lower CPP_{2019} for their total articles (CPP_{2019} = 12), inter-institutionally collaborative articles (CPP_{2019} = 12), first-author articles (CPP_{2019} = 11), and corresponding-author articles (CPP_{2019} = 11). A bias appeared because the Chinese Academy of Sciences has over 100 branches in different cities [57]. At present, the publications of the institute were pooled as one heading and publications divided into branches would result in different rankings.

3.5. The Most Frequently Cited Articles and the Most Impact Articles in 2019

Highly cited publications would not always have high impact or visibility after publication [53]. The number of citations received in the most recent year of 2019 (C_{2019}) might provide additional information for readers to understand the impact of a highly cited article today [28]. The 12,955 mangrove articles ranked differently if sorted by TC_{2019} than sorted by C_{2019}. A total of 4256 articles (33% of 12,955 articles) had no citation in the most recent year (C_{2019} = 0), and 1343 (10%) articles had no citation from their publication year to the end of 2019 (TC_{2019} = 0). Furthermore, among the top 100 C_{2019} articles, 52% of the articles were among the top 100 TC_{2019} articles.

The 12,955 mangrove-related articles were searched out with search keywords in their title, abstract, and author keywords from SCI-EXPANDED in the last three decades. A total of 7495 articles (58% of 12,955 articles), 11,947 articles (94% of 12,752 articles with an abstract), and 5523 articles (53% of 10,508 articles with author keywords) contained search keywords in their title, abstract, and author keywords, respectively. The title of an article is a label that supplies reasonable details of the article's subjects [58]. Author keywords are given by authors to offer more information about the main research focused on by articles. Articles that contain search keywords only in their abstract might not relate to the search topic directly. The ten of the top 20 articles on TC_{2019} contained search keywords in their abstract only. Typical examples, including articles by Waycott et al. [59], Chave et al. [60], Loarie et al. [61], and Knowlton and Weigt [62], ranked first with a TC_{2019} of 1535, second with a TC_{2019} of 1376, third with a TC_{2019} of 1031, and 10th with a TC_{2019} of 601, respectively. Citation histories of the top ten most frequently cited articles with search keywords in their title or author keywords are presented in Figure 5. An article by Giri et al. [2] ranked at the top on annual citations from 2014 to 2019 in mangrove research. Articles entitled "Mangroves among the most carbon-rich forests in the tropics" [6] with a C_{2019} of 171 (ranked third) had high impact in recent years.

Table 6 shows the top ten most frequently cited articles with TC_{2019} > 330. The top ten articles were published by 40 institutes from 16 countries. The USA published six of the top ten most frequently cited articles, followed by Australia (5 articles), Canada (2), China (2), Indonesia (2), the UK (2), and one each by Belgium, Finland, India, Japan, Kenya, Malaysia, Mexico, Philippines, Singapore, and Vietnam, respectively. The University of Queensland (Australia) published four of the top ten most frequently cited articles, followed by the Australian Institute of Marine Science (Australia) and the U.S. Geological survey (USA), which published two top ten articles, respectively. Six articles with search keywords in their title or author keywords were ranked on both the top 16 TC_{2019} as the most frequently cited articles and C_{2019} as the most impact in the most recent year articles. These six highly cited and most impactful articles among 2019 articles are summarized as followed:

i. Status and distribution of mangrove forests of the world using earth observation satellite data [2]

Table 5. Top 20 productive institutions (*TP* > 120).

Institute (Country)	TP	TPR (%)	TP CPP	IPR (%)	IP PP	CPR (%)	CP CPP	FPR (%)	FP CPP	RPR (%)	RP CPP	SPR (%)	SP CPP
Chinese Academy of Sciences (China)	473	1 (3.7)	18	3 (1.4)	20	1 (4.8)	18	1 (2.2)	19	1 (2.1)	19	87 (0.21)	3.0
Sun Yat Sen University (China)	318	2 (2.5)	15	3 (1.4)	20	2 (3.0)	14	2 (1.8)	15	3 (1.6)	16	N/A	N/A
Xiamen University (China)	307	3 (2.4)	15	1 (2.3)	13	4 (2.4)	16	3 (1.8)	14	2 (1.8)	14	156 (0.10)	3.0
University of Sao Paulo (Brazil)	248	4 (1.9)	14	26 (0.56)	9.3	3 (2.6)	15	8 (0.81)	13	6 (0.86)	13	47 (0.31)	6.7
University of Queensland (Australia)	226	5 (1.7)	36	18 (0.66)	32	5 (2.3)	37	7 (0.83)	36	7 (0.84)	36	14 (0.83)	26
City University of Hong Kong (China)	205	6 (1.6)	34	8 (1.0)	44	7 (1.9)	32	5 (0.89)	41	4 (1.0)	38	87 (0.21)	33
National University of Singapore (Singapore)	186	7 (1.4)	21	5 (1.4)	26	10 (1.5)	20	6 (0.85)	23	8 (0.84)	21	3 (1.2)	11
U.S. Geological Survey (USA)	184	8 (1.4)	47	45 (0.40)	27	6 (1.9)	49	18 (0.58)	54	15 (0.61)	53	47 (0.31)	64
Florida International University (USA)	183	9 (1.4)	44	14 (0.82)	51	8 (1.7)	42	12 (0.65)	43	14 (0.62)	44	28 (0.41)	33
Annamalai University (India)	170	10 (1.3)	20	1 (2.3)	18	32 (0.84)	22	4 (0.97)	17	5 (0.94)	18	9 (0.93)	24
University of Malaya (Malaysia)	166	11 (1.3)	16	7 (1.2)	16	12 (1.3)	17	10 (0.73)	13	11 (0.7)	13	47 (0.31)	29
National Autonomous University of Mexico (Mexico)	166	11 (1.3)	12	16 (0.70)	14	9 (1.6)	12	12 (0.65)	11	12 (0.67)	11	28 (0.41)	23
Griffith University (Australia)	155	13 (1.2)	29	19 (0.63)	35	10 (1.5)	28	15 (0.60)	33	15 (0.61)	34	14 (0.83)	75
University of Hong Kong (China)	149	14 (1.2)	26	11 (1.0)	29	14 (1.2)	24	14 (0.64)	27	13 (0.66)	27	2 (1.7)	33
Australian Institute of Marine Science (Australia)	149	14 (1.2)	57	6 (1.3)	67	20 (1.1)	52	11 (0.71)	60	9 (0.74)	60	1 (1.9)	102
University of Calcutta (India)	146	16 (1.1)	16	13 (0.87)	19	13 (1.3)	15	9 (0.73)	17	10 (0.73)	17	N/A	N/A
University of Ryukyus (Japan)	130	17 (1.0)	17	19 (0.63)	20	16 (1.2)	16	24 (0.45)	18	20 (0.48)	17	N/A	N/A
James Cook University (Australia)	124	18 (1.0)	33	39 (0.42)	15	15 (1.2)	36	27 (0.42)	48	26 (0.42)	48	28 (0.41)	19
Ocean University of China (China)	123	19 (0.95)	17	17 (0.68)	26	24 (1.1)	14	16 (0.59)	17	19 (0.50)	17	N/A	N/A
Federal University of Parana (Brazil)	121	20 (0.93)	15	21 (0.61)	12	20 (1.1)	16	16 (0.59)	13	17 (0.56)	14	N/A	N/A

TP: total number of articles; *TPR* (%): rank of total number of articles and percentage; *IPR* (%): rank of single-institute articles and percentage in all single-institute articles; *CPR* (%): rank of inter-institutionally collaborative articles and percentage in all inter-institutionally collaborative articles; *FPR* (%): rank of first-author articles and percentage in all first-author articles; *RPR* (%): rank of corresponding-author articles and percentage in all corresponding-author articles; *SPR* (%): rank of single-author articles and percentage in all single-author articles; *CPP*: number of citations (TC_{2019}) per publication (*TP*); N/A: not available.

Table 6. The top ten most frequently cited articles with $TC_{2019} > 330$.

Rank (TC_{2019})	Rank (C_{2019})	Title	Country	Reference
4 (856)	2 (179)	Status and distribution of mangrove forests of the world using earth observation satellite data	USA, Kenya, Australia	[2]
5 (821)	9 (97)	Present state and future of the world's mangrove forests	Australia	[1]
6 (805)	12 (85)	Mangrove forests: One of the world's threatened major tropical environments	USA	[63]
7 (793)	3 (171)	Mangroves among the most carbon-rich forests in the tropics	USA, Indonesia, Finland	[6]
8 (643)	26 (48)	Mangroves enhance the biomass of coral reef fish communities in the Caribbean	UK, Mexico, USA, Canada	[64]
9 (634)	8 (103)	Global carbon sequestration in tidal, saline wetland soils	Canada, USA	[15]
16 (428)	10 (88)	The loss of species: Mangrove extinction risk and geographic areas of global concern	USA, UK, Australia, Philippines, India, Belgium, Japan, Vietnam, Malaysia, Indonesia, China, Singapore	[65]
18 (385)	62 (29)	Spatial variation of heavy metals in surface sediments of Hong Kong mangrove swamps	China	[66]
20 (357)	39 (40)	Factors influencing biodiversity and distributional gradients in mangroves	Australia	[67]
21 (331)	104 (22)	Why do juvenile fish utilise mangrove habitats?	Australia	[68]

TC_{2019}: the total number of citations from the Web of Science Core Collection since publication year to the end of 2019; C_{2019}: the number of citations of an article in 2019 only.

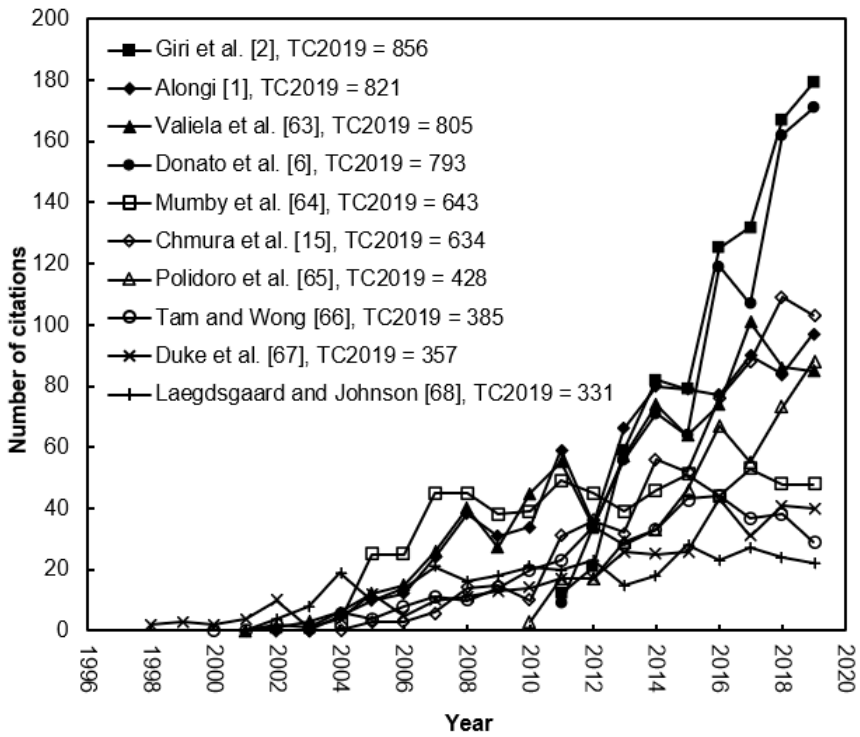

Figure 5. The citation life of the top ten most frequently cited articles with $TC_{2019} > 330$.

This article was published by eight authors from five institutes: the U.S. Geological survey (USA), United Nations Environment Programme (Kenya), United Nations Environment Programme (USA), National Aeronautics and Space Administration (USA), and the University of Queensland (Australia) with a TC_{2019} of 856 (ranked fourth) and C_{2019} of 179 (ranked second). In the paper, the authors mapped the global distribution and status of mangroves using data from the Global Land Survey (GLS) and satellite observations. Apart from identifying the extent of mangroves, the authors also found that 75% of the world's mangroves are located in just 15 countries, of which only about 7% are protected under the existing protected area networks (IUCN category I-IV). Using consistent and high resolution (30 m) satellite images, the authors also confirmed that the global coverage of mangroves is 12.3% less than previously thought, a large proportion of which is found between 5° N and 5° S latitude.

ii. Present state and future of the world's mangrove forests [1]

This article by Alongi from the Australian Institute of Marine Science with a TC_{2019} of 821 (ranked fifth) and a C_{2019} of 97 (ranked ninth) presents a comprehensive review of mangrove ecosystems, their management, and their threats. The author indicated human pressure as the major threat to mangroves worldwide, followed by urban development, aquaculture, mining, overexploitation for timber, and aquatic resources such as fish, crustaceans, and shellfish. The authors also predicted the future of mangroves until 2025 and found it to be optimistic, as the number of mangrove rehabilitation and restoration projects increased locally, with some countries expanding their area coverage of mangroves. The author concluded that after 2025, the management of mangroves will depend on technological and ecological advances such as silviculture, genetic improvements of species, and forestry modelling, although the reduction of human pressure will remain the key priority.

iii. Mangrove forests: One of the world's threatened major tropical environments [63]

This article was published by three authors from the Boston University (USA) with a TC_{2019} of 850 (ranked sixth) and a C_{2019} of 85 (ranked 12th). In their article, the authors estimated the global mangrove area losses from various human activities to be around 36×10^3 km^2. The magnitude and relative contributions of various human activities to

such losses were, however, different across continents. Overall, the percentage losses of mangrove area increased as per capita GNP increased. Mariculture, or more specifically shrimp culture, plays a significant role in reducing mangrove forest area in many tropical countries. The authors also found that, globally, the increase of mangrove forest area from restoration and natural re-growth is still negligible when compared with mangrove area losses.

iv. Mangroves among the most carbon-rich forests in the tropics [6]

This article was published by six authors from three institutes: the USDA Forest Service (USA), Center for International Forestry Research (Indonesia), and University of Helsinki (Finland) with a TC_{2019} of 793 (ranked seventh) and a C_{2019} of 171 (ranked third), and it provides a comprehensive whole-ecosystem carbon budget of the mangrove ecosystem using data from 25 mangrove forest sites distributed across the Indo-Pacific region. In their study, the authors used 10 estuarine and 15 oceanic mangrove forest sites and found a mean carbon storage of 1074 Mg C ha^{-1} and 990 Mg C ha^{-1}, respectively, in estuarine and coastal sites. The authors, based on their global assessment, found that mangroves are amongst the most carbon-rich forests in the tropics, with an average carbon density of 1023 Mg C ha^{-1}. Their study also suggests that below-ground carbon accounts for 71–98% and 49–90% of the total storage in estuarine and oceanic sites, respectively. Below-ground carbon (stored in the top 30 cm of soil) also represents the most vulnerable pool of carbon to land-use change in mangrove ecosystems.

v. Global carbon sequestration in tidal, saline wetland soils [15]

This article was published by four authors from four institutes: McGill University (Canada), Yale University (USA), and the U.S. Geological Survey (USA) with a TC_{2019} of 635 (ranked ninth) and a C_{2019} of 103 (ranked eighth). In their study, Chmura et al. [15] compiled data for 154 mangrove and salt marsh sites from the Atlantic and Pacific coasts, as well as the Indian Ocean, Mediterranean Sea, and Gulf of Mexico. The authors found the average soil carbon density of mangrove swamps significantly higher than salt marshes, which declines with increasing average annual temperature. They estimated the carbon sequestration by mangroves and salt marshes to be around 44.6 Tg C yr^{-1} globally. Carbon sequestration rates were not significantly different between mangroves and salt marshes, and variability in sediment accumulation rates was found to be a major control of carbon sequestration.

vi. The loss of species: Mangrove extinction risk and geographic areas of global concern [65]

This article was published by 21 authors from 19 institutes: Old Dominion University (USA), Nature Conservancy (USA), University of Plymouth (the UK), the University of Queensland (Australia), Harvard University (USA), University of Tasmania (Australia), New England Wild Flower Society (USA), University of Philippines (Philippines), Annamalai University (India), Vrije University of Brussel (Belgium), Tohoku Gakuin University (Japan), University of New Hampshire (USA), Nong Lam University (Vietnam), University of Sains Malaysia (Malaysia), Southeast Asian Fisheries Development Center (Philippines), Central Luzon State University (Philippines), Indonesian Institute of Sciences (Indonesia), Shandong University (China), and Nanyang Technological University (Singapore) with a TC_{2019} of 428 (ranked 16th) and a C_{2019} of 88 (ranked 10th). In their article, the authors compiled species-specific information on global distribution, population status, life history traits, and major threats for each of the 70 true mangrove species. Each species' probability of extinction was also assessed using the IUCN Red List of Threatened Species criteria. It was found that 11 of the 70 mangrove species are facing the risk of extinction. The Atlantic and Pacific coasts of Central America are particular areas of geographical concern, where as many as 40% of the known mangrove species are threatened with extinction.

3.6. Research Foci and Their Trends

Ho's group proposed a distribution of words in article titles, abstracts, author keywords, and *KeyWords Plus* in different time periods as information to evaluate the main research foci and find their development trends in research topics [69,70]. Accordingly, we examined keywords in article titles, abstracts, author keywords, and *KeyWords Plus* and ranked them according to the whole study duration and 10-year study period (Supplementary Materials A, B, and C). Table 7 below represents the 25 most frequently used author keywords according to their ranking. Except for searching the keywords, mangrove and mangroves, salinity was found to be the most-frequently used author keyword (in 224 articles; 2.1% of total 10,508 articles in 1992–2019), followed by estuary (218; 2.1%), climate change (215; 2.0%), and *Avicennia marina* (207; 2.0%). The author keyword "blue carbon" appeared in the last decade only. Four blue carbon related mangrove articles were published in 2012, including two highly cited articles with a TC_{2019} of 100 or more [36]: "Seagrass ecosystems as a globally significant carbon stock" [71] with a TC_{2019} of 565 (rank 11th) and a C_{2019} of 116 (rank seventh) and "Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems" [72] with a TC_{2019} of 462 (rank 12th) and a C_{2019} of 120 (rank sixth). Quite interestingly, remote sensing emerged as a popular keyword used in mangrove-related studies in recent years and is positioned immediately after mangroves. In 2011, a remote sensing article by Giri et al. [2] had a TC_{2019} of 856 (rank fourth) and a C_{2019} of 179 (rank second). Our findings are also coherent with the findings reported in Sharma [73].

Table 7. Top 25 author keywords in publications related to mangroves.

Author Keywords	*TP*	1990–2019 Rank (%)	1990–1999 Rank (%)	2000–2009 Rank (%)	2010–2019 Rank (%)
mangrove	2079	1 (20)	1 (25)	1 (22)	1 (18)
mangroves	1381	2 (13)	2 (21)	2 (15)	2 (11)
salinity	224	3 (2.1)	3 (3.7)	3 (2.4)	8 (1.8)
estuary	218	4 (2.1)	28 (1.2)	4 (2.3)	4 (2.1)
climate change	215	5 (2.0)	63 (0.78)	133 (0.41)	3 (2.9)
Avicennia marina	207	6 (2.0)	6 (2.4)	4 (2.3)	9 (1.8)
remote sensing	198	7 (1.9)	33 (1.1)	9 (1.7)	5 (2.1)
mangrove forest	197	8 (1.9)	33 (1.1)	6 (2.1)	7 (1.9)
taxonomy	182	9 (1.7)	8 (2.0)	34 (1.0)	6 (2.0)
sediment	172	10 (1.6)	25 (1.3)	13 (1.6)	10 (1.7)
conservation	155	11 (1.5)	13 (1.7)	11 (1.6)	13 (1.4)
Rhizophora mangle	150	12 (1.4)	5 (2.5)	8 (1.8)	18 (1.1)
biodiversity	148	13 (1.4)	75 (0.67)	28 (1.1)	12 (1.6)
seagrass	142	14 (1.4)	28 (1.2)	15 (1.6)	14 (1.3)
heavy metals	131	15 (1.2)	33 (1.1)	19 (1.3)	16 (1.2)
stable isotopes	131	15 (1.2)	191 (0.34)	17 (1.5)	15 (1.3)
Avicennia germinans	124	17 (1.2)	17 (1.6)	7 (1.9)	31 (0.85)
fish	118	18 (1.1)	63 (0.78)	23 (1.2)	17 (1.1)
blue carbon	117	19 (1.1)	N/A	N/A	10 (1.7)
brazil	109	20 (1.0)	41 (1.0)	10 (1.7)	36 (0.8)
sediments	109	20 (1.0)	21 (1.5)	23 (1.2)	27 (0.93)
diversity	108	22 (1.0)	25 (1.3)	43 (0.85)	20 (1.1)
Australia	107	23 (1.0)	8 (2.0)	15 (1.6)	49 (0.68)
Rhizophora	106	24 (1.0)	4 (2.9)	21 (1.3)	53 (0.67)
nutrients	104	25 (1.0)	7 (2.1)	18 (1.4)	46 (0.69)

TP: total number of articles; N/A: not available.

The results of our keyword analyses provide information about the main and possible research foci based on word cluster analysis, where a serious synonymic single word and the congeneric phrases from the results of words analysis were summed up, which could represent the possible research hotspots related to a field [74]. Each word cluster is composed of several supporting words [21]. Thus, the five possible main research foci

related to mangroves are Rhizophora, climate change, remote sensing, biodiversity, and blue carbon. Figure 6 shows the development trends of research on these topics.

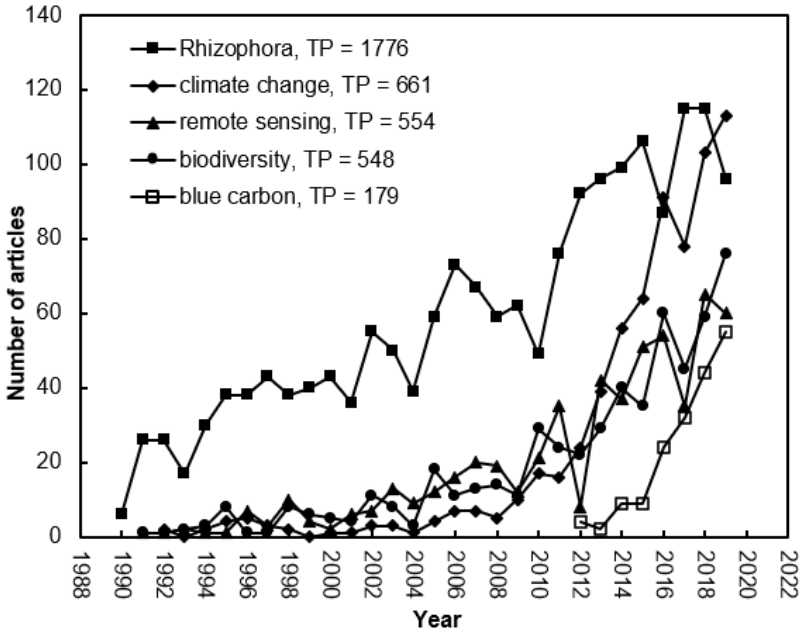

Figure 6. Development trends of the five main research foci of mangroves.

Rhizophora (with supporting words: *Rhizophora mangle*, Rhizophoraceae, and Rhizophorae) emerged in our word cluster analysis and author keyword search both as *Rhizophora mangle* (12th position, *TP* = 150) and Rhizophora (24th position, *TP* 106). Rhizophora appeared also in our words in title (27th position, *TP* = 370) as well as abstract (30th position, *TP* = 1459) searches. Rhizophora represents a major genus of true mangroves and mangrove trees. The most notable species of Rhizophora is–*Rhizophora mangle*, also known as red mangrove [8]. Many species of Rhizophora can easily grow and be dispersed by water. Therefore, they are commonly used for mangrove restoration and vertical expansion of estuarine mangrove ecosystems throughout the tropics and sub-tropics [8].

Climate change (and climate changes) emerged in our word cluster analysis (Figure 6) and in the top 25 in author keywords (fifth position, *TP* 215) and the *KeyWords Plus* (13th position, *TP* 378) searches. Climate change is a global phenomenon, and it is affecting mangroves in many ways [75]. Climate change and the resulting sea-level rise are likely to affect the aerial extent of mangroves and species diversity [18]. Climate change will also cause more frequent catastrophic events such as cyclones (synonymous with hurricanes and typhoons), tidal surges, and floods, affecting mangrove forests globally [4]. In recent years, mangroves are also recognized for their potential role in climate change mitigation, as they store more carbon than any other terrestrial ecosystems [6].

Remote sensing, as already mentioned, has been gaining increasing attention from mangrove researchers in recent years, although there is evidence of past research too (Figure 6). Remote sensing (with supporting words: remote sensed and landsat) emerged in our word cluster analysis and in the top 25 in the author keywords (seventh position, *TP* = 198) search. With the advancement of science and easy access to satellite imagery, remote sensing is progressively becoming a new tool for monitoring changes in mangroves and vegetation dynamics such as changes in species composition, forest structure, area, etc. [16,76]. As ground-based surveys in mangrove forests are often difficult, costly, and time-consuming, remote sensing also offers scientists an alternative way to study mangroves, the temporal change effects of catastrophic events on mangrove forests, etc. [2,76].

Biodiversity (with supporting words: biodiversidad and biodiversities) appeared both in our word cluster analysis and in the top 25 in the author keywords (13th position,

TP = 148) search. Other keywords, such as diversity and conservation, found in our author keywords and *KeyWords Plus* searches may also be related to biodiversity. Mangroves are recognized for their exceptionally high biodiversity, both terrestrial and aquatic [8,64]. The aquatic (including marine) biodiversity of mangroves is a major source of livelihood and protein in tropical developing countries [9]. Because of their position in the interface between coastal and terrestrial ecosystems, mangroves provide a wide array of habitats to wildlife and encompass a self-sustaining food web that includes large and small mammals, birds, reptiles, insects, fishes, and crustaceans such as crabs and shrimps [75]. Mangrove biodiversity is also on the verge of extinction due to overexploitation, unplanned coastal development, climate change and the resulting sea-level rise, etc. [10,18].

Blue carbon (with supporting words: blue carbon ecosystem, blue carbon sinks, blue carbon stocks, coastal blue carbon, and blue carbon emissions) emerged both in our word cluster analysis and in the top 25 in the author keywords (19th position, *TP* = 117) search, although it appeared in mangrove-related articles only in the last decade. "Blue carbon" is still an emerging concept, and it is the term used for carbon captured by coastal and ocean ecosystems, mostly mangroves, salt marshes, seagrasses, and macroalgae [72]. As already mentioned, mangroves can absorb carbon from the atmosphere as much as 40 × faster than terrestrial ecosystems. Therefore, they are widely promoted as a cost-effective climate change mitigation measure [13,14,17]. Besides climate change mitigation, blue carbon also offers livelihood and economic opportunities for coastal communities, including climate change adaptation [10].

4. Conclusions

Mangroves are increasingly recognized for their diverse social, environmental, and economic benefits. They also provide essential ecosystem services, so significant losses of mangrove forests will have important consequences. Our bibliometric study has brought together the knowledge on publications related to mangroves and mangrove forests that are available from the Web of Science database from the period of 1990 to 2019. We performed Science Citation Index Expanded (SCI-EXPANDED) analysis of 12,955 publications to visualize publication patterns that include the most prominent authors, institutions, countries, research categories, and journals. A total of 93% of the published documents were articles, followed by proceedings papers (4.6%). When considering the most productive Web of Science subject category, the majority of the articles that were found belong to marine and freshwater biology, followed by environmental sciences, ecology, oceanography, and plant sciences. The USA and China were the leading countries in ranking, according to the number of publications on mangroves. The articles published by the USA and Australia, however, had higher impact in the research.

We also identified the most impactful articles on mangrove forests by using updated citation parameters, where instead of relying only on total citations, we also considered recent citations. Research hotspots on the basis of our bibliometric study were identified, especially after analyzing words in author keywords, article titles, abstracts, and *KeyWords Plus*. Leading articles and institutions working on mangroves were also identified. These indicators are intended to facilitate researchers in the analysis of existing literature, which could improve the research direction for better scientific contribution. Our bibliometric study also identified emerging fields of research, researchers, and institutions useful in facilitating potential venues for future research, collaboration, and knowledge exchange on mangrove forests.

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