

A Characterization of Fire-Management Research: A Bibliometric Review of Global Networks and Themes

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Abstract: Although humans have interacted with wildfires for millennia, a science-based approach to fire management has evolved in recent decades. This paper reviews the development of fire-management research, focusing on publications that use this term in their title, abstract, or keywords identified on the Scopus platform. This resulted in the identification of 5624 documents published between 1973 and 2021. Publication rates have particularly increased since 2010. The paper details the characteristics of this body of the literature, including the main authors, institutions, and countries. Furthermore, it considers the bibliographic networks, main research foci, and the publications' study areas. First, these analyses provide researchers interested in fire management an overview of the field and its most prominent sources, authors, and publications. Second, they invite reflection on the current state of fire-management research. In particular, the considerable disparities in spatial foci and countries of authorship suggest that the challenges of today's problems in fire management are more likely to be overcome with a more balanced global research effort.

Keywords: wildfire management; vegetation fire; wildland fire; network analysis; citation analysis; bibliographic review; bibliometric database



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1. Introduction

Fire has been present on Earth, almost since the appearance of burnable fuel provided by terrestrial plants, and is a crucial element in many ecosystems. However, through the disruption of natural-fire regimes caused by human activities and, more recently, the effects of climate change, fire is now one of the most significant challenges in environmental conservation [1–4]. Furthermore, it presents a risk to society in many areas, damaging infrastructure and threatening human lives, both directly and indirectly, through the effects of smoke [5–7]. Particularly vulnerable in this context is the wildland–urban interface of cities in fire-prone areas; the size and population of these areas has increased over the last decades [8]. In addition, wildfires cause the release of greenhouse-gas emissions and exacerbate climate change [9].

Therefore, it is of the utmost importance to manage fire adequately, based on thorough multi-disciplinary scientific research. This implies producing knowledge on fire ecology and behavior as well as constant monitoring of fire occurrence and effects, a regular revision of management approaches, and exploration of new techniques [10–13]. Fire management is not only limited to fire suppression but also includes various activities, such as fire-prevention measures and the application of prescribed burning in areas of fire-prone vegetation [14,15]. In many places, it also comprises the traditional burning practices of the local communities [16,17].

A growing body of research on these themes has evolved in recent years. Several reviews synthesized the results of studies on a particular aspect of fire management, e.g., fuel loading [18], prescribed burning [19], or decision-making [20], or have adopted a specific perspective, such as resilience theory [10]. These reviews generally consider a

selection of studies, analyzing them regarding their content. Our study, on the contrary, proposes to consider fire-management research as a whole and to describe it based on methods from bibliometric research, using quantitative methods focused on the production and development of the academic literature. These techniques aim to show the tendencies and structures in distinct spatial and temporal scales, regarding a specific subject of scientific research [21–23].

This kind of analysis consists of identifying variables within publications, which can be divided into the following categories of focus: personal, productivity, citation, content, and methodological [24,25]. Two types of analysis are used. The first relates to evaluation of performance based on scientific production metrics; the second focuses on bibliometric mapping. The end result is a visual representation of the publications' dynamics and structure, from applying network-analysis techniques [23,26]. Through these techniques, it is possible to obtain parameters on the role of specific authors within a field and the relevance of countries, institutions, and journals [27,28]. Studies offering a particular perspective on the spatial characteristics of publications have gained ground in recent years [29–31]. This paper follows these novel approaches and further advances the graphic representation of the publications' spatial foci, including the main study areas, integrating the data in a geographic-information system.

By applying these techniques, we provide an overview of the development and characteristics of fire-management research on a global scale. Thus, we offer researchers in the field a comprehensive outlook on the larger context of their studies and give academics new to fire management the possibility to identify the main research themes and the most prominent sources, authors, and publications. Moreover, it can be the starting point for a critical reflection and discussion of the current state of fire-management research.

2. Materials and Methods

Bibliometric research has evolved progressively, thanks to the development of information technology. This way, ever greater quantities of data can be managed and processed [22]. In this context, specific software stands out, such as Bibexcel [32] and Bibliometrix [33]. Although both programs offer practical tools for managing and analyzing large amounts of bibliometric data, the data visualization of the results is rather rudimentary. Complementary software can resolve this issue, considering programs such as VOSviewer [34], Pajek, or Gephi [35].

The present paper follows the advances from previous studies in bibliometric research. It retrieved data in BibTeX format from the Scopus database [36], which offers detailed information on publications in indexed journals [27]. Data can be selected using Boolean search terms. The search term applied ("*fire management"; the "*" sign permits it to include closed compounds such as wildfire and bushfire) was designed to be as simple as possible, in order not to bias the selection regarding the thematic focus of the research. The search was carried out in January 2022 and included all studies which contain this term within their title, abstract, or keywords (Query: (TITLE-ABS-KEY ("*fire management") AND (EXCLUDE (PUBYEAR, 2022))). Publications from 2022 were excluded to give a full account of the publications per year, for all years considered in the study.

The first step of data processing used the Bibliometrix package embedded in the R Studio software to give a panorama of authors, publications, institutions, and countries and their impacts within the field of research. Further analyses relied on specialized software for network analysis. Gephi allowed us to obtain centrality metrics of the authors, countries, and calculations regarding the network structure and density.

Scopus includes data on the countries where the authors are based. However, there is no information on the studies' spatial focus. In order to obtain an approximate result on this aspect, a manual search on Scopus was applied, including the names of the world's countries (Query: TITLE-ABS-KEY ("*fire management") AND TITLE-ABS-KEY ("name of the country") AND (EXCLUDE (PUBYEAR, 2022))). The resulting data were integrated into a geographic information system and visualized using QGIS software.

Furthermore, an analysis of keywords was applied using the online software Word Art [37], which provides a measure of the frequency of keyword use within the documents and a thematic grouping of the keywords.

3. Results

3.1. Development of Fire-Management Research

The Scopus search resulted in 5624 publications on fire management, with the first records dating from 1973; thus, the total period covers 49 years (Table 1). However, before the beginning of the 21st century, the number of publications was relatively low, with only 7.2% dating from 1973 to 1999 (see Figure 1). The yearly number of publications started to rise in the mid-1990s. Since then, there has been a steady increase. More than two-thirds (68.3%) of the documents are from 2010 to 2021. In 2003, more than 100 publications were identified. The year with the highest number of documents (507) was 2021. Most of the documents (82.8%) were research articles, followed by proceedings from scientific conferences (7.0%), revisions (5.9%), and book chapters (2.0%). The increase in fire-management publications has been slightly higher than the general growth of scientific publications. Comparing the years 2011 and 2021, for instance, the yearly number of publications on fire management increased by 48.9%, while scientific production in general, according to data from the SciVal platform of Scopus [38], increased by 45.7%.

Table 1. Meta information of the database.

Description	Results
Period of study	1973–2021
Sources (journals, books, etc.)	1327
Total number of publication items	5624
Average years from publication	10.2
Average citations per documents	24.34
Scopus keywords	16,270
Author's keywords	11,527
Authors	13,037
Author appearances	21,711
Authors of single-authored documents	623
Authors of multi-authored documents	12,414
Single-authored documents	773
Documents per Author	0.431
Authors per document	2.32
Co-authors per document	3.86
Collaboration Index	2.56

Elaboration on Bibliometrics based on data from Scopus.

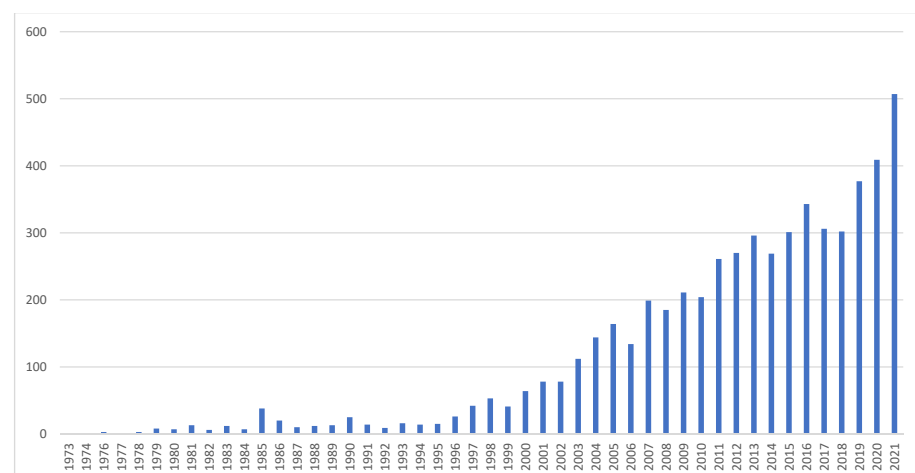


Figure 1. Scientific production on fire management indexed in Scopus per year (1973–2021).

A total of 1327 different sources have published works on fire management. The *International Journal of Wildland Fire* stands out with 307 publications, followed by *Forest Ecology and Management* with 270 publications (Figure 2). Together these two sources make up about 11% of all selected documents. *Fire Ecology* and the *Journal of Environmental Management* follow, with 97 publications each. Journals on forestry, environmental management, and ecology dominate the field. Besides the *International Journal of Wildland Fire* and *Fire Ecology*, another journal focused on fire research, which has gained ground in recent years, is *Fire*. From its foundation in 2018 till 2021, it has published 51 articles related to fire management, making it the fourth-most-productive source over this period.

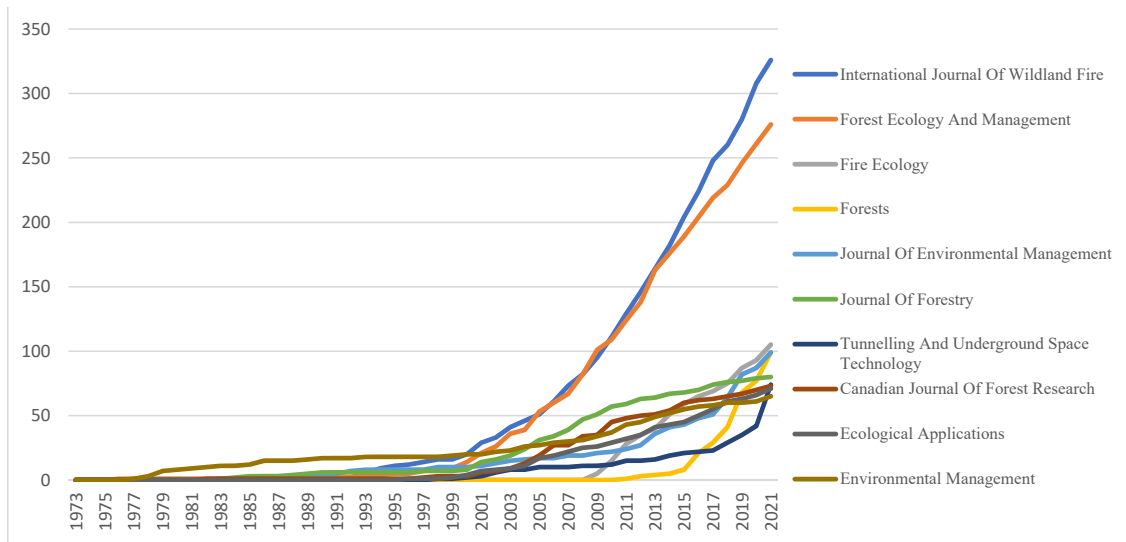


Figure 2. Yearly number of publications of the 10 main sources on fire management indexed in Scopus (1973–2021).

The published documents were cited 256,644 times by other publications indexed in Scopus. The most-cited sources were *Forest Ecology and Management* with 13,801 citations and the *International Journal of Wildland Fire* with 12,170 citations. However, the most-cited document was published in the journal *Science* in 2009, by a group of authors headed by David Bowman, with the title “Fire in the Earth System” [2]. Its number of citations in Scopus by 2021 ascended to 2358 in total, with 1666 citations by other publications on fire management, almost doubling the number of the second-most-cited publication within this scope, by Agee and Skinner (885 citations by 2021) [14]. Table 2 shows the remainder of the 20 most-influential publications in the field of fire management; together with Bowman et al. (2009) and Agee and Skinner (2005), they make up 4.9% of all citations of the selected 5624 documents.

Table 2. Most-influential publications on fire management by number of citations registered in Scopus (1973–2021).

Authors	Year	Title	Source Title	Citations by Other Fire Management Publications
Bowman et al. [2]	2009	Fire in the Earth system	<i>Science</i>	1666
Agee and Skinner [14]	2005	Basic principles of forest fuel reduction treatments	<i>Forest Ecology and Management</i>	885
Paul et al. [39]	2002	Change in soil carbon following afforestation	<i>Forest Ecology and Management</i>	832
Flannigan et al. [40]	2005	Future area burned in Canada	<i>Climatic Change</i>	608
Bowman et al. [41]	2011	The human dimension of fire regimes on Earth	<i>Journal of Biogeography</i>	591
Dennison et al. [42]	2014	Large wildfire trends in the Western United States, 1984–2011	<i>Geophysical Research Letters</i>	584

Table 2. Cont.

Authors	Year	Title	Source Title	Citations by Other Fire Management Publications
Lentile et al. [43]	2006	Remote sensing techniques to assess active fire characteristics and post-fire effects	<i>International Journal of Wildland Fire</i>	582
Marlon et al. [44]	2008	Climate and human influences on global biomass burning over the past two millennia	<i>Nature Geoscience</i>	529
Lindenmayer et al. [45]	2006	General management principles and a checklist of strategies to guide forest biodiversity conservation	<i>Biological Conservation</i>	482
Stocks et al. [46]	1998	Climate change and forest fire potential in Russian and Canadian boreal forests	<i>Climatic Change</i>	468
Mckenzie et al. [47]	2004	Climatic change, wildfire, and conservation	<i>Conservation Biology</i>	454
Keeley et al. [48]	2011	Fire in Mediterranean ecosystems	<i>Ecology, Evolution and Management</i>	438
Wan et al. [49]	2001	Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis	<i>Ecological Applications</i>	431
Lal [50]	2004	Carbon sequestration in dryland ecosystems	<i>Environmental Management</i>	429
Fernandes and Botelho [19]	2003	A review of prescribed burning effectiveness in fire hazard reduction	<i>International Journal of Wildland Fire</i>	417
Moody and Field [51]	2000	Perfluorinated surfactants and the environmental implications of their use in fire-fighting foams	<i>Environmental Science & Technology</i>	417
Flannigan et al. [3]	2009	Impacts of climate change on fire activity and fire management in the circumboreal forest	<i>Global Change Biology</i>	415
Nepstad et al. [52]	2001	Road paving, fire regime feedbacks, and the future of Amazon forests	<i>Forest Ecology and Management</i>	409
Syphard [53]	2007	Human influence on California fire regimes	<i>Ecological Applications</i>	396
Andersen et al. [54]	2005	Estimating forest canopy fuel parameters using LIDAR data	<i>Remote Sensing of Environment</i>	393

Moreover, it is notable that 17 of the 20 most-influential publications were published in the first decade of the 21st century, suggesting that this period was particularly fruitful for scientific innovations in fire management. The oldest publication on the list was published just two years before the turn of the millennium, in 1998. Thus, none of the documents published between 1973 and 1997 reached the list in Table 2.

3.2. Authorship

The author with the highest number of publications within the scope of this paper is David M. J. S. Bowman, from the University of Tasmania, with a count of 60, followed by two USFS-based researchers, Matthew P. Thompson and Dave E. Calkin, with 52 and 50 publications, respectively (Table 3). The majority of the most prolific researchers are based at research institutes or governmental services in the US and Australia. The author with the highest number of publications from outside these two countries is Paulo M. Fernandes from Portugal, with 43 publications. He is also the only author listed in Table 3 who is not based in an English-speaking country. Furthermore, it is apparent that male researchers largely dominate research on fire management; the only female researcher in Table 3 is Alexandra D. Syphard, from the Conservation Biology Institute.

Regarding the total number of citations by other publications on fire management, Jon E. Keely from San Diego State University ranks first, with 5929 citations (174 per document), followed by David M. J. S. Bowman with 4746 citations (79 per publication), and Max Moritz from the University of California with 3739 citations (and an outstanding average of 220 citations per document). Different indices can further measure each author's impact [55]. In terms of the h-index, which counts the highest number h of publications per author that have been cited at least h times, Bowman is ranked first with an index of 30, followed by Keeley with 29, and Ross Bradstock from the University of Wollongong with 27. Regarding the g-index (the highest number g of publications with at least g² citations), Bowman again is listed first with an index of 60; second are Dave E. Calkin and Jeremy

Russell-Smith from the Charles Darwin University, with an index of 45 each. The ranking changes when applying the m-index (the median number of citations received by papers ranking smaller than or equal to h), with Matthew P. Thompson in first place with an index of 2.167, followed by Keeley (1.318) and Stephens (1.125).

Table 3. Most prominent authors in the field of fire management, listed by h-index (2021).

Author	Publications ¹	Citations ¹	H-Index ¹	G-Index ¹	M-Index ¹	Year of First Publication ¹	Country	Affiliation
David M. J. S. Bowman	60	4746	30	60	0.857	1988	Australia	University of Tasmania
Jon E. Keeley	34	5929	29	34	1.318	2001	USA	San Diego State University
Scott Stephens	38	3421	27	38	1.125	1999	USA	University of California Berkeley
Ross Bradstock	37	2714	27	37	0.931	1994	Australia	University of Wollongong
Dave E. Calkin	50	2126	27	45	1.5	2005	USA	US Forest Service
Matthew P. Thompson	52	1612	26	39	2.167	2011	USA	US Forest Service
Jeremy Russell-Smith	45	2549	23	45	0.885	1997	Australia	Charles Darwin University
Brian W. Van Wilgen	27	1562	22	27	0.564	1984	South Africa	Stellenbosch University
Paulo M. Fernandes	43	2001	21	43	1.05	2003	Portugal	University of Trás-Os-Montes and Alto Douro (UTAD)
Brandon Collins	23	2072	19	23	0.95	2003	USA	University of California
Robert E. Keane	35	1882	19	35	0.792	1999	USA	Rocky Mountain Research Station (US Forest Service)
Mike Flannigan	27	2163	18	27	0.692	1997	Canada	University of Alberta
Alan Ager	27	878	18	27	1.2	2008	USA	US Forest Service
Brett Murphy	26	905	17	26	1.063	2007	Australia	Charles Darwin University
Owen F. Price	25	826	17	25	1.063	2007	Australia	Centre for Environmental Risk Management of Bushfire
Mark A. Finney	20	1412	16	20	0.696	2000	USA	US Forest Service
Alan Andersen	21	1377	16	21	0.64	1998	Australia	Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Alexandra D. Syphard	18	1183	16	18	1	2007	USA	Conservation Biology Institute
David Martell	26	1032	16	26	0.39	1982	Canada	University of Toronto
Brian M. Wotton	18	1660	15	18	0.6	1998	Canada	Canadian Forest Service

¹ Values refer only to publications related to fire management listed on Scopus.

Some of the authors mentioned in the list have a long trajectory in the field. Particularly Van Wilgen and Bowman stand out, having published their first articles on fire management in 1984 and 1988, respectively. Most of the principal authors entered the field around the turn of the millennium or some years later. The most recent among them is Thompson, who participated in 52 works on fire management just between 2011 and 2021. In general, the field of fire-management research, thus, is dominated by several leading experts who have focused mainly on this area. In contrast, about 76% of the authors have only participated in a single publication on fire management.

3.3. Spatial Characteristics of Fire-Management Research

English-speaking authors dominate fire-management research, particularly authors from the US and Australia (Table 3). Figure 3 further outlines this fact, representing the number of publications per country in terms of the affiliation of the corresponding authors. The US leads the field, with 1665 documents, more than twice as many as Australia, with

748 publications. Far behind are, China in third (317), Spain in fourth (258), and Canada in fifth (238). Portugal (119), the UK (106), and Brazil (102), as well as Italy and South Africa (87 each), complete the top 10. In terms of continents, North America (the US, Canada, and Mexico) is the most productive region, with 1945 publications, followed by Europe (1028), Oceania (766), and Asia (557). Far behind are Central/South America and the Caribbean (167) and Africa (146) (more detailed data can be found in the Supplementary Materials, Table S1).

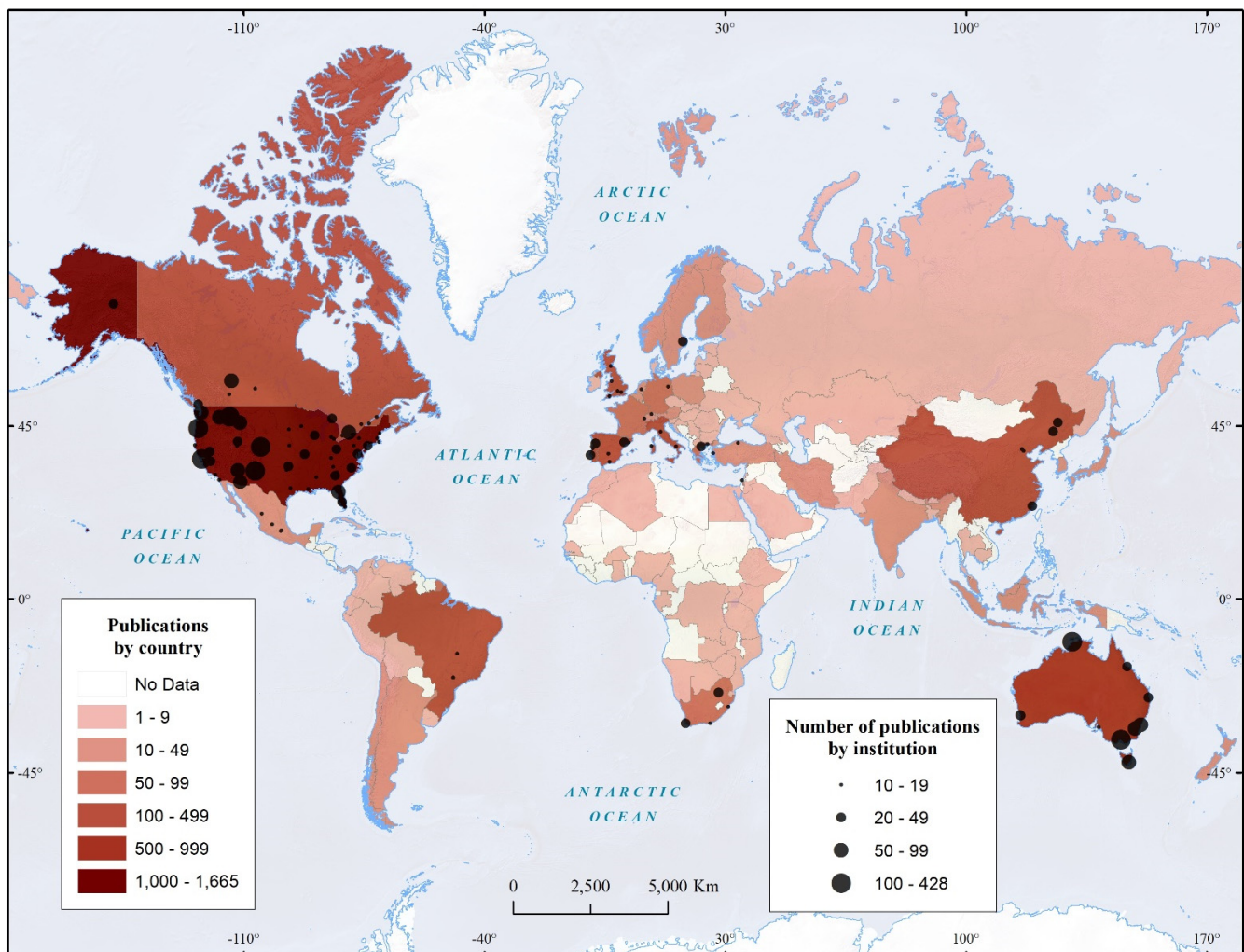


Figure 3. Publications in terms of affiliation of corresponding authors per country and institution listed in Scopus (1973–2021).

It is worth noting that in the case of the main countries, most of the documents were published solely by authors from these countries, without any international collaboration. This is the case of 87.5% of the publications from the US, 86.6% from Australia, 76.0% from China, 58.9% from Spain, and 79% from Canada. On the contrary, in the case of 17 countries, mainly from Africa, Asia, and Latin America, all their documents were published together with authors from other countries.

The US also has the most citations within the selected publications, with more than 57,000, that is, 35 per document (Figure 4). Australia ranks in second place with 20,664 citations and an average of 28 per document, followed by Canada (8696), Spain (6427), Portugal (3847), South Africa (3195), China (3002), the UK (2837), Italy (2268), and Brazil (1690). Interestingly, several countries with a low total number of publications present a high average of citations, led by Swaziland with an average of 55 (3 articles and 165 citations),

Slovenia with an average of 48 (2 publications, 96 citations), and Switzerland with an average of 46.6 (25 publications, 1165 citations).

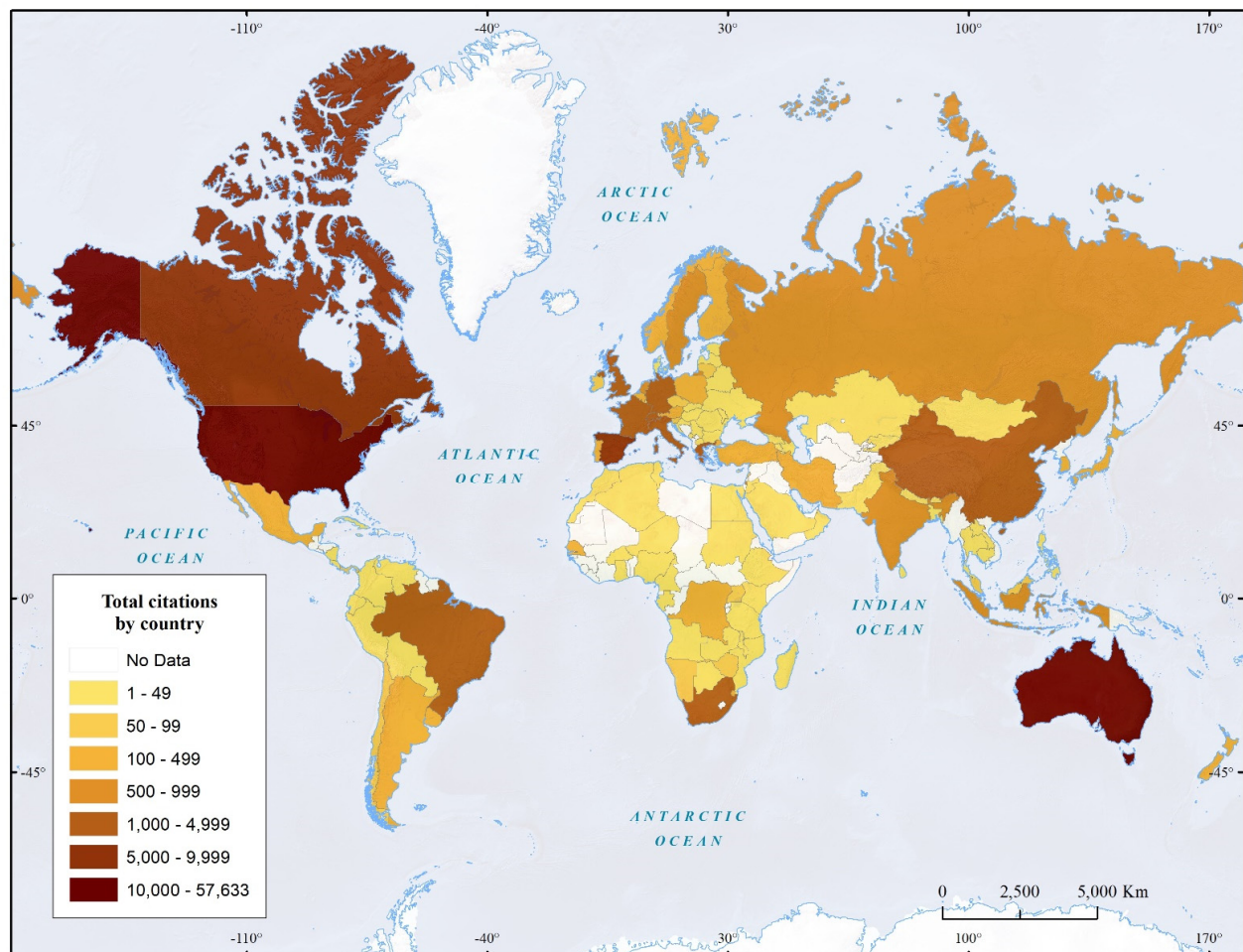


Figure 4. Citations listed in Scopus (1973–2021) per country.

Seven of the ten most-productive institutes are in the US, while the other three are in Australia. First is the US Forest Service, with 420 publications on the topic, followed by the University of California (with all its campuses totaling 250 publications), and the University of Oregon (151 publications). The most important research institute outside the US is the Charles Darwin University in Australia (147). Other highly productive institutes are Colorado State University (140), the University of Melbourne (137), the University of Idaho (98), the University of Tasmania (98), the University of Arizona (85), and Northern Arizona University (85).

Most of the remaining institutes with 10 publications or more on fire management are also located in the US and Australia (Figure 3). In the former case, western states stand out, with 37 research institutes having published 2027 documents in this field. In the eastern states, the most productive institute is the University of Florida, with 61 publications. In Australia, apart from Charles Darwin University in the Northern Territory, most of the highly productive institutes are found in the country's southeastern part.

In Europe, most of the highly productive institutes are found in the Mediterranean region, led by the University of Lleida (Spain) with 39 documents; in total, there are thirteen institutes with at least 10 publications, four each in Portugal and Spain, three in Italy, and two in Greece. One exception from the north of Europe is the Swedish University of Agricultural Sciences, with 31 publications. The UK stands out, too, with five research institutes that have published 10 documents or more on fire management.

All African institutes (a total of five) with more than 10 publications are located in South Africa, the most productive being the University of Cape Town and the University of Witwatersrand, with 27 and 25 documents, respectively. In Asia, the most important institutes are all found in China, which is home to six institutes that have published more than 10 works on fire management. The most productive are the Northeast Normal University (26 publications) and the Fujian Agriculture and Forestry University (22 publications). In Latin America, there are no research institutes with 20 publications or more and only six with 10 publications or more; four are in Mexico, and two are in Brazil (for further details see the Supplementary Materials, Table S2).

Figure 5 presents the number of publications per country in terms of their geographical focus. Likely, these numbers are not complete, as the country name is not always mentioned in the title, abstract, or keywords. However, the map gives an idea of the spatial tendencies of publications in the field of fire management. Once again, the US (further search terms used were “United States” and “USA”) stands out, with 1232 documents, followed by Australia (768), Canada (231), Spain (195), China (191), South Africa (116), Brazil (113), Portugal (97), Mexico (96), and Indonesia (91). Particularly in the case of the US, the number of documents might be much higher, as many publications only mention the state name. The state of California alone, for instance, is mentioned prominently in 279 documents, more than any other country besides the US and Australia. Florida comes next with 101 publications, followed by Oregon (78), Colorado (64), and Arizona (61).

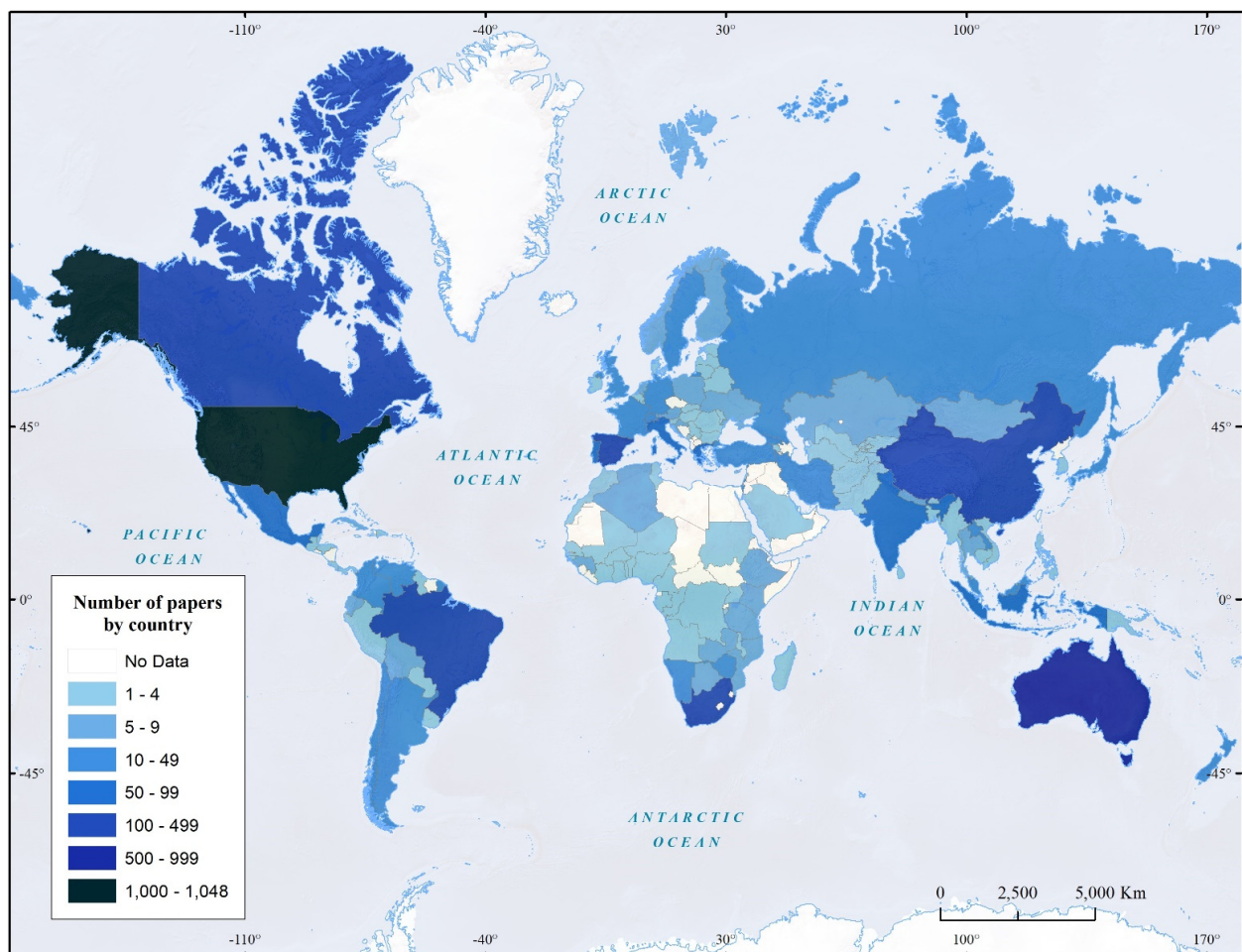


Figure 5. Publications listed in Scopus (1973–2021) per country in terms of spatial focus (country name mentioned in the title, keywords, or abstract).

North America is the world's most studied area in terms of fire management, with at least 1453 documents. The remaining countries from the Americas sum up 217 documents; besides Brazil, other countries with more than 10 publications are Argentina (32 publications), Chile (26), and Venezuela (17). The second-most-studied continent is Europe (including Russia), with 577 published documents. Besides Spain and Portugal, further important countries with a significant number of studies in Europe are Greece (78), Italy (65), and France (49). In the case of Asia, there are 394 documents in total, the principal countries besides China and Indonesia being India (50), Turkey (33), and Malaysia (23). In Africa, there are 212 total works, most from the southern part of the continent, with South Africa making up more than half of all publications. Other countries with more than 10 documents published are Zimbabwe (17), Tanzania (12), and Namibia (12) (for more information see the Supplementary Materials, Table S3).

3.4. Thematic Focus and Methodological Approaches

It is beyond the scope of this paper to carry out a detailed analysis of the content of all 5624 identified publications. However, the list in Table 2 gives a first glimpse at the thematic variety of fire-management research. Moreover, an analysis of the keywords gives an idea of the principal research themes and methodological approaches. The word cloud in Figure 6 (further details in the Supplementary Materials, Table S4) shows the 50 most-mentioned keywords in different thematic categories. Regarding the spatial focus, this underlines again the dominating role of the United States (mentioned 988 times as a keyword) and Australia (mentioned 609 times), as well as the prominent position of the state of California (230 mentions, more than any other country besides the US and Australia).



Figure 6. Word cloud made up of keywords used in fire-management publications included in Scopus (1973–2021).

Regarding the methodological approaches of fire-management research, risk assessment stands out (645 mentions), followed by a focus on remote sensing (460 mentions); furthermore, there are 175 mentions of satellite imagery. Thus, together such methodological approaches using remote-perception technologies account for 635 publications. Other prominent methodological approaches are GIS (geographic information systems) with 209 mentions, regression analysis with 205 mentions, probability with 186 mentions, and computer simulation with 171 mentions.

Regarding the studies' thematic approaches, the focus on fire management from a forestry perspective stands out, with the keyword forestry mentioned 955 times and the keyword phrase forest management mentioned 578 times. Next, comes climate change

with 585 mentions and deforestation with 493. Several prominent keywords are related to an ecological perspective on fire management, with the highly mentioned terms being biodiversity (495), ecosystems (384), vegetation (325), ecosystem (299), and ecology (258). The primary individual ecosystems are savanna (235) and coniferous forest (207). Moreover, several prominent keywords are specific fire-management terminology: prescribed burning (456), fire behavior (412), and fuels (346). Furthermore, there are studies with an organizational focus, with the keyword decision-making appearing 386 times, as well as publications dealing with fire from a perspective of risk management, with risk assessment (also classified as a methodological approach) mentioned 645 times, fire protection mentioned 365 times, and fire hazards mentioned 280 times.

3.5. Bibliometric Networks

Regarding collaboration between researchers, the overall network in fire-management research presents a density of 0.001, which means relatively few connections between the authors. The authors with the highest number of collaborations are D.M.J.S. Bowman (collaborations with 196 other authors), J. Russel-Smith (171), R.E. Keane (137), R.A. Bradstock (128), and G.J. Cary (116). Between the 50 authors with the highest degree of cooperation, there is a much stronger network (Figure 7, details in the Supplementary Materials, Table S5), with a density of 0.168. This means that 16.8% of all potential connections within this network are actually present. The most connected researchers within this sub-network are D.M.J.S. Bowman (collaborations with 20 other authors), M.A. Cochrane (17), R.A. Bradstock (16), O.F. Price (16), and G.J. Cary (15). Two authors, I. Giglio and J. Li, while having a substantial number of collaborations within the overall network of authors, are not connected to any other of the 50 authors with most collaborations.

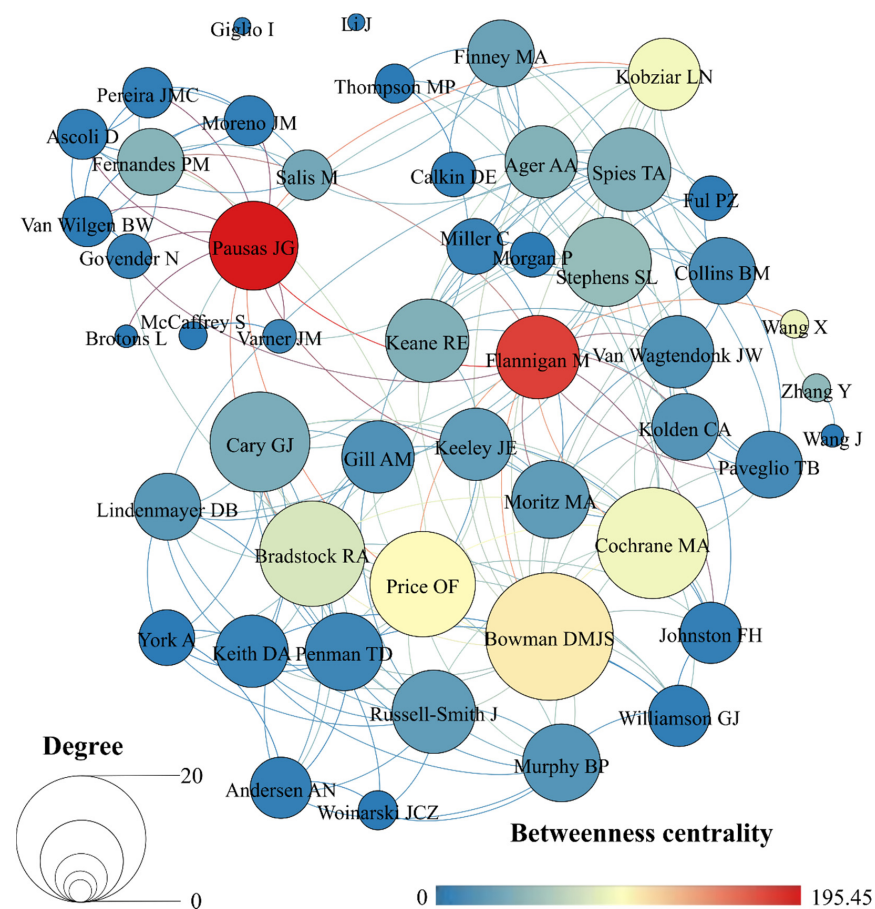


Figure 7. Collaboration network of the 50 authors with most collaborations in fire-management research according to Scopus (1973–2021).

Several clusters of collaboration can be identified (Figure 8). Geography heavily influences the formation of these clusters. Authors in cluster 1 are entirely from Australia, those in cluster 2 are all from the USA, and those in cluster 5 are based in China, or are of Chinese origin. Clusters 0 and 4 group together authors from diverse countries, although there are also clear spatial orientations towards English-speaking countries (USA, Australia, Canada) in cluster 0 and mostly European countries in cluster 4. This does not mean that there are no connections between these clusters. Several authors stand out as connecting different groups of researchers, shown by their high betweenness centrality (Figure 7). The authors with the highest values in this regard are J.G. Pausas (195.45), M. Flannigan (178.50), D.M.J.S. Bowman (105.83), O.F. Price (99.57), and L.N. Kobziar (92.55). Figure 9 further shows the collaboration network between countries at the global level (for more detailed information see the Supplementary Materials, Table S6).

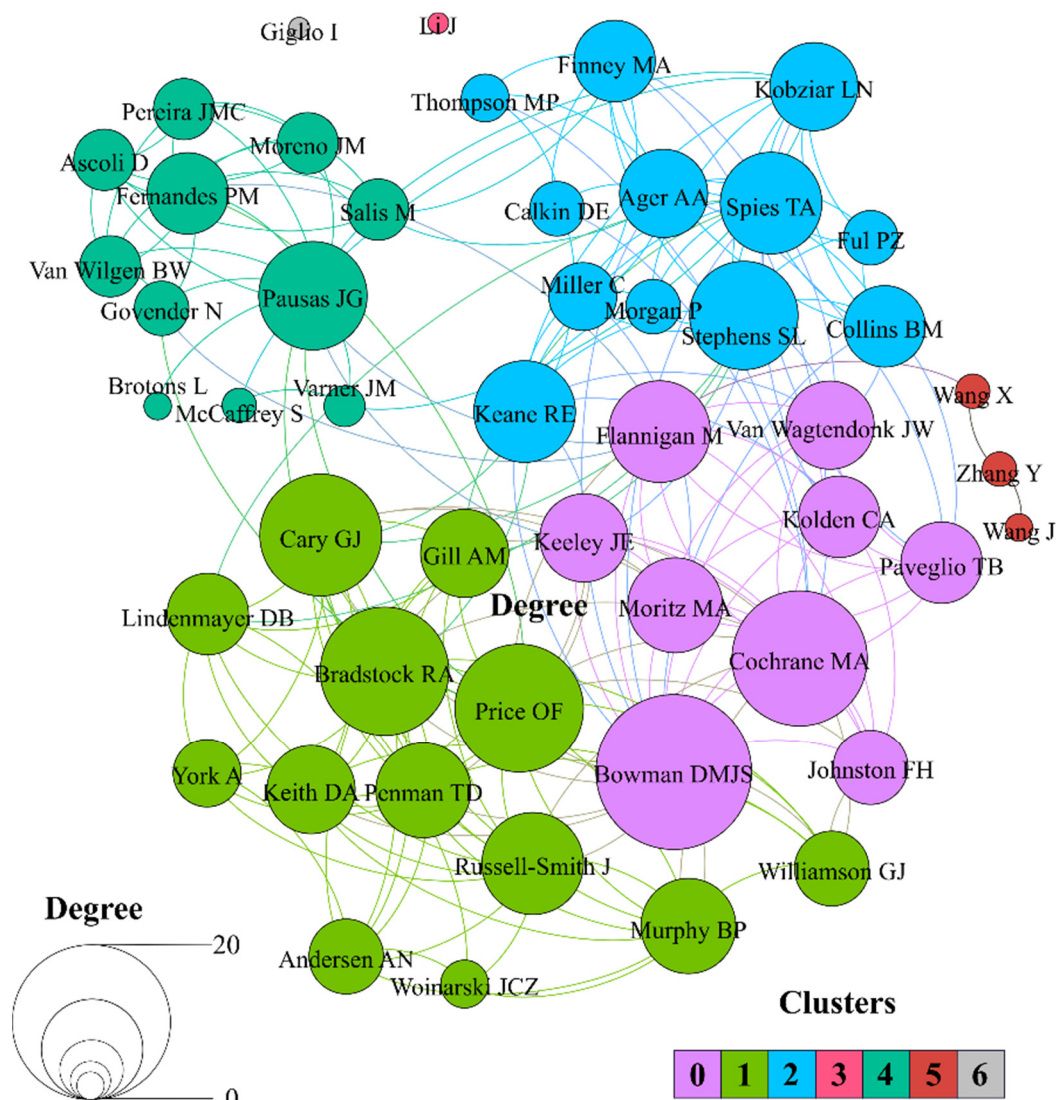


Figure 8. Collaboration communities of the 100 authors with most collaborations in fire-management research according to Scopus (1973–2021).

The co-citation network between the authors is naturally far more complex than the collaboration network. Just between the 50 authors identified by Bibliometrix as having a high number of co-citations, there are 1224 connections, resulting in an overall density of 0.5. The authors’ affiliation influences the clusters identified in Figure 10 less (detailed information in the Supplementary Materials, Table S7). They are, rather, oriented by other factors, such as their thematic focus.

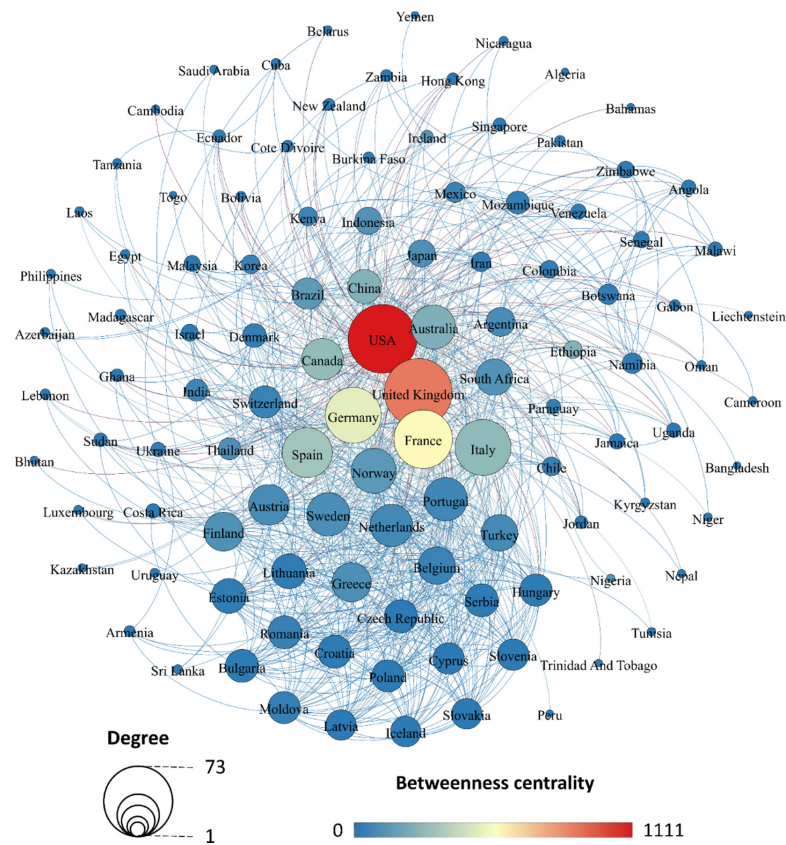


Figure 9. Collaboration network in fire-management research between countries according to Scopus (1973–2021).

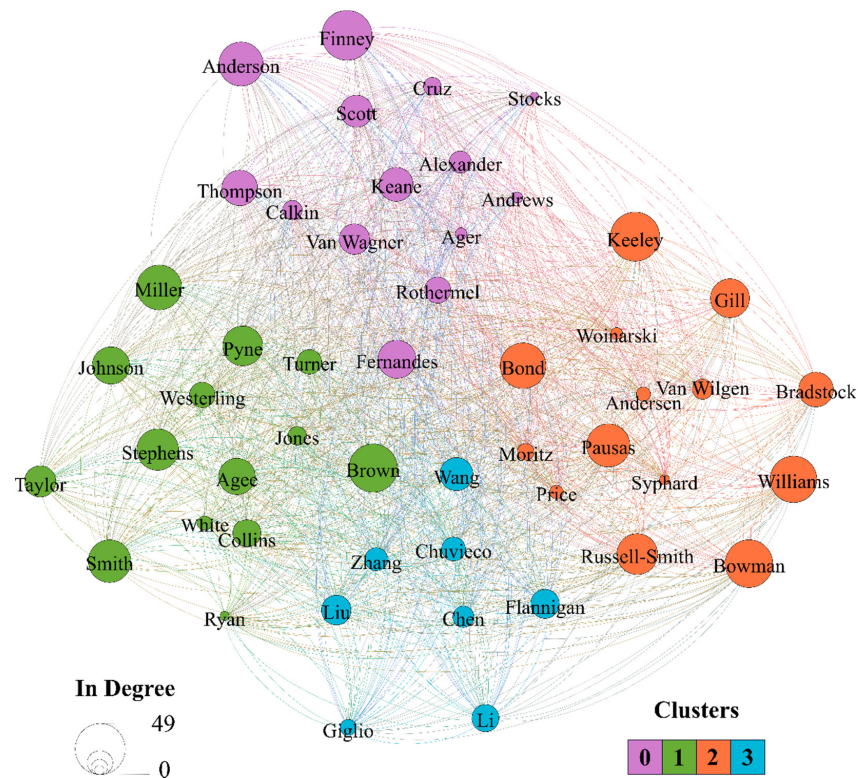


Figure 10. Co-citation network of 50 authors with a high number in co-citations in fire-management research according to Scopus (1973–2021), selected using Bibliometrix. Note: In the case of author co-citation networks, Bibliometrix only provides the author’s surname.

4. Discussion

The bibliometric analysis of data from Scopus has proved useful in outlining the development and characteristics of fire-management research. While most of the techniques adapted approaches from previous bibliometric studies, the paper advanced the methodology by including spatial analysis of the study areas. This was based on mentions of country names in the papers' title, abstract, and keywords, as Scopus does not contain the aspect of research areas as a general criterion. Thus, the analysis carried out here can only approximate this question but surely overlooks several studies that do not include this information. In this sense, it would be interesting for publication platforms such as Scopus to include data on studies' geographical focus. Furthermore, it is important to note that by processing Scopus data in Bibliometrix, we detected several errors. For instance, several authors are listed more than once, depending on how their first names are registered. This should be considered in future studies utilizing these tools.

One of the outstanding results of this study is the substantial increase in fire-management studies, especially over the last two decades. This partly relates to the general increase in scientific-publishing activity over the last several decades [38]. However, this increase has not been equal in all research fields, and publications on fire management have increased above average. One of the reasons for this is the growing interest in fire as a global challenge, particularly concerning the climate crisis [9]. A further contributing factor is the strong connection of fire-management research to the rise of technologies such as remote sensing, GIS, and computer-based statistical analysis, as the thematic analysis shows.

Another important aspect of the thematic analysis is that fire-management studies seem to focus mainly on questions related to forestry and ecology. The human component, with an importance that is outlined in the introduction [8,16,17], seems to have received less attention; thus, fire-management research is a field dominated by the natural sciences, with a much less-represented minority of studies from the social sciences. However, these observations are not conclusive, given the generalized character of the present analysis. Indeed, the list of the most-influential publications in Table 2 features several articles that highlight the role of human societies. A further theme that deserves discussion is male authors' dominance in fire-management research, although this aspect would also need more-thorough analysis.

However, what is clear from this bibliometric analysis is that fire-management research is highly centralized. This includes the rates of production and citations of authors, journals, institutions, and countries, as well as the spatial foci of the studies and collaborations between the researchers. The regional disparities in productivity and citations are related to general trends. Those can be identified in Scopus's SciVal platform [38], with an even more prominent role for the US in fire-management research than in overall scientific output, a much less-important role for China, and a relatively outstanding position for Australia. This undoubtedly has to do with an increased interest in fire management in such countries and regions with a high incidence of wildfires; further examples are the concentration within Europe in the Mediterranean area and within the US in the Western states, particularly California. The same is true for the number of publications per country regarding study areas.

However, this observation cannot be generalized globally. There are regions, especially in developing countries, which are known to possess high incidences of wildfires [56] but have received much less interest to date from fire-management research. This applies primarily to developing countries, including most of Africa, except for South Africa; most of Latin America, except for Brazil and Mexico; and most of Southeast Asia. Indonesia has received some attention but much less than other countries with similar fire incidences. Russia is a further example of a country with a high number of areas burnt annually but relatively little research indexed in Scopus.

This bias of the general spatial focus of fire-management research is problematic given the international implications of fire in these countries, regarding the climate and biodiversity crisis. Thus, increased attention by the global fire-management research

community on these areas is needed, ideally with the participation of and support to local researchers.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fire5040089/s1>, Table S1: Publications and citations of countries, in terms of affiliation of corresponding authors, regarding publications on fire management included in Scopus (1973–2021), ordered by the number of publications; Table S2: Publications per research institution in terms of affiliation of corresponding authors (showing all institutions with more than 10 ten publications); Table S3: Papers by country, in terms of areas studied by publications on fire management, included in Scopus (1973–2021), listing all countries with at least one publication; Table S4: 50 most mentioned keywords of the publications on fire management, included in Scopus (1973–2021); Table S5: Author collaboration network among the 50 authors with most collaborations regarding publications on fire management, included in Scopus (1973–2021); Table S6: Country collaboration network regarding publications on fire management, included in Scopus (1973–2021); Table S7: Co-citation network of 50 authors with a high number in co-citations in fire management research according to Scopus (1973–2021), selected using the Bibliometrix software.

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