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Research on Wildfires, Soil Erosion and Land Degradation in the XXI Century

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Abstract: This study carries out a comprehensive bibliometric analysis of scientific production on wildfires, soil erosion and land degradation, with the aim of understanding trends, critical gaps in scientific knowledge and research patterns. A total of 1400 articles published between 2001 and 2023 were analyzed with bibliometric tools (Bibliometrix and VOSviewer), revealing a steady growth in the number of publications over time. International collaboration between countries such as the United States, Spain, China and Portugal is evident, highlighting the global approach to tackling these issues, as well as the mobility and collaboration between scientists. Analyzing the conceptual structure through the co-occurrence of keywords reveals central themes such as “soil erosion” and “wildfire”, indicating areas of primary focus in research. This study highlights the continuing importance of these themes and the need for global collaboration to tackle the environmental challenges affecting forest ecosystems, and particularly the soil layer, caused by wildfires, which affect wildlands all over the world.

Keywords: wildfire; soil erosion; land degradation; bibliometric analysis

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1. Introduction

The occurrence of wildfires is currently a serious environmental problem that is widespread across the planet [1]. It is also an important contributing factor to soil erosion and land degradation. Although the problem of wildfires is ancient [2–4], their severity, frequency and intensity have been increasing, as have the consequences and impacts on the soil [4–6]. For these reasons, the study of wildfires and their effects on soils has attracted the attention of the scientific community, which, especially since the last two decades of the 20th century [7], has devoted special attention to this issue, particularly in North America and Mediterranean Europe [8].

1.1. Wildfires

Wildfires cover a spectrum from low severity, localized prescribed fires to high-severity, landscape-level wildfires and are an essential factor for the functioning of many ecosystems. But they are also a major disturbance factor in most wildland areas around the world, albeit with a heterogeneous global distribution, and are believed to have been more or less common since the late Devonian [9,10]. We can also mention evidence of fire between the Permian and Triassic considering the increase in wildfires followed by soil erosion due to the loss of vegetation [11]. Fire has been an evolutionary factor in many ecosystems ever since plants arose as a combustible fuel on the planet [12,13]. In the Holocene Epoch of the past 10,000 years, humans have played a major role in fire spread across the planet [14].

Ongoing global changes may increase the occurrence of large and severe wildfires, with earlier initiations and later cessation, with potentially significant feedbacks to the earth system and soil formation, affecting the biomass of terrestrial ecosystems and their development [14,15].

1.2. Soil Erosion and Land Degradation

Soil erosion and degradation is a serious problem, currently greatly aggravated by the occurrence of wildfires, which are one of the main environmental disturbances contributing to their increment, often requiring the implementation of recovery measures [4].

In fact, at different time scales, wildfires can play an important role in the hydrological and geomorphological changes of fire-prone landscapes [9,16]. While rocky surfaces can be weathered, changes in the landscape occur through the degradation and loss of vegetation [12], and these changes affect the natural system. Wildfire is a major cause of desertification in most of the fire-prone forest lands in the world [17,18]. Fire also destroys the soil's organic layer, and by heating the soil, it changes its physical and chemical properties as well as alters the infiltration and percolation capacity of bare soil, including water repellency and the stability of aggregates [9,19–21]. Erosion triggered by fire also enhances the depletion of nutrients and seed banks [22].

Fire-induced soil water repellency (hydrophobicity) is commonly seen as one of the main causes of the substantial increases in runoff and physical erosion on slopes observed after wildfires [20]. Studies show that, under certain conditions, repellency was typically absent or relatively weak before fires and strongly increased in the topsoil or subsoil after a fire [20,23,24]. These changes often result in increased hydrological and geomorphological activity, such as greater surface flow, increased discharge, changes in watercourses and substantial redistribution of soil and sediment production [9].

Under certain conditions, fire-induced changes can cause increased erosion, gravitational flow of dry sediments, landslides and debris flows after wildfires [9,25]. In addition, subsequent rainfall of high intensity and short duration can initiate gully erosion in recently burnt areas, as a consequence of reduced erosion thresholds and increased runoff [26,27].

In fact, several examples, presented by researchers in different parts of the world, illustrate adequately the strong impact on soils and landscape of severe, often localized rainstorms on slopes affected by wildfires, showing strong and sometimes extreme responses in runoff generation and soil loss following fires [28–32].

Wildfires' frequency and severity influence their hydrological and geomorphological impacts [17]. Wildfires' frequency varies widely between vegetation types and climates [9]. An increase in the frequency or severity of wildfires can interfere with ecosystem services, soil erosion, soil carbon sequestration, water supply and the preservation of biodiversity [33].

Some authors consider that wildfires represent one of the greatest threats to the environment and biodiversity worldwide [6,26]. The growing intensity and frequency of these fires has caused global concern, not only because of the immediate destruction of vegetation, but also because of the long-term consequences [34,35]. Among these consequences, soil erosion has emerged as one of the main concerns, leading to significant degradation of the ecosystems affected [36,37]. The intricate relationship between wildfires, soil erosion and land degradation is a topic of great relevance, requiring in-depth analysis for better understanding and effective management.

1.3. Research Proposal

Scientists use different qualitative and quantitative approaches in literature research to understand and organize previous findings [8]. Among these approaches, bibliometrics stands out by offering a systematic and reproducible method based on the statistical measurement of science, scientists or scientific activity [38]. Unlike other techniques, bibliometrics provides more objective and reliable analyses to assess the impact that a researcher, a topic, research groups, institutions, countries or journals have had [8]. In a scenario of constant flows of new information, conceptual developments and data, bibliometrics proves to be a powerful tool, offering a structured analysis of a vast body of information. It makes it possible to infer trends over time, and by carrying out this type of analysis, it seeks to provide valuable insights to guide future research [39] and to present an overview of existing research [38].

In this context, this study seeks to understand what has been produced in the literature on wildfires, soil erosion and land degradation in the last 23 years by incorporating a bibliometric analysis, examining trends, critical gaps in existing scientific knowledge and research patterns in scientific publications on these topics, identifying emerging areas of study and significant academic collaborations.

2. Materials and Methods

The research was based on the bibliometric analysis approach, with quantitative data from reference articles being used to produce graphs, tables, bibliographic data networks and textual data networks.

The study was organized in two parts, the first of which included choosing the search databases and identifying the relevant terms for the subject, i.e., selecting the keywords and implementing the search filters. In this phase we selected the databases containing the bibliometric data, filtered the main set of articles and exported the data from the selected database. The second part was related with data analysis, in which we used the open source Bibliometrix package in R language [38] and data visualization and interpretation.

In the data collection phase, we decided that the analysis would only consider publications in journals (articles). Reviews, conference proceedings, book chapters and books were not considered, as they include works that may have been published more than once, in different media sources [8,40]. The data were obtained from the Web of Science and Scopus databases, using the keywords "*erosion*" AND "soil erosion" OR "soil degradation" OR "land degradation" OR "desertification" OR "denudation" OR "wearing" OR "postfire soil losses" AND "*fire*" OR "Large Forest Fire" OR "Mega Fire" OR "Giga Fire" OR "Extreme Fire" OR "Wildfire" OR "Wildland Fire" OR "Forest Fire" OR "Bush Fire" OR "Vegetation Fire".

These terms were searched in the titles, abstracts and keywords of publications from 1 January 2001 to 31 December 2023. After the searches, the data were loaded and converted into a format suitable for the bibliometric tools used. The search returned 1012 articles on the Scopus database and 1004 articles on the Web of Science. Of these, 616 articles were duplicates, so only a total of 1400 articles were analyzed.

Based on the work carried out by Folharini et al. [39], in which a bibliographical analysis on wildfires and protected areas is presented, the way in which the results are presented was defined. Firstly, we analyzed the articles over time, using the "annual scientific production" option, which shows the evolution of scientific production by year.

To analyze the social structure, which reveals the cooperation networks between institutions and countries, we explored collaborations by creating a table containing the total number of citations per country and the average number of citations, calculating the intra-country collaboration index (SCP) and inter-country collaboration index (MCP), which indicates whether the research is carried out mainly by the country's internal institutions (SCP) or supported by international collaboration (MCP). The most relevant country affiliations quantify the frequency of distribution of all the authors' affiliations to article and present the countries where the institutions are located. Finally, the collaboration map of the countries was created, identifying the collaboration networks between them.

With regard to analyzing the performance of the sources, we sought to understand the sources with the most publications and the most citations. With regard to authors, we identified the production of the main authors over time, the h-index and total citations of the top 10 authors by category and Lotka's law [41,42]. The top authors metric was calculated by considering the number of publications and total citations per year. The h-index of authors is based on the set of the most-cited papers and the number of citations they have received in other publications. Lotka's Law describes the publication frequency of authors in any field as an inverse square law, where the number of authors who publish a certain number of articles is a fixed proportion compared to the number of authors who publish a single article [38,39].

Concerning the conceptual structure, the co-occurrence network was organized based on the keywords that appear in the article, forming the network. The network of words that are most representative of the subject under investigation, according to the network of authors, and their links to other networks of words are shown. The words most used over time are indicated in the frequency of the keywords. With the coupling analysis, we identified thematic networks and defined the clusters of terms most used to refer to a given topic and their relationship with other terms [39,43].

3. Results and Discussion

3.1. General Information

A total of 1400 articles related to soil erosion and degradation and wildfires were analyzed from 1 January 2001 to 31 December 2023. The publications had an average citation per article of 33.29. These publications were written by 4287 authors, 79 (1.8%) of whom were single authors (Table 1).

Table 1. Statistic description. Source: Scopus, Web of Science and Bibliometrix.

Description	Results
Timespan	2001–2023
Sources	457
Articles	1400
Annual Growth Rate %	7.85%
Average age of articles	8.97
Average citations per article	33.29
References	70,233
ARTICLE CONTENTS	
Keywords Plus (ID)	6783
Author's keywords (DE)	3676
AUTHORS	
Authors	4287
Authors of single-authored article	79
AUTHORS' COLLABORATION	
Single-authored articles	97
Co-authors per article	4.71
International co-authorships %	10.79%

An analysis of the annual distribution of the number of articles published is shown in Figure 1. Eighteen articles were published in 2001, marking a modest start. There were fluctuations in the following years, but the general trend was towards a gradual increase. The leap occurred in 2007, when the number of articles published rose to 48. In subsequent years, there was a rise in publications, peaking in 2022 with 119 articles.

Over the period studied, the number of publications showed a consistent upward trend (R^2 = 0.8758). The years 2001 to 2016 account for 53.1% of all publications. There was a drop in the number of publications between 2017 and 2018, accounting for only 9.8% of publications, before returning to a pattern of growth from 2019 to 31 December 2023, comprising 37.1% of publications.

3.2. Social Structure

This section examines quantitative production data, such as the country where the research was conducted, as well as the countries that play a crucial role in the production of this topic [39].

An analysis that contributes to understanding its coverage is the spatial distribution of the countries that publish on the topic studied. These data reflect the diversity and breadth of scientific production from various affiliations, demonstrating the variety of knowledge and expertise that contribute to the global academic scene (Figure 2).

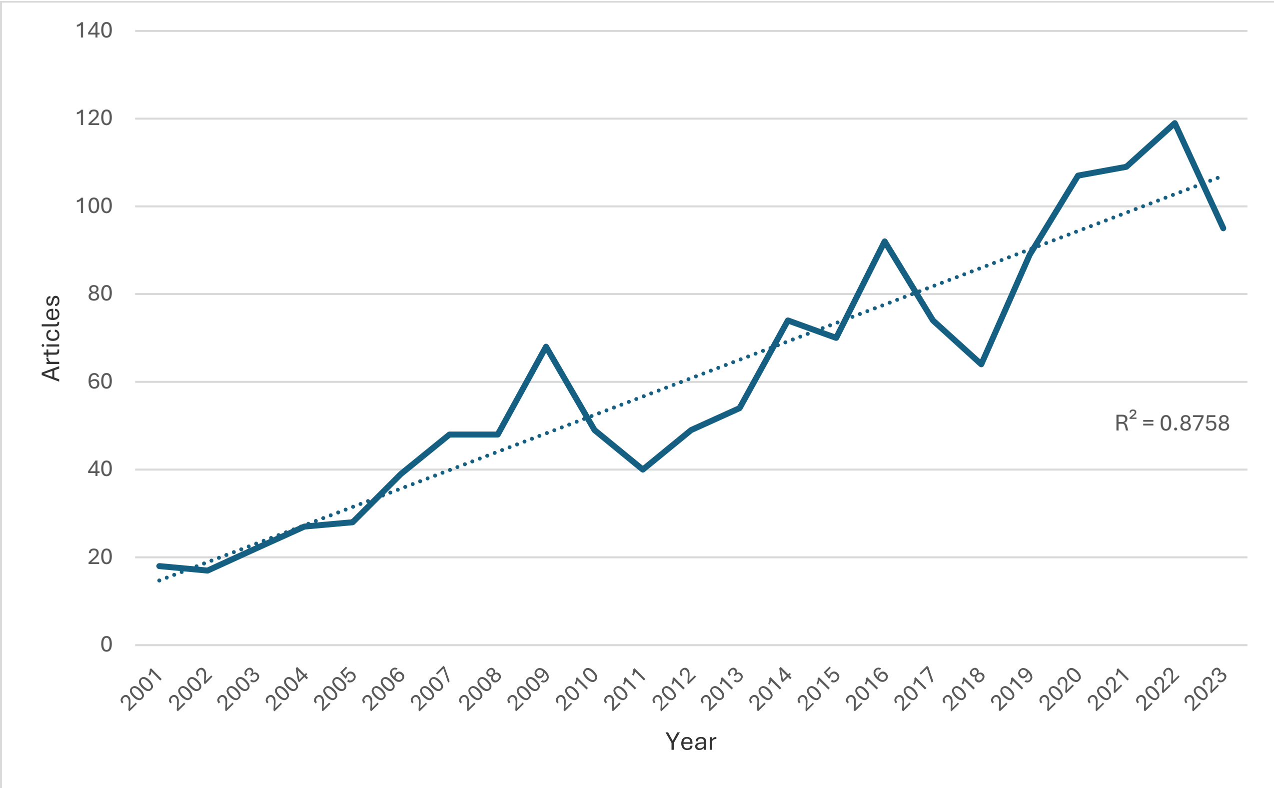

Figure 1. Annual scientific production. Source: Scopus and Web of Science.

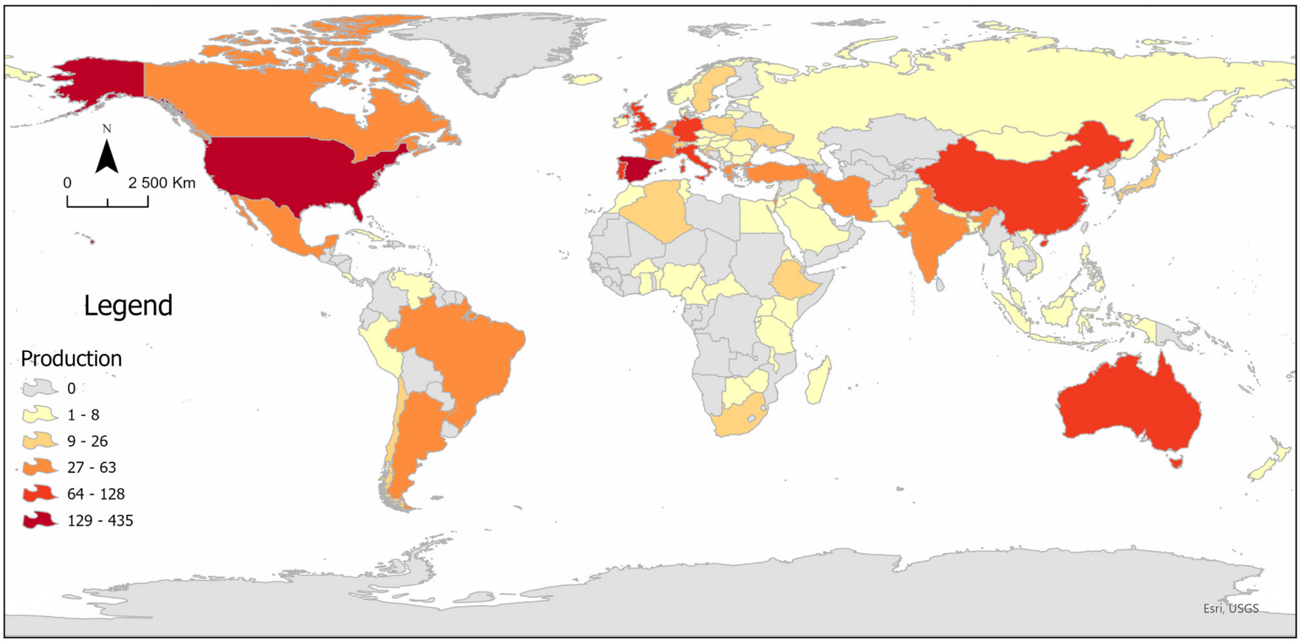

Figure 2. Map of research output by country. Source: Scopus and Web of Science.

All the articles have been produced in just 89 countries, of which 21 have published only one article, probably as a result of sporadic collaborations.

Of the 89 countries, the USA stands out, with 435 articles; followed by Spain, with 289; China, with 128; Portugal, with 126; and, closing out the top five, Germany with 101.

It should be noted that four countries with a high production of articles on wildfires (wildland fires, forest fires, and bushfires), namely, Australia, Canada, South Africa and Chile, only appear in sixth (99 articles), 14th (35 articles), 23rd (18 articles) and 26th (14 articles) place, respectively.

In the top 20 most productive countries, there are nine from Europe (Spain, Portugal, Germany, UK, Italy, France, Greece, the Netherlands and Belgium), five from the Americas (USA, Mexico, Brazil, Canada and Argentina), five from Asia (China, India, Iran, Israel and Turkey) and one from Oceania (Australia).

Of these, four (Germany, the UK, the Netherlands and Belgium) are not countries particularly affected by forest fires, but they are countries with an extensive network of collaborations with other countries, particularly Mediterranean ones, which are often affected by forest fires.

In addition to analyzing the number of articles produced per country, an assessment of citations and an analysis of collaborations between countries provides an even better insight into the internationalization of academic production. The first way to assess the importance of scientific production is by analyzing citations (Table 2).

Table 2. Total number of citations per country and average number of citations per article. TC = Total citations. Source: Scopus and Web of Science.

Country	TC	Average Article Citations
USA	10,283 (31.2%)	45.10 (10.0%)
Spain	7057 (21.4%)	35.60 (7.9%)
United Kingdom	2991 (9.1%)	63.60 (14.0%)
Portugal	2247 (6.8%)	32.60 (7.2%)
Australia	1965 (6.0%)	31.20 (6.9%)
Germany	1905 (5.8%)	54.40 (12.0%)
Italy	1859 (5.6%)	29.50 (6.5%)
China	1816 (5.5%)	24.90 (5.5%)
Brazil	1404 (4.3%)	78.00 (17.2%)
France	1387 (4.2%)	57.80 (12.8%)
Total	**32,914**	**452.7**

The data presented reveal a detailed overview of academic production in different countries. The United States leads the way, with a total of 10,283 citations and an average of 45.10 citations per article. Spain follows in second place, with 7057 citations and an average of 35.60 per article. The United Kingdom, despite having fewer citations (2991), has a significantly high average of 63.60 citations per article, indicating a strong international influence and recognition in its research. Portugal (2247 citations) and Australia (1965 citations) also have high averages, with 32.60 and 31.20 citations per article each. Germany also has a high impact of its production (1905 citations), with an average of 54.40 citations per article. Countries such as Italy (29.50), China (24.90), Brazil (78.00) and France (57.80) also contribute to global research, with a high number of average citations per article. These data emphasize the diversity and quality of academic production in different geographies.

However, the USA, with 31.2% and Spain, with 21.4% of total citations have fewer average article citations, with 10.0 and 7.9, than the United Kingdom (9.1%), Germany (5.8%), Brazil (4.3%) and France (4.2%), which have 14.0, 12.0, 17.2 and 12.8 average article citations.

Brazil, with 17.2, and China, with 5.5, are the countries with the highest and lowest numbers of average article citations.

Collaboration between countries is analyzed using an index that assesses whether publications are produced intra-country (SCP) or inter-country (MCP) (Figure 3).

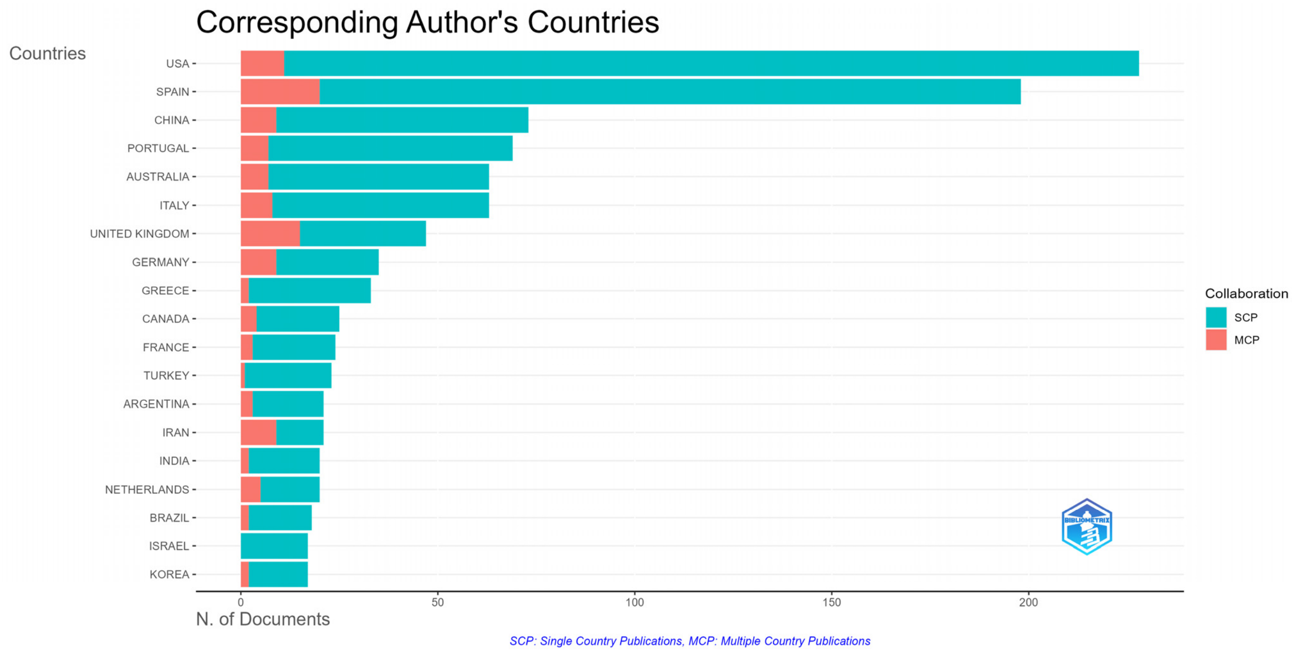

Figure 3. Corresponding author's country. Source: Scopus and Web of Science.

Analyzing these data reveals a deep insight into the dynamics of academic production and international collaboration between countries and institutions. Through the SCP (Citations per Article Produced Intra-Country) and MCP (Citations per Article Produced Inter-Country) indices, we can discern not only the quantity of articles produced, but also the quality and impact of these publications. Countries such as the United States and Spain, with more than 195 articles, and China, Portugal, Australia and Italy, with more than 60 articles, not only lead the way in terms of scientific production, but also demonstrate robust international collaboration, as evidenced by their high MCP. The United Kingdom, Germany and Iran are also included in this group, indicating global recognition of their international collaborative research. On the other hand, countries with low SCP and MCP may be in the early stages of global collaboration or may be focusing on more national research. These indices offer a valuable perspective on how academic research is perceived both nationally and internationally, providing crucial insights into global scientific collaboration and the impact of academic publications.

Data on the top 10 research institutions on the subject, highlighting the number of scientific articles published by each of them, are shown in Table 3. The University of Aveiro (Portugal) maintains its leading position, with a total of 154 articles, demonstrating its significant involvement and contribution to research in the area in question. In second place is Colorado State University (USA), with 37 articles, followed by the United States Department of Agriculture (USDA—USA), with 36 articles. These institutions display a high level of scientific activity, as evidenced by the specific number of publications. The list also includes other renowned universities and research centers, such as the Centro de Investigación Forestal-Lourizán (Spain), the University of California (USA), the University of Haifa (Israel), Aristotle University of Thessaloniki (Greece), Castilla-La Mancha University (Spain), the University of Arizona (USA) and the University of Idaho, highlighting the geographical diversity and internationality of contributions to the scientific field in question. Of the 10 institutions, five are from the United States of America, two are from Spain and the remaining three are spread across three countries, Portugal, Israel and Greece. These figures not only quantify scientific production, but also highlight the collaboration and global reach of the research carried out by these institutions.

Table 3. Institution affiliations. Source: Scopus and Web of Science.

Affiliation	Articles
University of Aveiro (PT)	154
Colorado State University (USA)	37
United States Department of Agriculture (USDA) (USA)	36
Centro de investigación Forestal-Lourizán (SP)	32
University of California (USA)	29
University of Haifa (IL)	29
Aristotle University of Thessaloniki (GR)	26
Castilla-La mancha University (SP)	26
University of Arizona (USA)	26
University of Idaho (USA)	26

3.3. Performance of the Sources

The 20 journals, of the total 457 sources identified, with the most published articles on the topic account for 37.8% (530 articles). The top 10 journals, with a total of 394 articles published (28.14%), are as follows:

- Catena—70 articles—988 citations;
- Science of the Total Environmental—63 articles—368 citations;
- International Journal of Wildland Fire—41 articles—484 citations;
- Geoderma—38 articles—394 citations;
- Land Degradation and Development—36 articles—351 citations;
- Forest Ecology and Management—35 articles—569 citations;
- Earth Surface Processes and Landforms—31 articles—389 citations;
- Geomorphology—31 articles—509 citations;
- Journal of Environmental Management—27 articles—298 citations;
- Journal of Hydrology—22 articles—434 citations.

The 10 most cited sources are shown in Figure 4. Catena, the journal with the most articles published (70), is the journal with the highest number of citations, with 988 (with an average of 14.11 citations per article); followed by Forest Ecology and Management (the journal with the sixth-highest number of articles published—35), with 569 citations (with an average of 16.25 citations per article); Geomorphology (the journal with the eighth-highest number of articles published—31), with 509 citations (with an average of 16.41 citations per article); Hydrological Processes (does not make the top 10), with 506 citations; International Journal of Wildland Fire (the journal with the third-highest number of articles published—41), with 484 citations (with an average of 11.80 citations per article); Journal of Hydrology (the journal with the 10th highest number of articles published—22), with 434 citations (with an average of 19.72 citations per article); and Geoderma (the journal with the fourth highest number of articles published—38), with 394 citations (with an average of 10.36 citations per article).

The most cited article from this period, with over 1400 citations, is a review of wildfires, fire intensity, severity and the relationship with soil published in the International Journal of Wildland Fire [44].

3.4. Authors

Figure 5 shows the productivity of the main authors, out of a total of 4287, over time in terms of the number of publications and total citations per year.

In this group of authors, we can find some pioneering scientists in this field and in his country (i.e., Robichaud, p., Vega, J., Shakesby, R.) and some younger authors.

While, in countries such as the USA, Canada and Australia, the occurrence of large wildfires awakened the scientific community many years ago to the relationship between it and soil erosion and land degradation, in Europe, scientists began to pay special attention to these issues from the 1980s onwards.

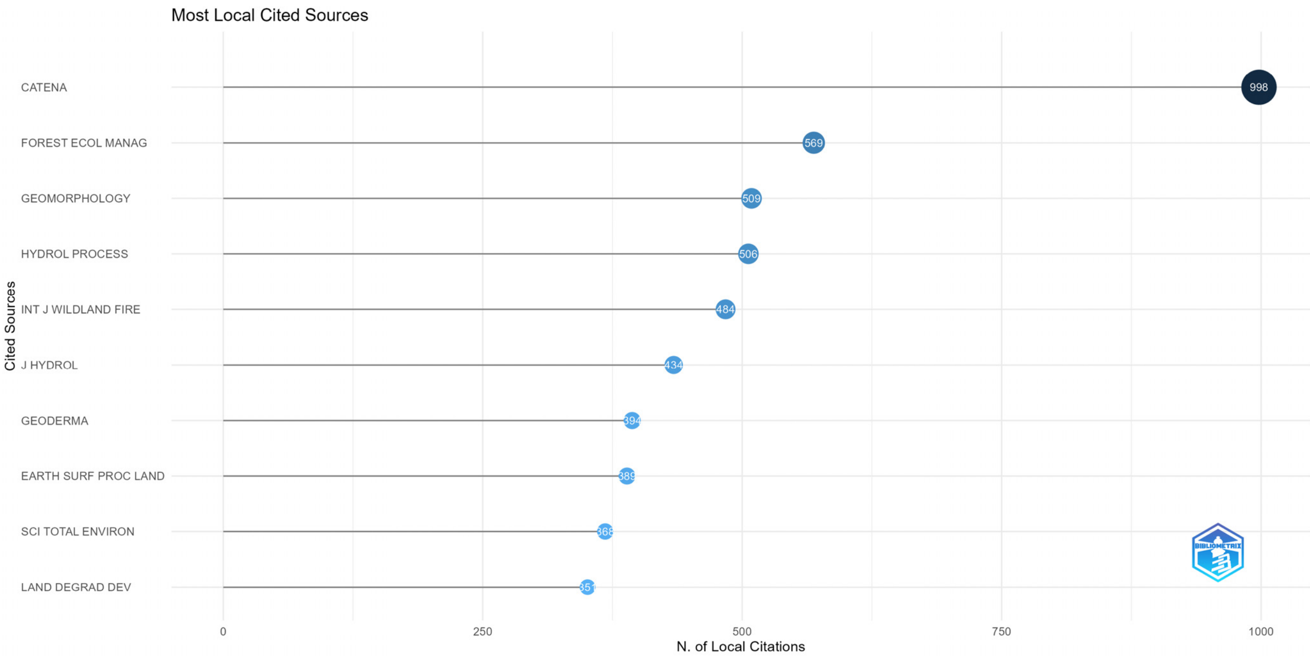

Figure 4. Most cited sources. Source: Scopus and Web of Science.

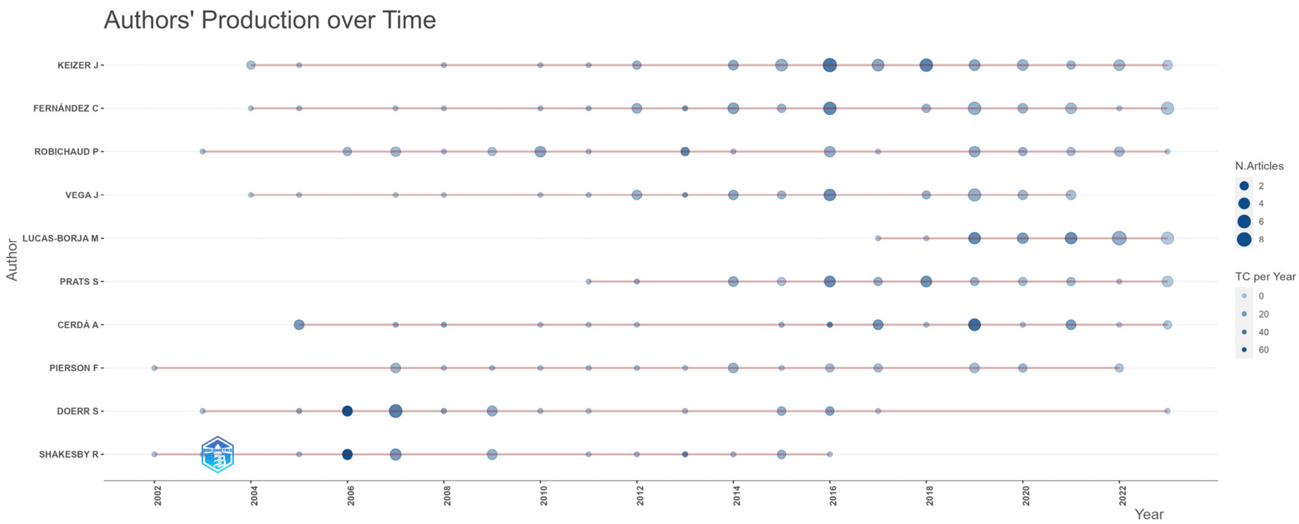

Figure 5. Authors' production over time. Source: Scopus and Web of Science.

In the 1980s and the beginning of the 1990s, the European Commission (Directorate General XII), within the framework of its Community Programs, created the conditions for European scientists from the North (e.g., the UK and the Netherlands) to interact with those from the South (e.g., Portugal and Spain), and projects emerged, such as ForFire and Iberlim, coordinated by some of the pioneering scientists in these areas, such as Anton Imeson, Celeste Coelho, Jean Poesen, José Luis Rubio, José Vega, John Barrie Thornes, Luciano Lourenço, Maria Sala and Richard Shakesby, whose collaborators are now some of the most recognized scientists in the field (i.e., Artemi Cerdá, Stefan Doerr, Xavier Úbeda).

During the same period, more specifically, in August 1992, at the same time that Internet use was growing rapidly in the West (from the 1990s to the early 2000s), the Study Group on Erosion and Desertification in Regions of Mediterranean Climate was established at the XXVII Congress of the IGU in Washington, which was responsible for many actions, in particular, the organization of several meetings and which although maintaining a strong emphasis on soil erosion and soil hydrological processes, the meetings were diversifying in a very positive way to consider links between geomorphology and soil science *per si* and other disciplines, often with wildfires as a crucial factor in the origin or intensification of the processes.

The courses promoted by the European Commission's European School of Climatology and Natural Hazards Unit, also under Directorate General XII, were very important in the training of many young people (who are now recognized scientists), and also in making it possible to establish personal relationships, which later turned into scientific partnerships. In this context, and in order to analyze the efficiency of the main authors, the H-index is a widely used metric for evaluating the productivity and academic impact of researchers. In Table 4, we have a quick overview of the number of articles and the H-indexes of the top 10 scientists. J. Keizer (University of Aveiro—Portugal) leads with an index of 27, indicating that he has 27 articles, out of its 51, with at least 27 citations each, showing a strong influence and productivity in this area of science. C. Fernández (Centro de Investigación Forestal-Lourizán—Spain) and J. Vega (Centro de Investigación Forestal-Lourizán—Spain), with 44 and 34 papers, follow, with an H-index of 23 each. Also noteworthy are researchers P. Robichaud (USDA Forest Service—USA), S. Doerr (Swansea University—UK), A. Cerdá (University of Valencia—Spain), R. Shakesby (Swansea University—UK), F. Pierson (Agricultural Research Service—USA), S. Prats (University of Aveiro and Évora—Portugal) and C. Coelho (University of Aveiro—Portugal), with H-indices between 21 and 16. These figures illustrate the diversity and wealth of knowledge represented by these researchers in their respective fields of study.

Table 4. Authors, number of papers (NP), total citations (TC) and H-index. Source: Scopus and Web of Science.

Element	NP	TC	H-Index
Keizer, J. (PT)	51	1782	27
Fernández, C. (SP)	44	1649	23
Vega, J. (SP)	34	1589	23
Robichaud, P. (USA)	34	1691	21
Doerr, S. (UK)	24	3147	20
Cerdá, A. (SP)	26	2133	19
Shakesby, R. (UK)	20	2640	19
Pierson, F. (USA)	25	914	18
Prats, S. (PT)	28	1060	17
Coelho, C. (PT)	16	1118	16

The numbers of total citations (Figure 6) for the top 10 authors (as first author) indicate the influence and impact of their academic work, the work of their team members and the network of collaborations they have established. In this top 10 list, S. Doerr leads, with a total of 3147 citations (131 citations on average per article), indicating the wide reach and recognition of his research. R. Shakesby, who shares a large number of articles with S. Doerr, is also highly cited, with a total of 2640 citations (132 citations on average per article), followed by A. Cerdà with 2133 citations (82 citations on average per article), and J. Keizer, with 1782 citations (35 citations on average per article). P. Robichaud, C. Fernández and J. Vega (these two authors also share authorship of several articles) are also notable, with 1691, 1649 and 1589 citations respectively. It should be emphasized that there are authors with just one or two articles who have achieved a high impact, as in the case of D. Frank, with only two articles, who accumulates 2406 citations (1203 citations on average per article); J. Keeley, with just one article, has 1425 citations and K. Thonicke, with two articles, reached 1237 citations.

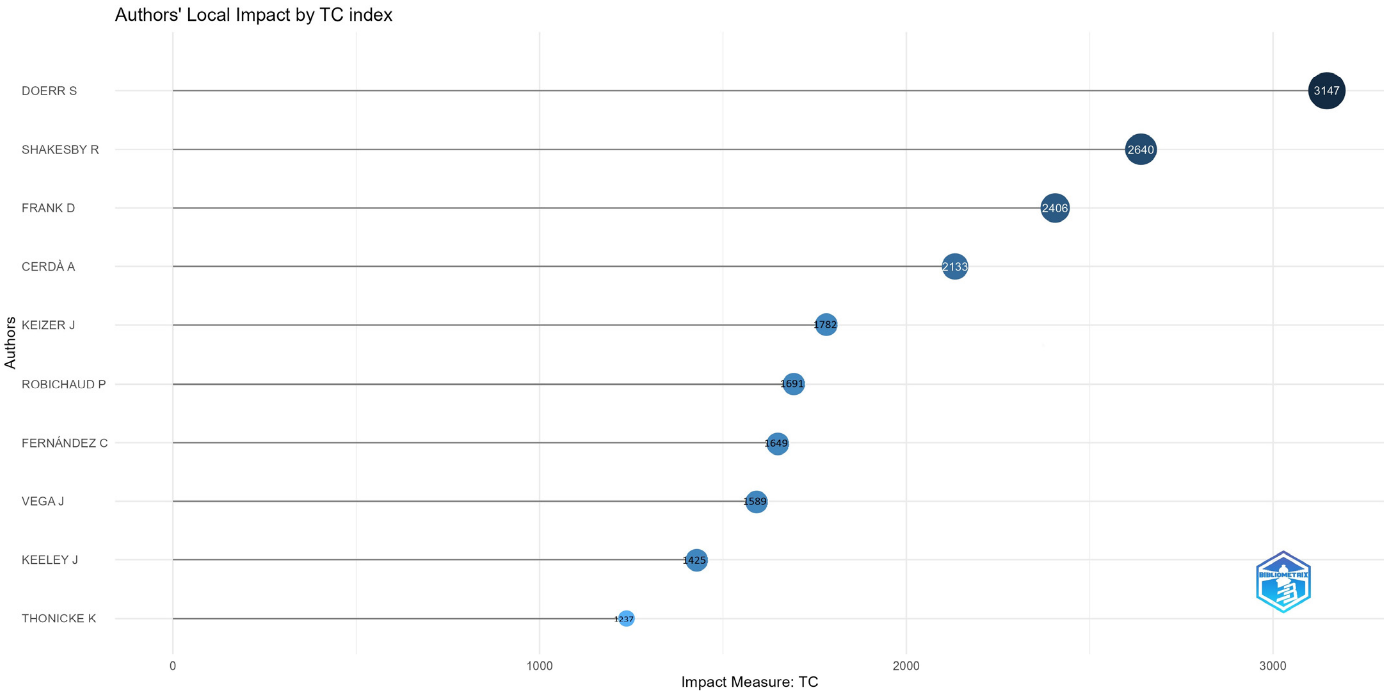

Figure 6. Authors' local impact by TC index. Source: Scopus and Web of Science.

These numbers indicate the lasting impact of their research and reflect the scientific recognition of their studies/publications.

Figure 7 shows author productivity in relation to Lotka's Law, an empirical law that describes the distribution of author productivity in academic publications.

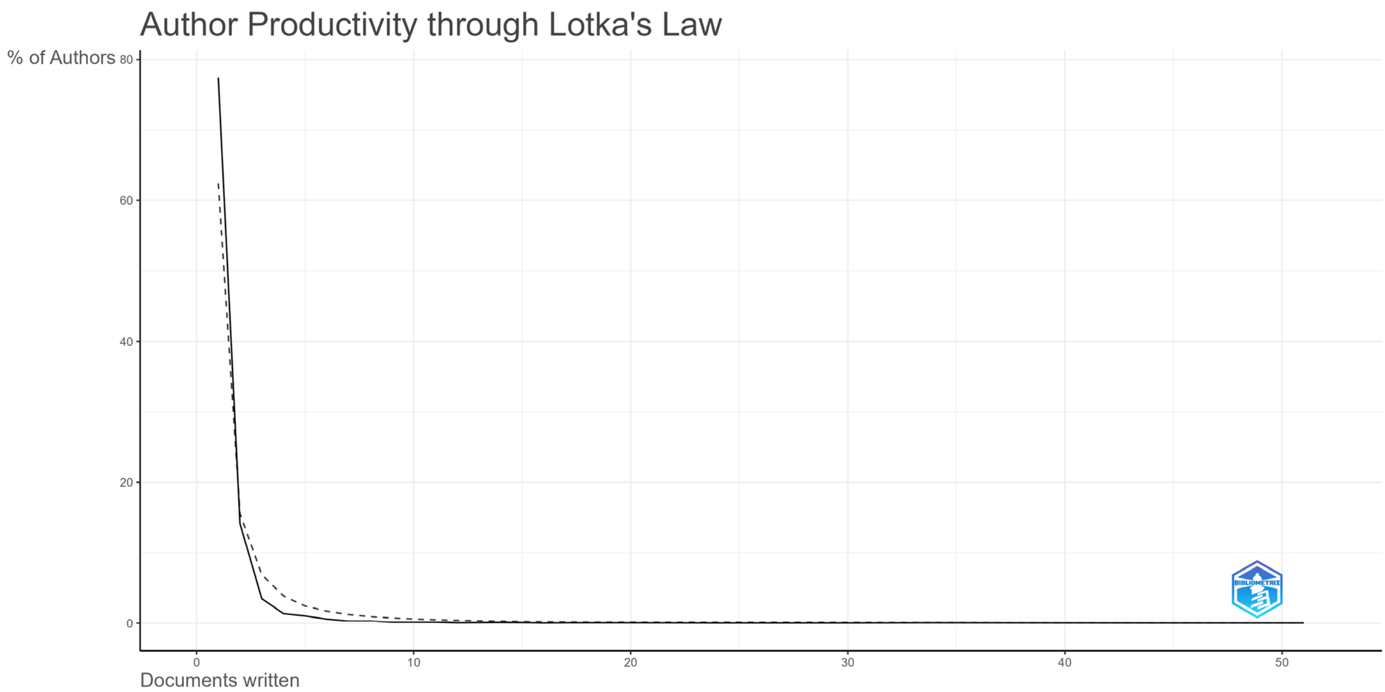

Figure 7. Author productivity through Lotka's Law (continuous line—observed distribution; dashed line—expected distribution). Source: Scopus and Web of Science.

At the beginning of the graph, you can see that the solid line is above the dashed line, indicating that there are more authors than expected publishing a low number of articles. This may suggest that there are more new or less productive authors than expected.

Then there is a reversal, and the continuous line is below the dashed line, indicating that there are fewer authors than expected publishing a high number of articles. This may suggest that there are fewer highly productive authors than predicted by Lotka's Law.

According to Lotka's Law, the majority of authors (around 77%) will write only one article, while a smaller percentage of authors will write two articles (approximately 14%), three articles (around 3.5%), and so on. Figure 7 highlights the number of articles written by a given number of authors and the proportion of authors in that particular group. For example, there are 3221 authors who have written just one article, representing 77% of the authors analyzed. As the number of articles written increases, the number of corresponding authors decreases significantly, reflecting the general trend observed by Lotka's Law. In fact, 29 authors produced between 10 and 19 articles, only 10 authors wrote between 20 and 49 articles and only one author wrote more than 50 articles.

This distribution is crucial to understanding the dynamics of author productivity in various academic fields, providing valuable insights into publication patterns and individual contributions to scientific research.

In fact, the main authors who have produced the most work on the subject over time have focused on fundamental questions about the effects of fire on carbon dynamics in the landscape and soils, as well as on the quality of ecosystem services. Production also focuses on the effects of wildfires on hydrological and erosion processes, with a relevant interest on improving techniques for preventing, combating and modelling erosion processes after fires.

3.5. Conceptual Structure

With regard to the conceptual structure, the co-occurrence network was organized on the basis of related keywords. It is made up of the most representative words on a given topic, according to the authors' network and their links to other word networks (Figure 8). The frequency of words over time shows the words most used over time.

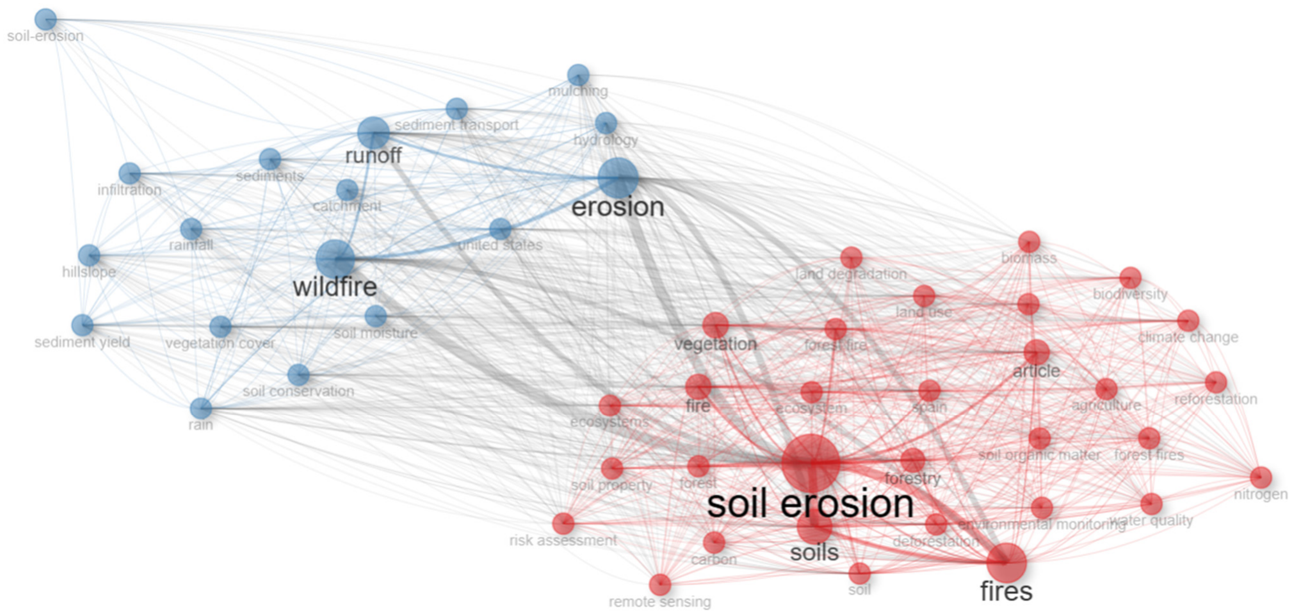

Figure 8. Co-occurrence network. Source: Scopus and Web of Science.

This analysis offers insights into related themes and concepts in a specific field, highlighting which terms are frequently associated and which occupy central positions in the network. The co-occurrence network generated two clusters that divide the dataset according to its occurrence and relationship with other keywords.

In cluster 1 (Figure 8) the words "soil erosion", "fires", "soils", "fire", "vegetation" and "forestry" stand out, while in cluster 2, the words "wildfire", "erosion" and "runoff" stand out. So, the word "soil erosion" is the main keyword in cluster 1, made up of 31 other keywords. In cluster 2, "wildfires" is the main keyword, and this cluster is made up of a further 18 keywords. Keywords can also be analyzed temporally in Figure 9.

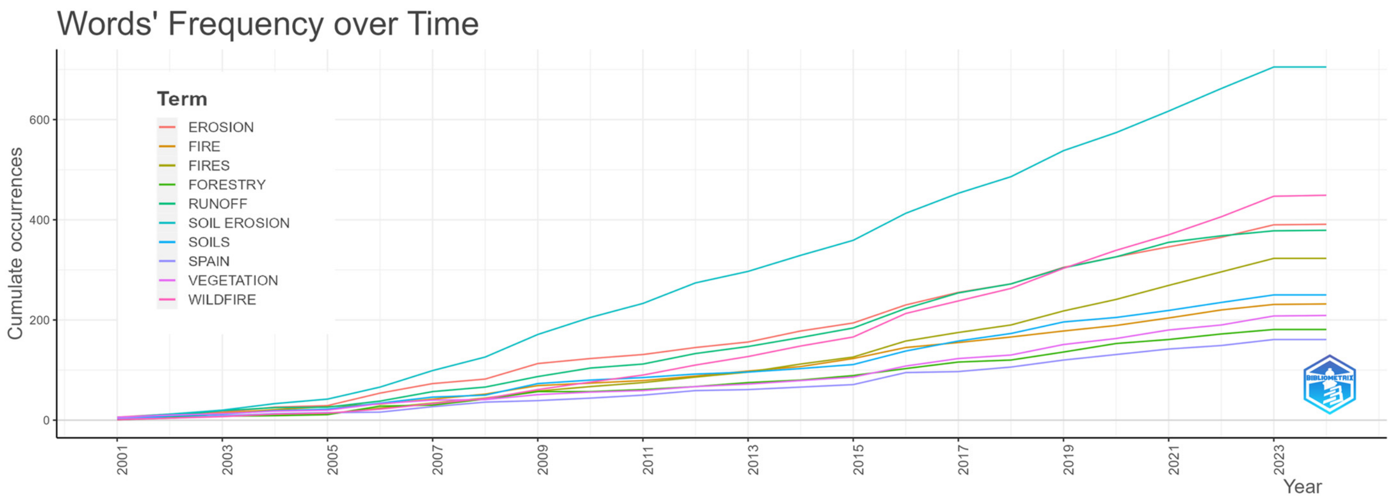

Figure 9. Words' frequency over time. Source: Scopus and Web of Science.

Since 2001, the word "soil erosion" has been used more frequently, followed by the words wildfire, erosion, runoff, fires, vegetation, forestry, soil, wildfires, rain, deforestation, climate change, land use, biodiversity, infiltration, sediment transport, ecosystems, soil moisture and vegetation cover.

As the number of articles increased, so did the frequency of use of each word, and even though there was no regular increase, it was constant, going from units to hundreds. So, as can be seen in Figure 9, soil erosion was used five times in 2001 and 705 times in 2023, wildfire increased from one time to 449 times and erosion grew from six times to 391 times.

Figure 10 shows the Treemap, a way of visualizing the frequency of use of words, with soil erosion standing out, with 12%; followed by wildfire, with 7%; and erosion, with 7%.

This network analysis provides a valuable insight into the thematic landscape of the research in question, indicating not only common keywords but also how they are interconnected. This information can be crucial for researchers who want to understand trends in their field, identify research gaps or explore potential collaborations with other academics and scientists.

Next, the coupling analysis was developed (Figure 11), identifying thematic networks and defining clusters of the most used terms and their relationship with other terms. It is displayed in a matrix with two dimensions; the X axis measures the centrality of the cluster (by the Callon centrality index) or the importance of the themes in the field of research and the Y axis measures the density, or the measure of the development of the theme [39,43].

The coupling analysis shows that the driving terms with the highest density are fire, vegetation and forestry, while the driving terms with the highest centrality are soil erosion, wildfire and erosion. The emerging or declining terms are holocene, charcoal, anthropogenic effect, with the highest centrality and density, and organic-matter, postfire runoff and cover, with the lowest centrality and density.

Considering the scientific production included in this analysis, we can identify the significant diversity of specific topics object of research along the whole studied period, even if soil erosion and wildfires are the generic topics receiving more attention.

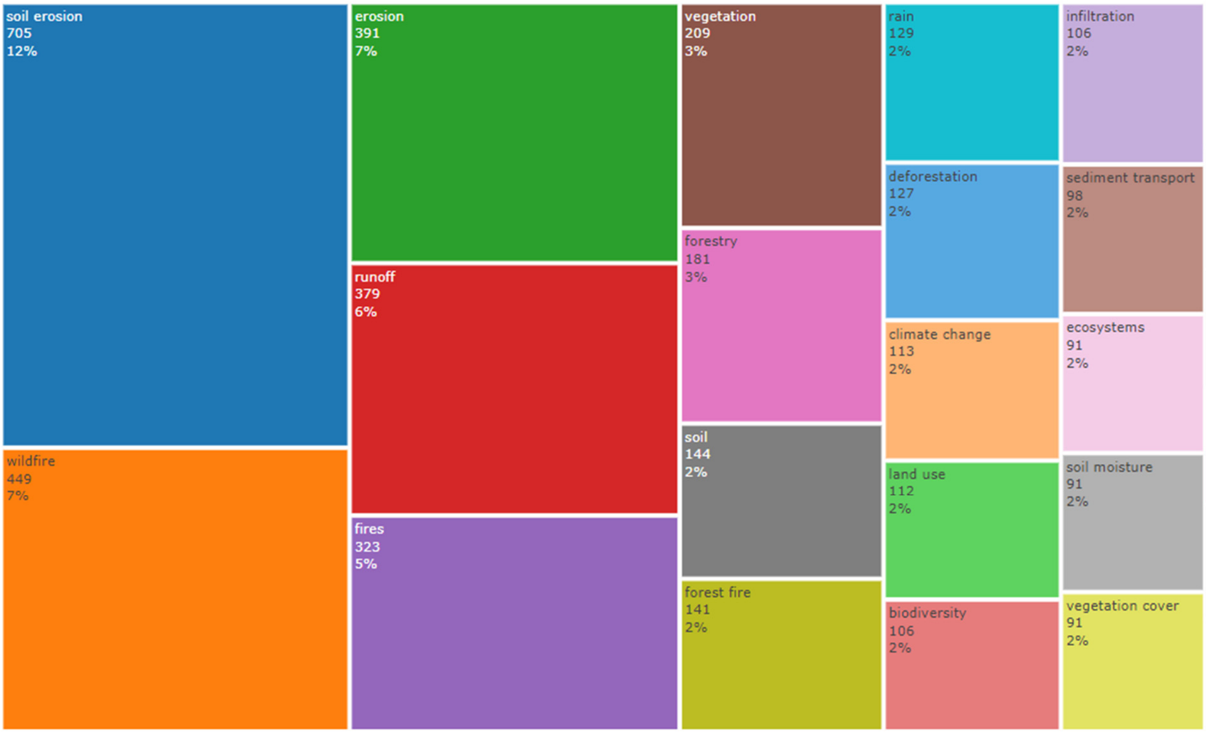

Figure 10. Treemap of the percentage of use of each word. Source: Scopus and Web of Science.

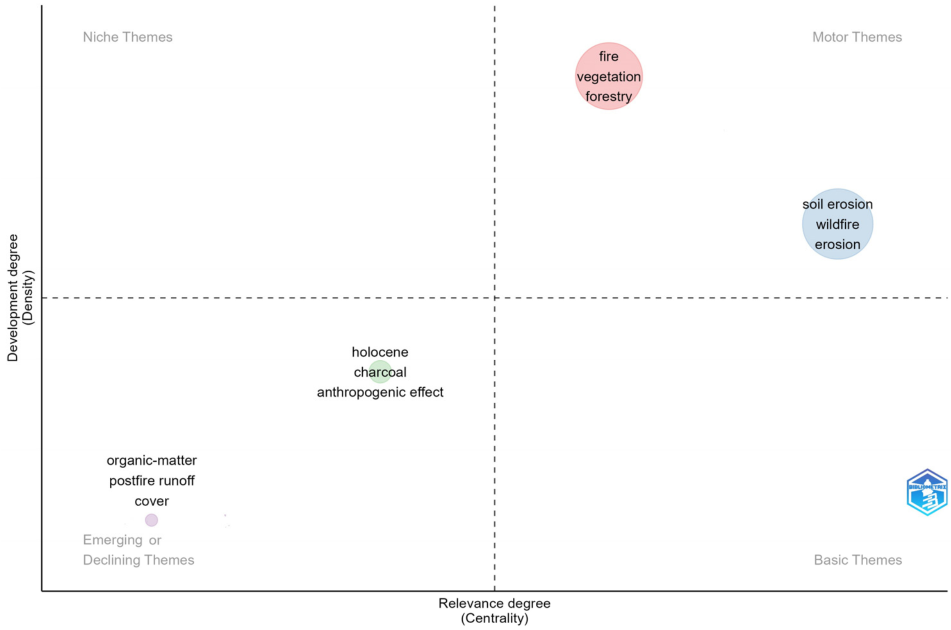

Figure 11. Coupling analysis. Source: Scopus and Web of Science.

In the first years under review, the topics most frequently addressed were related with the quantification of runoff and soil erosion, under different conditions and based on in situ monitoring or applying rainfall simulation methods [45–49]. The importance of this topic continues along the whole studied period [6,50–52].

Also relevant are concerns about the impact of fires on hydrological properties and other impacts on hydrological dynamics in burnt areas [20,53–55].

A topic that was already present in the first decade of study but which is progressively becoming more relevant is the implementation and evaluation of measures to mitigate soil erosion after fires [56], varying in the type of solutions (nature-based or using compounds) [57–59] and in the materials and techniques used (applying native species, different types of mulching, etc.) [60–64], and its relation with carbon loss and capture, and organic matter [65–67]. Having already been among the concerns of researchers at the beginning of the 21st century, it has gained prominence and has become one of the most studied topics in recent years [68–71].

Other topics have emerged alongside scientific developments in other areas, namely, those related to modelling soil erosion and associated processes [72–74] and the application of higher quality technologies, such as the use of higher resolution satellite images capable of extracting more spectral information [75–77], or the use of UAVs and LiDAR cameras, among other technologies [78–80]. Recent trends are focused on the use of AI techniques to support modelling [81,82].

Some topics, although frequently present throughout the period analyzed, have a lower frequency but show great interest on the part of the scientific community, such as the impact of fires on soil nutrients, organic matter and soil water repellency [83–86]. In the same situation are topics such as the evaluation of several parameters related to fires or soil erosion in specific prescribed fire situations [87–90], or the effects of fires on vegetation [75,87,91].

On the contrary, some topics seem to have lost some of the importance they initially had, as is the case of ash studies [19,92–94], which in recent years have been almost absent from the scientific publications analyzed [95].

4. Discussion

The bibliometric analysis shows an upward trend in the number of publications over the studied period. Articles published on the subject from 2001 (18 articles) onwards showed a gradual increase, with a significant figure in 2022 (119 articles). This increase in scientific production indicates a growing and ongoing interest in the intersection between wildfires, soil erosion and land degradation. However, the temporary drop in publications between 2017 and 2018 may suggest possible gaps or changes in the focus of research during this period, particularly dramatic years, with mega-fires, in Portugal, Greece and the USA (California) and with great attention to the issues of wildland–urban interfaces.

The Scopus and Web of Science databases have provided an overview of the main scientific articles, making it possible to identify how scientific production on the subject is being carried out. Research that seeks to understand the relationship between wildfires, soil erosion and land degradation [36,37] is an important area of study because it is considered a threat to the environment and biodiversity worldwide [6,26], due to its long-term consequences [20,34,35]. The intricate relationships between wildfires, soil erosion and land degradation are highly relevant issues, requiring in-depth analysis for better understanding and effective management.

There are well-established international collaborations between leading countries in scientific production, such as the United States, Spain, China and Portugal. These collaborations not only demonstrate a global approach to tackling issues related to wildfires and soil erosion, but also emphasize the importance and international recognition of the research produced by these countries. In addition, leading research institutions such as the University of Aveiro in Portugal and Colorado State University in the USA play significant roles in the production and dissemination of knowledge in this area.

Analyzing the citation and productivity indices of the main authors reveals the influence and recognition of researchers in different geographies. Authors such as J. Keizer [96,97], a researcher at a university with a strong tradition in research on these topics, with a strong team of collaborators, and S. Doerr [20,98,99], with an extensive and consolidated network of international collaborations, emerge as leaders in terms of the productivity and impact of their research. The results presented highlight not only individual excellence, but also collaboration and the exchange of knowledge between researchers around the world. It is also interesting to note that these two authors belong to two, among others, of the institutions (the Universities of Aveiro and Swansea) that pioneered in Europe, with C. Coelho and R. Shakesby, the study of these themes and, above all, the establishment of an international network of academic relations.

The analysis reveals that these authors have played a significant role in generating knowledge and advancing understanding on these topics. The first 10 main authors are concentrated in different countries (very affected and not affected by wildfires and their consequences), reflecting the international nature of research into wildfires, soil erosion and land degradation. Based on the data presented in the results, we can see that these authors represent a variety of institutional affiliations in different countries. Although there is a significant presence of authors from countries such as Portugal, Spain, the United States and the United Kingdom, it is important to emphasize that research in these areas involves collaborations and contributions from academics all over the world, from 89 different countries.

Analyzing the network of co-occurrence and coupling of keywords reveals the central and emerging themes in research on wildfires and soil erosion. Terms such as "soil erosion", "wildfires", "vegetation", "hydrology" and "biodiversity" emerge as central themes, indicating areas of primary focus within the research field, while others, such as "anthropogenic effect" and "Holocene", indicate emerging areas of interest. This understanding of the conceptual framework is fundamental for identifying research gaps and directing future investigations [44,59,97,100].

5. Conclusions

After analyzing scientific production on wildfires, soil erosion and land degradation, it is clear that this field of research is dynamic and growing, and that it has aroused the interest of scientists on a global scale. Over the studied period, a gradual increase in the number of publications was observed, highlighting the continued and growing interest in these crucial issues for the health of forest ecosystems around the world.

We can conclude that international collaboration between leading countries in scientific production, such as the United States, Spain, China and Portugal, demonstrates a global approach to tackling the challenges related to wildfires and soil erosion. Prominent research institutions, such as the University of Aveiro in Portugal and Colorado State University in the USA, play key roles in generating and disseminating knowledge in these areas.

In addition, analyzing the conceptual framework through the co-occurrence of keywords revealed central and emerging themes in the research, with terms such as "soil erosion", "wildfires" and "biodiversity" standing out as primary focus areas, reflecting the fundamental concerns related to the impacts of wildfires on ecosystems. Interesting is the fact that in recent years, a growing number of publications are related with the implementation of modelling solutions for soil erosion based on remotely sensed data and the application of AI and higher quality technologies, revealing a shift on data collection procedures and methodologies and methodologies for soil erosion analysis.

In short, this bibliometric study offers a comprehensive view of the research landscape on wildfires, soil erosion and land degradation, highlighting the continuing importance of these topics and the need for global collaboration to address the environmental challenges affecting forest ecosystems worldwide.

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