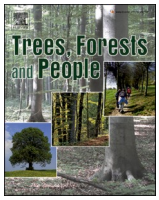
Trees, Forests and People 16 (2024) 100526

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people



Review Article

Forest fire management, funding dynamics, and research in the burning frontier: A comprehensive review

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ARTICLE INFO

Keywords:
Forest fire
Forest fire management
Funding dynamics
Wildfire

ABSTRACT

We indexed 8,970 scientific publications on forest fires in order to bridge the gap between research and policy discussions on forest fires. Journal articles and conference papers dominated the literature, with an emphasis on environmental science, agricultural and biological sciences, earth and planetary sciences, engineering, and computer science. Research in the field of fire has historically focused on terms such as "Forest Fire", "Wildfire", and "Deforestation", but recent trends have highlighted terms such as "MODIS," "Artificial Intelligence," "Algorithm," "Satellite Data," and "Prediction". The number of publications has steadily risen, particularly after year 2000, with funding predominantly from the National Science Foundation, National Natural Science Foundation, U.S. Forest Service, and National Aeronautics and Space Administration. Notable scientific contributions observed from the United States, China, Canada, Spain, Australia, and India. The International Journal of Wildland Fire had the maximum share in published articles among scientific journals, followed by Forest Ecology and Management, Forests, Science of The Total Environment, and Remote Sensing. A variety of aspects of forest fire research have been covered, such as data-driven studies, new discoveries, methodological advances, theoretical applications, and policy implications. In spite of our long interrelation with fires, we are lacking a comprehensive mechanism to combat them effectively. A multidisciplinary approach to the collection and analysis of forest fire information could provide an insightful tool for evidence-based policies and practices aimed to address emerging environmental challenges due to forest fire at global scale.

Introduction

Fire has played a significant role in human evolution and has been used by humans as a tool to shape the world since ancient times (Bond and Keeley, 2005). Forest fires are frequent natural occurrence, happening nearly every hour in various forests worldwide, and causing significant disturbances to forest ecosystems (Phillips et al., 2022). The origins of these fires can be broadly categorized into natural causes, such as lightning and high temperatures, and human-made sources like field cooking and burning (Hoover and Hanson, 2021). The earliest evidence of fire can be traced back to the Carboniferous age through the presence of fossilized charcoal in coal deposits (Spinage, 2012). This period was known for sufficient swampy terrestrial vegetation and atmospheric lightning evidences to ignite fires (Robison et al., 2023). Charcoal layers found in over 400 million years old fossils (Glasspool and Gastaldo, 2022) indicate that forest fire evidences are as old as forests themselves and species living in terrestrial environments (Komarek et al., 1973), including plants (Jones and Rowe, 1999), have been co-existed or co-evolved with recurrent fires (Pyne, 1996). Forest fires can occur naturally (Goldamme and Seibert, 1989) or due to human activities (Cochrane, 2002), with anthropogenic causes being responsible for most global fires (Lavorel et al., 2007; Archibald et al., 2013; Kelley et al., 2019). Lightning was believed to be the primary natural cause of forest fires (Plummer, 1912; Taylor, 1973; Latham and Williams, 2001), but nowadays, human activities strongly influence fire dynamics (Bowman et al., 2011; Scott et al., 2016). Global warming, coupled with changes in land use (Pachauri and Meyer, 2014), has altered the dynamics of wildfires worldwide, heat intensity, drought, and precipitation patterns,

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https://doi.org/10.1016/j.tfp.2024.100526

Available online 1 March 2024

thereby increasing the risk and frequency of forest wildfires (Jolly et al., 2015; Abatzoglou and Williams, 2016; Bargali et al., 2023).

The severity and duration of fire seasons are anticipated to rise globally, especially in boreal high-latitude forests, by the end of the century due to escalating greenhouse gas emissions and the intensification of global climate change (Flannigan et al., 2013). Human activities, accounting for over 80 % of wildfires, including the expansion of agricultural land into forests, contribute to forest fragmentation and degradation, diminishing the fire resistance of forests (Hansen et al., 2020; Xu et al., 2020). This intricate interplay of socio-ecological factors is driving regional shifts in forest wildfire severity and frequency, potentially influencing global climate through biophysical feedbacks, although the precise magnitude and direction of these long-term changes remain uncertain (Tyukavina et al., 2022). According to Goldammer and Furiaev (1995), boreal and temperate forests and other lands covering 10–15 million hectares, tropical rainforests covering 20–40 million hectares, and up to 500 million hectares of tropical and subtropical savannas, woodlands, and open forests affected by fires each year globally. From 2012 to 2021, the USA experienced an average of 7.4 million acres of land affected by approximately 61,289 wildfires each year. In 2021 alone, 58,968 wildfires burned 7.1 million acres (Hoover and Hanson, 2021). The deliberate burning of land by humans for hunting (Bird et al., 2005), cooking (Roebroeks and Paola, 2011), agriculture (Shi et al., 2014), forestry (Taylor, 2010), and reducing fire hazards began the anthropogenic alteration of the environment (Pyne and Goldammer, 1997). The use of fire for human welfare had significantly disrupted the natural fire cycle (Prestemon et al., 2002), leading to more frequent fires in many parts of the world (Bargali et al., 2017; Bargali et al., 2022). Forest fires, whether natural or human-caused, have significant impacts on the environment, economy, and human health (Negi, 2019). Despite enormous resources and efforts invested in understanding and managing forest fires over the past century (Shah, 2020), fire has become a serious concern in tropical regions due to recent demographic and land-use changes (Goldammer, 1990; Cochrane, 2003). Fire represents a complex ecological phenomenon with dual impacts on animal and plant life, as well as the potential for environmental damage. However, it also plays a crucial role in promoting plant regeneration and nutrient recycling (Rowell and Moore, 2000). The impact of fire on ecosystems depends on several factors such as its origin, frequency (Bargali et al., 2022a, 2022b), history (MacCarthy et al., 2022), vegetation types and the extent of damage it causes. The intricate interconnection of socio-ecological factors is leading to regional shifts in the severity and frequency trends of forest wildfires. These changes have the potential to impact the global climate through biophysical feedbacks, though the precise scale and direction of these long-term alterations remain uncertain (Tyukavina et al., 2022). In many ecosystems, fires are essential to maintain biodiversity, species composition, and structure and referred as fire-dependent ecosystems (Semwal and Mehta 1996; Bond and Keeley, 2005; Kraus and Goldammer, 2007; Verma and Jayakumar, 2012; Bargali et al., 2020). Fire is also a natural part of the forest cycle in many boreal forests, and some tree species such as Lodgepole Pine (*Pinus contorta* Douglas ex Loudon) and Jack Pine (*Pinus banksiana* Lamb.) require exposure to fire for their cones to open and seeds to germinate (Alexander and Cruz, 2012). In some cases, flowering trees in temperate Australia such as Mountain ash (*Sorbus aucuparia* Poir.) require complete site burn for species regeneration by exposing them to sunlight (Vertessy et al., 2001). Fire can also promote plant growth by reducing forest diseases through rapid decomposition of organic matter into mineral components (DeBano et al., 1998).

Fire can have negative impacts on ecosystems, posing physical, biological, ecological, and environmental risks (Jaiswal et al., 2002). The extent, intensity, temperature, and frequency of fires determine their impact on a given ecosystem (Kennedy, 1997). Historically fire has played a crucial role in shaping forest ecosystems globally, although some ecosystems depend on fire for regeneration, while others are vulnerable to severe damage (e.g., peat forests, tropical lowlands) (Bond and Keeley, 2005). Fire can also cause species extinction (Parashar and Biswas, 2003), changes in species composition (Neeraja et al., 2021) and succession (Zhong et al., 2023); Porter et al., 2023), and significant changes in ecosystem functioning (DeBano, 2000). Human activities have altered the natural fire regimes of forest ecosystems by suppressing fires and modifying the landscape (Cochrane and Bowman, 2021), leading to changes in fire behaviour compared to what would occur naturally (Pyne et al., 1996). Globally, the complex relationship among humans, forests, and fires has been extensively studied and documented (Fernandes and Cruz,2012). Forest fires can have a global impact through their emissions of gases and particles, which may affect the composition and functioning of the atmosphere and contribute to climate change (Thonicke et al., 2008; Radke et al., 1978). Besides, the destruction of tropical forests due to fire could also have unpredictable effects on weather systems (Oliveira et al., 2023).

Natural Resources Canada estimates that Canada is home to about 9% of the world's forests and faces frequent forest fire (Coogan et al., 2021), particularly in the boreal region (Parisien et al., 2020), which contains the majority of the nation's forests (https://natural-resources.canada.ca/). Over the past ten years, the cost of managing fires, such as suppression and control, has ranged from $500 million to $1 billion annually in Canada (Simon et al., 2022), whereas the average annual burned area of forest is roughly 2.5 million hectares (https://cwfis.cfs.nrcan.gc.ca/). High winds, acute drought conditions, and flammable fuel types are significant contributors to the behaviour of high-intensity forest fires in the United States (Abram et al., 2021). In the US, different techniques have been employed to categories fire regimes based on fire intensity, which is directly related to how disturbances affect the type and structure of forest cover (Agee, 1993; Morgan et al., 1994; Frost, 1998). Reports indicates that in 2016, forest fires burned over 119,000 hectares in eight states in the Southeast US (Brown and Smith, 2000). Similarly, forest fires are a significant concern in European countries, including France, Portugal, Italy, Greece, and Spain (Tedim et al., 2015).

The most extensive forest fire documented in Greece in 2023 spread in an area of 96,000 hectares (https://effis.jrc.ec.europa.eu/). In 1888, near Athens, a fire engulfed over 16,000 hectares of land before reaching the sea (Liocas, 2015). In southwest France, the largest recorded fire occurred in the Landes Forest in 1949, burning approximately 50,000 hectares of maritime pine forests and tragically claiming the lives of 82 firefighters (source: https://www.lemonde.fr/). In Portugal, the Serra de Sintra fire in 1966 affected about 2660 hectares of forest and resulted in the loss of 26 firefighters' lives (Tedim et al., 2015).

In West Germany, fire incident burned approximately 7418 ha of pine dominated forest in 1975, leading to the death of six firefighters (Tedim et al., 2015). According to White et al. (1996), Africa has some of the most driest ecosystems in the world and prone to fire. In the north, center, and south of these three formations, there are humid forests covering dry and wet savannas (International Forest Fire News, 2001). Fires have been a common occurrence in tropical savannas and forests for more than a century (Goldammer, 1990). The fire season in the Central African Republic typically begins around November in the northeast and reaches its peak in December or January (Andela and van der Werf, 2014), following the Harmattan winds in the southwest (Jenik and Hall, 1966). Asia, boasts some of the most pristine forests in the world (Durst and Brown, 2001), including those in India, China, Indonesia, Sri Lanka, and Malaysia. China has 158.9 million ha forest (16.55 % of the country's total geographical area), however, forest fires posed a significant threat to China's forests by burning about 1330 ha of forest area and claiming the lives of many people (Shu et al., 2003).

As per the searches in the bibliographic database like Web of Science and Scopus, earliest scientific records published in forest/ wildfires dates back to 1862 (Gam, 1862) and in 1933 on wildfires (Moore, 1933). However, these incidences of forest fires are increasing over the years and severely impacting environment, flora, fauna, economy and humans' life worldwide (IPCC, 2007; Kier, *et al.* 2005; Singh and

Thadani, 2015).

Wildfires have garnered global attention in recent years, with extreme events in Brazil, Australia, and California (Requia et al., 2021; Boer et al., 2020; Dillis et al., 2022). These recurrent wildfires may serve as indicators of changing fire conditions worldwide, offering valuable insights for responding to widespread fires in various environments (Lindenmayer and Taylor, 2020). Despite the significant damage caused by wildfires, they have been a fundamental aspect of the global ecosystem, actively managed by society for thousands of years (Shuman et al., 2022). Wildfires play a crucial role in renewing forest ecosystems and shaping landscape patterns. Moderately occurring wildfires contribute to forest patchiness, create diverse microhabitats, and enhance ecosystem service functions. They can promote tree species turnover, optimize above-ground species patterns, and regulate hydrological processes on a landscape and regional scale. Additionally, wildfires aid in reducing the spread of pests and improving soil nutrients, fostering overall ecosystem health (Guinto et al., 1999; Bastias et al., 2006; Reilly et al., 2006).

On a global scale, wildfires impact the carbon-water cycle, surface albedo, atmospheric aerosols, cloud properties, and surface energy balance (Poulter et al., 2014; Rother and De Sales, 2021; Chan et al., 2006). Allowing a portion of wildfires to burn naturally can serve as an effective means to prevent and control larger-scale forest wildfires (Reverchon et al., 2012; Hamilton et al., 2018). While wildfires cause significant destruction, they remain a vital component of the Earth's ecosystems, contributing to the exchange of materials between the land and atmosphere and driving ecosystem succession.

Therefore, strong initiatives are required not only to utilize but also to further strengthen the existing database on forest fires to enhance our understanding and address the environmental and social challenges. In order to evaluate the current state of knowledge and availability of scientific data, we explore the thematic research interests, regional contribution, funding paradigm, nation contribution, and temporal trends in the quality of research in the forest and wildfire. This synthesis of scientific information and research gaps in the forest fires provides future directions for the formulation of a data-driven and evidence-based research and governance policy to achieve amelioration of research and sustainability in the region. In the context of international forest wildfire research, bibliometrics provide an innovative approach to analyze past literature systematically. This review paper aims to conduct a bibliometric analysis of current state of knowledge and availability of scientific data, we explore the thematic research interests, regional contribution, funding paradigm, nation contribution, and temporal trends in the quality of research in the forest and wildfire.

Material and methods

The methodology employed in this research involves conducting a bibliometric analysis on global forest wildfire literature. A comprehensive search of Scopus (www.scopus.com) database was conducted to collect scientific literature on forest fires. Bibliometric research, often termed as the "science of science" (Li et al., 2021), serves as a quantitative means to analyze extensive data from the literature (Kumar et al., 2019; Rodrigo-Comino et al., 2023). This analysis assists researchers in gauging the current state of research, identifying emerging trends, and fostering potential collaborations for future research endeavors (Viana-Lora and Nel-lo-Andreu, 2022). All English-language publications published till June 1st, 2023, were searched for titles, abstracts, and keywords. Because of the language barrier, publications that were indexed in other languages were not included in the study. Among the most comprehensive databases of global research output, Scopus contains over 82 million documents from over 25,100 titles published by 5000 SCI-indexed international publishers.

Our search was limited to a single database, and which may lack some relevant scientific literature on forest fires. To mitigate this limitation, we performed a search using the same strategy and keywords on the Web of Science database. Since 99 % of the journals indexed in Web of Science are also indexed in Scopus (Singh et al., 2021), we focused our further analysis on the Scopus database. The primary objective of our study was to understand temporal research trends related to forest fires by analyzing the huge database. To identify relevant scientific literature for analysis, we followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines developed by Page et al. (2021) (Fig. 1). For each selected publication, we collected information such as subject area, journal/publisher name, author names, title, publication year, corresponding author's country, author affiliations, funding agency, acknowledgements, and keywords. To account for variations in keywords represented by singular, plural, and synonyms, we organized them alphabetically, checked for synonyms, and merged words with the same meaning.

For instance, the keyword "forest fire" was combined with "forest fires" to form a single keyword. Regarding journal articles, we retrieved the impact factor from the latest Journal Citation Report (Clarivate Analytics, 2021) for all relevant journals.

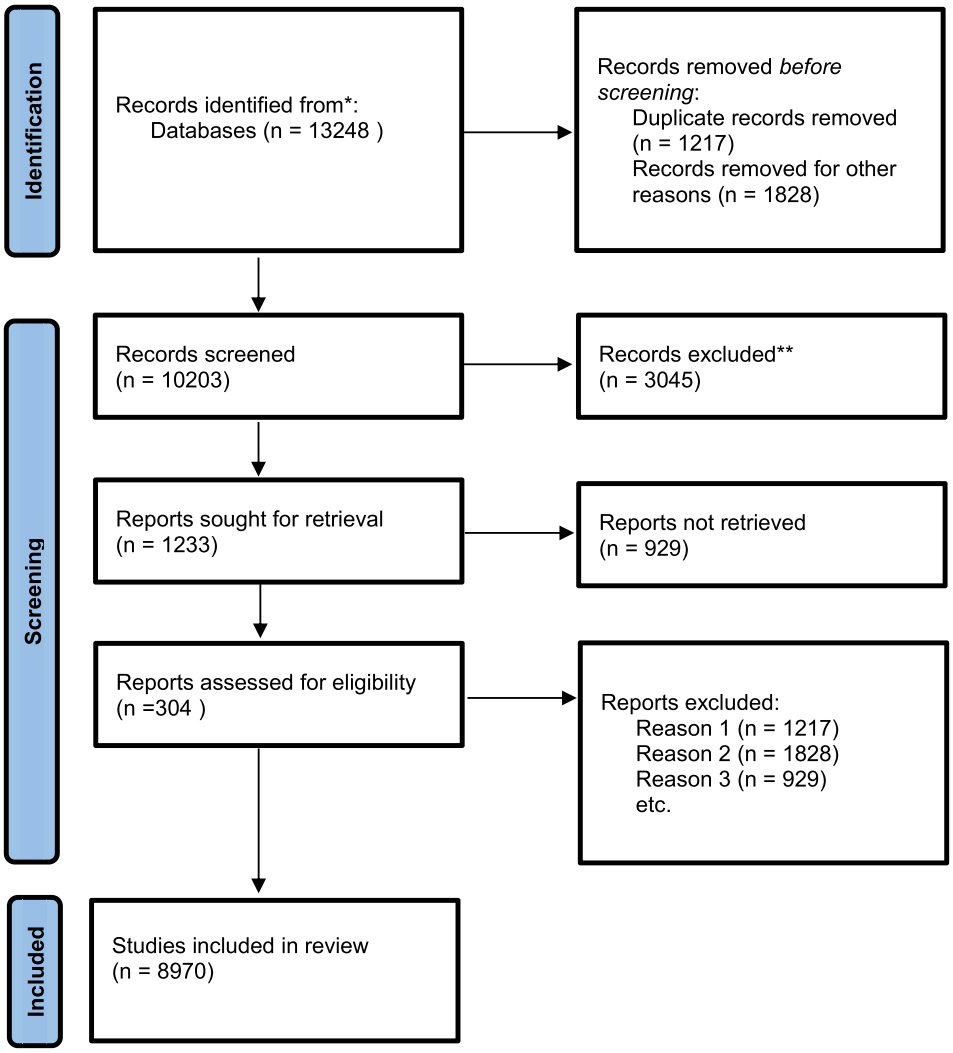
Results

Research themes

We have identified a total of 8970 research outputs in the field of forest/wildfire studies. Among these, 72.0 % (6459) were research articles, 19.3 % (1731) were conference papers, 3.2 % (286) were review papers, 2.2 % (198) were book chapters, 1.0 % (90) were notes, and 2.3 % (206) falling into other publication categories (Fig. 2a). The dominant theme in these research outputs was Environmental Science, accounting for 24.4 % of the published literature. Similarly, Agricultural and Biological Sciences represent 17.9 %, Earth and Planetary Sciences represent 13.2 %, Engineering represents 10.5 %, Computer Science represents 10.2 %, Social Sciences represent 6.6 %, and Mathematics represents 4.5 % of the total publications. It's worth noting that some publications had interdisciplinary scope and these might indexed in multiple subject areas, resulting in overlapping across themes. Therefore, disciplines with smaller contributions in the forest fires were combined in the "others" category (Fig. 2b). In terms of geographical distribution, approximately 27.8 % of the studies were published from the United States, 9.5 % from China, 7.3 % from Canada, 5.5 % from Spain, 5.5 % from Australia, 3.0 % from India, and 41.5 % from other countries (Fig. 4). As expected, studies in the fields of Social Sciences and Medicine were more localized in administrative regions and have a lower representation in regional studies. In terms of author's keywords, the most frequently used keyword was "Fires," appearing in 14.2 % of the publications. It was followed by "Wildfire" (12.1 %), "Deforestation" (6.1 %), "Forest fire" (5.8 %), "Forest Fires" (5.4 %), and "fire hazards" (4.4 %) respectively. The relative size of each keyword depicted in Fig. 3 represents its frequency of use. Among the trending keywords used over time in publications, "Fires" was the most popular, being used since the 1930s until the present. It was followed by "Wildfire," "Deforestation," "Forest Fire," "Fire Hazards," and others. However, terms like "MODIS," "Artificial Intelligence," "Algorithm," "Satellite Data," and "Prediction" have gained popularity more recently in forest fire research (Fig. 3).

Temporal trends

Approximately 45 % of the journal articles published on forest/wildfires were covered in the Science Citation Index (SCI), while the rest were published in non-Impact Factor journals. The number of journal articles published annually in both Impact Factor and non-Impact Factor journals has shown steady increase, with a notable acceleration after 2000 (Fig. 4). From 1932 to 1940, there were relatively few studies conducted on forest fires, with only a small number of studies each year. This could be attributed to limited awareness or a lack of focused research on the subject during that period. In the successive years, there



*The number of records identified from each database.

** indicates records excluded based on multiple criteria.

Fig. 1. PRISMA flow diagram of the systematic literature review on the forest/wild fires (Page et al., 2020).

was a noticeable increase in the number of studies conducted. The counts fluctuate between one and two studies per year until the mid-1950s, after which the trend was shifted towards lower numbers. Between the late 1950s and the early 1970s, the number of studies remains relatively low, with occasional peaks in certain years. Starting from mid-1970s, there was a notable upward trend in the number of studies conducted on forest fires. The study count ranged from one to four studies until early 1990s. During the 1990s, there was a significant surge in research activity related to forest fires. The number of studies gradually increased, with occasional peaks in certain years. This signifies a growing recognition of the importance of studying and comprehending forest fires during that period. From the early 2000s, there was a continuous and substantial increase in the number of studies conducted on forest fires. The counts were rise consistently, indicating an intensified research focus on understanding the impact of forest fires on the environment, climate, and human populations. However, it should be noted that the dataset has shown a significant incline until 2023, and a slight declined thereafter. As the studies carried out till June 2023 were used for the analysis, it does not reflect the complete picture of whole year. (Fig. 4).

Contribution and collaborations

The United States is the top contributor to publications on forest fires, accounting for approximately 28 % of the total. This is followed by China (around 10 %), Canada (approximately 7.26 %), Spain (about 6 %), Australia (around 5 %), and India (approximately 3 %) (Fig. 5). In terms of scientific journals, the International Journal of Wildland Fire has published the highest number of articles, with 312 publications. It is followed by Forest Ecology and Management (239), Forests (150), Science of The Total Environment and Remote Sensing (123 each), Proceedings of SPIE The International Society for Optical Engineering (120), and Fire (102) (Fig. 6). Among the scientific institutions, the USDA Forest Service has published the highest number of publications, with 610 articles. It is followed by the University of Alberta (202), Oregon State University (200), the United States Geological Survey (183), Colorado State University (176), the Canadian Forest Service (172), the USDA ARS Rocky Mountain Research Station (167), the University of Colorado Boulder (162), and Natural Resources Canada (157) (Fig. 7).

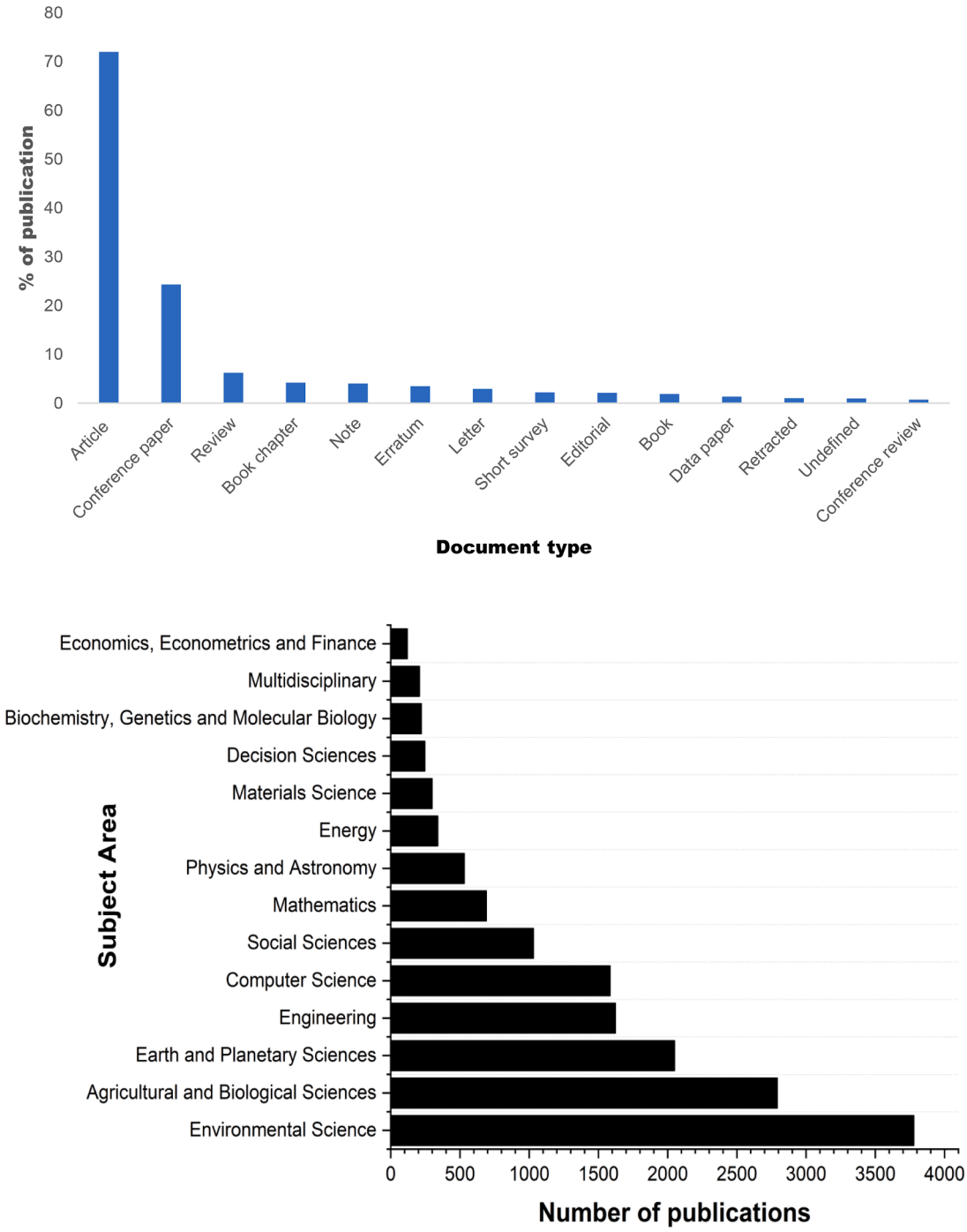


Fig: 2. (a) publications under different document types i.e., article, review, book chapters etc.; (b Number of publications in different subject area.

Funding sponsors

A significant portion of the research studies (469) conducted on forest fires has received funding from 148 funding agencies across 28 nations and 20 international organizations. The National Science Foundation has funded or been acknowledged in the highest number of papers (469). It is followed by the National Natural Science Foundation of China (303), U.S. Forest Service (212), National Aeronautics and Space Administration (NASA) (188), Natural Sciences and Engineering Research Council of Canada (163), U.S. Department of Agriculture (146), and Fundaçao para a Ciencia e a Tecnologia (142) (Fig. 8). Other notable funding agencies include the European Commission, European Regional Development Fund, U.S. Geological Survey, U.S. Department of Energy, and more (Fig. 8). These funding agencies have contributed to supporting research studies on forest fires and their associated disciplines.

Forest fire management

Wildfire management is a multifaceted challenge that necessitates a comprehensive understanding of ecological, social, and economic factors. Thompson and Calkin (2011) conducted a thorough review of forest fire management models, highlighting the need for robust modeling approaches to guide effective wildfire management strategies. Other researchers suggested for mathematical modeling to forecast fire behavior and identify high-risk areas (Quintero et al., 2021), enabling

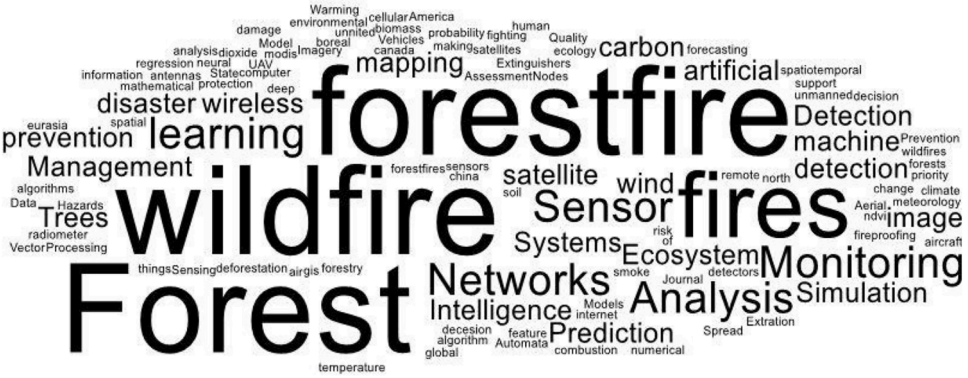


Fig. 3. Top 100 keywords in the publications on forest fires (The size of each keyword represents its proportion of usage in the number of publications).

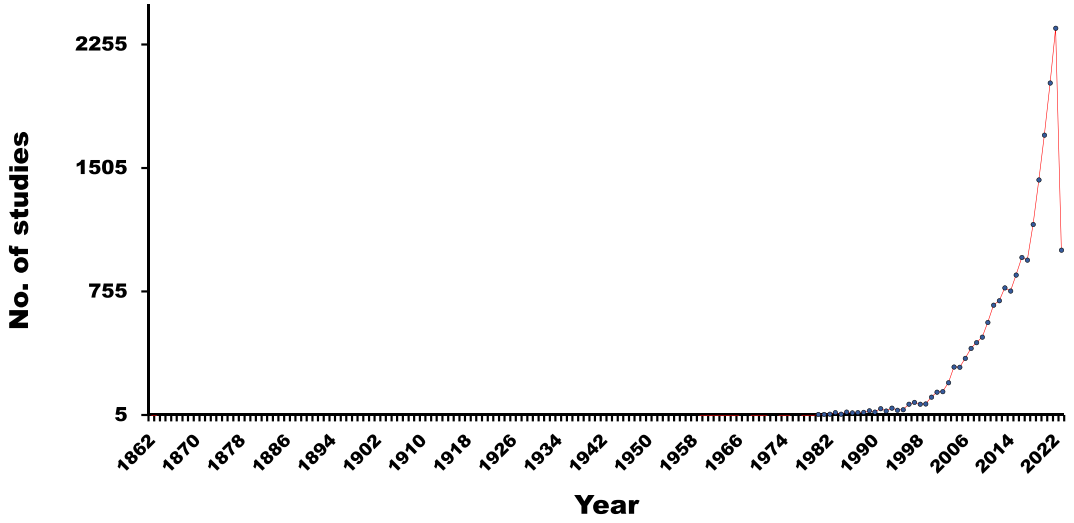


Fig. 4. Temporal trend of studies conducted on forest/wild fires globally, along with the corresponding number of studies for each year.

the implementation of planned burns to mitigate wildfire risk under diverse environmental conditions (Guinto et al., 1999, b; Long et al., 2014; Ma et al., 2015). Simulation models suggest the efficacy of prescribed burns in reducing wildfire occurrence by eliminating combustible materials, albeit with uncertainties regarding future extreme fire weather events (Wang et al., 2014; Taresh et al. 2021). Brenkert-Smith et al. (2017) emphasize the importance of adaptive practices in wildland fire management, urging the integration of ecological and social considerations to enhance fire resilience. Prescribed fire stands as a proactive strategy for wildfire prevention and management by deliberately initiating fires to eliminate combustible material from forested areas, thereby controlling the fire's intensity and spread (Mayer et al., 2020; Jones et al., 2022). While prescribed burning has been demonstrated as a valuable tool for wildfire management, blind implementation may yield adverse consequences such as damage to young forests (Davis et al., 2022). Thus, future research efforts should prioritize refining simulation accuracy and scale while adhering to planned burn management practices. Palaiologou et al. (2019) explore the intricate relationship between social vulnerability and wildfire risk, emphasizing the necessity of addressing disparities in vulnerability through targeted mitigation strategies. Abrams et al., 2015 identify key factors influencing community resilience to large wildfires, underscoring the importance of collaborative approaches and adaptive governance. Glicksman (2008) discusses the escalating threat of climate change on wildfire activity, advocating for proactive measures to mitigate risks and enhance ecosystem resilience. Bot and Borges (2022) employ decision tree analysis to predict wildfire occurrence, offering valuable insights for prioritizing prevention and mitigation efforts. Johnston et al. (2021) assess the effectiveness of fuel treatments in reducing wildfire risk, demonstrating the potential of mechanical thinning and prescribed burning to mitigate wildfire impacts. Boroujeni et al. (2024) evaluate the economic impacts of wildfires, emphasizing the importance of incorporating economic considerations into wildfire management decision-making processes. These studies collectively highlight the complex interplay of ecological, social, and economic factors in wildfire management and underscore the importance of interdisciplinary approaches to enhance wildfire resilience, mitigate risks, and protect both communities and ecosystems from the devastating impacts of wildfires.

Discussion

Scholars worldwide have shown significant interest in forest wildfire research, representing diverse research regions and institutions and generating a substantial body of literature. It is believed that timely incorporation of scientific research into management approaches is crucial for the preservation of ecosystem services provided by geological, biological, social, and cultural resources (Millennium Ecosystem Assessment, 2005; Payne et al., 2020; Tucker et al., 2021).

The analysis of nearly 9000 research outputs in the realm of forest and wildfire studies reveals a prominent emphasis on disseminating knowledge through peer-reviewed channels, with 72 % of the outputs identified as journal articles. This inclination towards journal publications underlines the commitment of the scientific community to rigorous evaluation and scrutiny. The dominant theme of Environmental Science

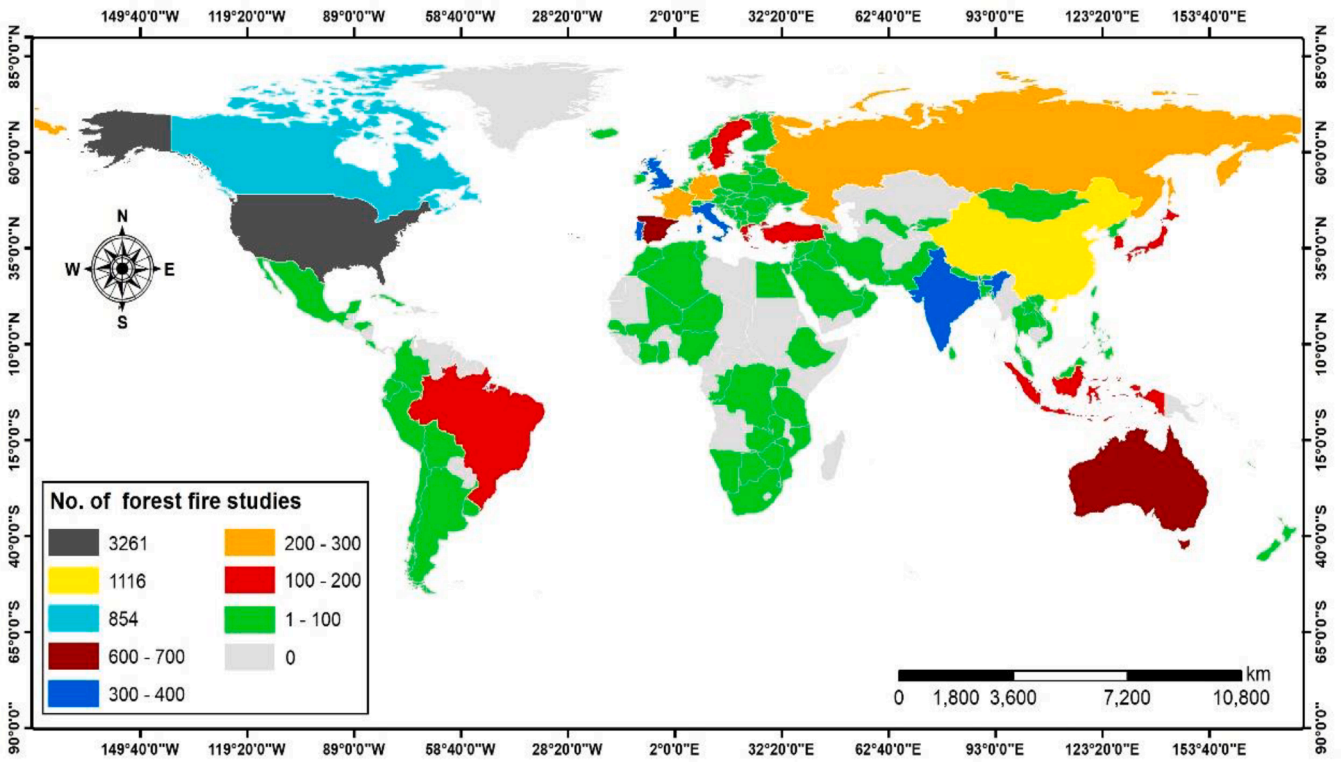


Fig. 5. Country wise number of studies carried in the field of forest fires.

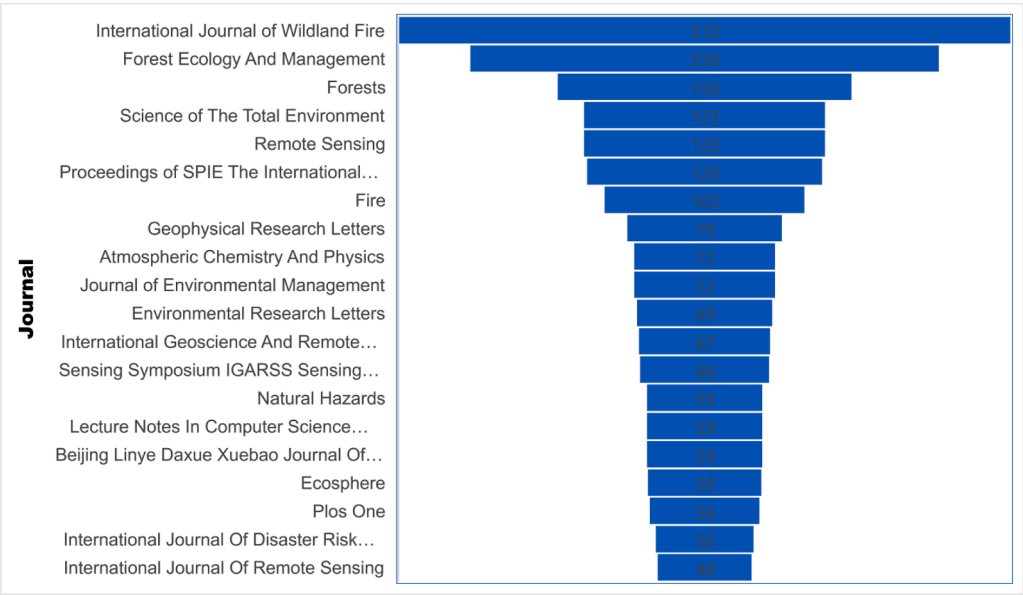


Fig. 6. Top twenty publishing journals on the forest fires.

(24.35 %) underscores a broad interest in comprehending the ecological repercussions of forest fires. However, the interdisciplinary nature of certain publications, spanning multiple subject areas, highlights the interconnectedness of different scientific domains in tackling the complexities of forest fires. Notably, the geographical distribution of publications reflects a global engagement, with substantial contributions from the United States, China, Canada, and other nations, emphasizing the universality of the challenge posed by forest fires. In order to tackle the urgent issue of forest fires, a comprehensive review has been conducted, with global research attention primarily focused on Environmental Science, followed by Agricultural and Biological Sciences, Earth and Planetary Sciences, and Engineering. The emerging fields of Computer Science and Engineering are also gaining recognition in terms of publication output. Among these disciplines, biological research has the longest history. The temporal analysis of research output over the years provides valuable insights into the evolving landscape of forest fire studies. The notable surge in research activity during the 1990s signifies a growing awareness of the environmental and societal implications of forest fires. From the early 2000s onwards, a sustained and substantial increase in the number of studies indicates an

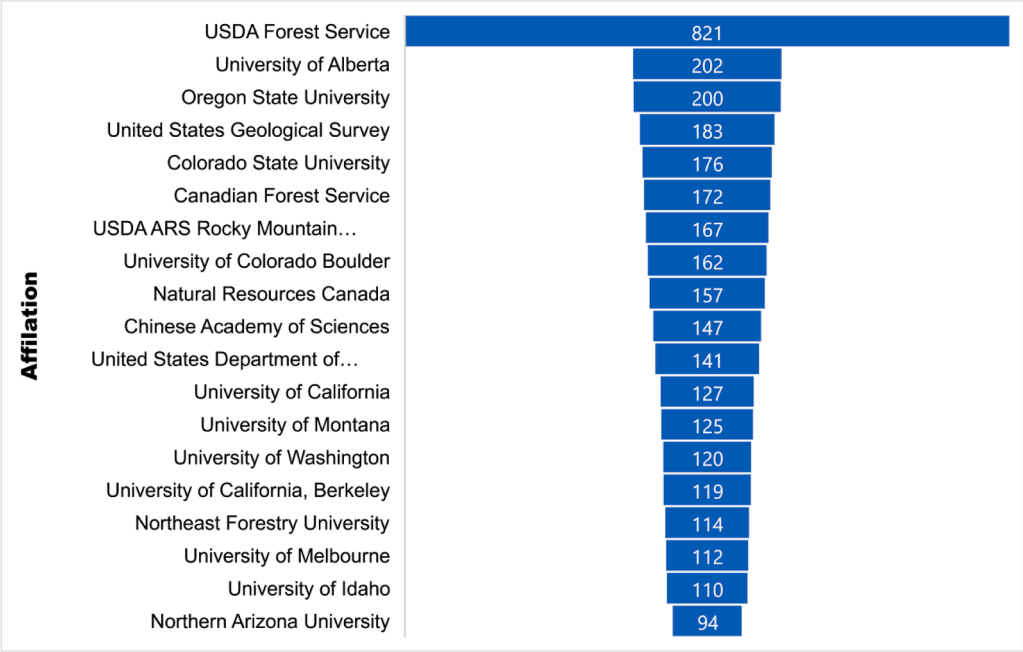


Fig. 7. Top nineteen publishing affiliations on the forest fires.

Fig. 8. Top twenty funding agencies on forest fires.

intensified commitment to unraveling the multifaceted impact of forest fires on the environment, climate, and human populations. The slight decline in research output post-2023, while possibly an artifact of incomplete data for the entire year, prompts consideration of the need for continuous vigilance and research in the face of this persistent challenge.

Furthermore, significant research has been conducted on agriculture, biodiversity, and environmental science in relation to forest fires (Basnet et al., 2019; Kandel et al., 2016; Wambulwa et al., 2021). Many studies quantify the risk to forests, carbon storage, biodiversity and forest loss using vegetation models, the connection between climate and forest characteristics, and the consequences of climate on forest loss (Anderegg et al., 2022). It is well known that throughout millions of years, forest fires have played a natural role in shaping ecosystems (Bowman et al., 2009). However, the escalating frequency and intensity of these fires have become a worldwide concern, primarily driven by climate change. The combination of rising temperatures, heightened droughts, and the historical practice of fire suppression has rendered ecosystems more vulnerable to wildfires, particularly in the southwest United States. According to the report of United Nations, the number of wildfires will

increase by 50 % in 2050. Climate change is modifying global wildfires by extending the fire season and expanding the areas affected by fires. Australian Academy of Science suggested that 2019–2020 wildfires are unprecedented and have burned 12 million hectares of forest and agricultural areas in the southeastern Australia (Lindenmayer and Taylor, 2020). Additionally, droughts, intensified by climate change, further contribute to the likelihood of wildfires (Smith et al., 2017). Examining the contributions of countries, journals, and institutions sheds light on the collaborative efforts within the scientific community. The United States emerges as a significant contributor, underlining a national commitment to addressing forest fire challenges. The collaborative network, as evidenced by the top publishing journals and affiliations, emphasizes the global nature of the research community's efforts. Journals like the International Journal of Wildland Fire and affiliations such as the USDA Forest Service play pivotal roles in not only disseminating knowledge but also driving research initiatives.

The financial backing of research is a crucial aspect, and the identification of funding sources elucidates the support structure for forest fire studies. The diversity of funding agencies, spanning 148 entities across 28 nations and 20 international organizations, emphasizes the global collaboration in this field. The preeminent role of the National Science Foundation in funding, followed by international bodies like the National Natural Science Foundation of China and NASA, underscores the widespread interest and commitment to advancing knowledge on forest fires. Noteworthy is the inclusion of funding from various sectors, including government agencies, foundations, and international organizations, showcasing the multifaceted approach to supporting this research. The keyword analysis reveals the evolving focus areas within forest fire research. While traditional keywords like "Fires," "Wildfire," and "Deforestation" remain prevalent, the emergence of terms like "MODIS," "Artificial Intelligence," "Algorithm," "Satellite Data," and "Prediction" indicates a contemporary shift towards integrating advanced technologies. This suggests a recognition within the scientific community of the potential of cutting-edge tools in enhancing our understanding and management of forest fires. In response to the importance of addressing forest fires, numerous global research and development initiatives have been established. These include the Global Wildland Fire Network (GWFN), which facilitates international cooperation in wildfire management and promotes research and development efforts to enhance fire management practices. The Global Fire Monitoring Center (GFMC), a collaborative effort of the United Nations, is dedicated to improving understanding and management of wildfires through research, training, and capacity-building activities. The International Association of Wildland Fire (IAWF) serves as a platform for researchers, practitioners, and policymakers to exchange knowledge and promote collaboration in fire science and management. Similarly, the European Forest Fire Information System (EFFIS), Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD), NASA's Fire Information for Resource Management System (FIRMS), the Joint Fire Science Program (JFSP), the Collaborative Forest Landscape Restoration Program (CFLRP), Fire Smart Canada, and the Australian Bushfire Cooperative Research Centre (Bushfire CRC) are notable initiatives focused on wildfire research, monitoring, and management (Pyne et al., 2012). Remote sensing technology has been proven by numerous studies as a practical and effective technique for thoroughly characterizing the pattern and extent of fire occurrence in forest ecosystems (Santos et al., 2021). Additionally, online satellite imagery resources have significantly improved the efficiency and coverage of wildfire mapping, such as in the Babeldaob watershed (Dendy et al., 2022). The imagery resource provides a more accurate picture of fire area, their patterns and provide important practical value to simulation efforts (Dendy et al., 2022). It is intriguing that despite the presence of various research and development initiatives, there has been a concerning increase in the incidence, affected area, and frequency of forest fires. This necessitates the planning and implementation of an integrated approach to monitoring and environmental protection of forest fires, with well-defined actions that align with shared objectives (Dong et al., 2017; Goodale et al., 2021; Sharma, 2017). However, it may be mentioned that research efforts in forest fires are not uniformly distributed across different geographical regions. The United States and China have been the focal points of the majority of studies, contributing 28 % and 10 % respectively. In the light of this, it will be fruitful to make a global appeal to the scientific community, urging them to collaborate and develop policies, management strategies, and practices aimed at reducing the frequency, incidence, and impact of forest fires. Wildfire research is isolated within disciplines such as forestry and atmospheric chemistry, therefore it is necessary to integrate disciplines by promoting coordination among physical, biological, and social science (Li et al., 2022a,b). Prescribed fire is a proactive approach to wildfire prevention and control by setting fires to remove combustible material from the forest by artificially controlling the intensity and extent of the fire (Mayer et al., 2020; Jones et al., 2022). In the controlled areas, low-intensity, controlled fires with little risk of spread are used to remove ground combustible material, allow old-growth stands to fall and breed new forests, and bring back the natural ecology to health. There are uses of low-intensity, controlled wildfires with little risk of spread to remove combustible material from the forest floor, dead wood that have not fallen, prescribed fires to prevent and control the major wildfires and allow forests to regenerate (Wang et al., 2015; Zhang et al., 2018; Tahmasbian et al., 2019; Reverchon et al., 2020; Jones et al., 2022). Allowing a portion of the wildfire to burn naturally or to burn out first is about removing flammable material from the forest for planned burning (Wang et al., 2014, 2015, 2020a, b). But the central question is how much to burn, where to burn, and how to burn it. Some scientists want to use mathematical equations to simulate fires (Quintero et al., 2021), to study where fire risk is greatest and how "planned burns" can minimize the risk of forest wildfires under different models of specific weather conditions, vegetation types, topography, fuel loads, etc. (Guinto et al., 1999a, b; Long et al., 2014; Ma et al., 2015; Wang et al., 2015, 2020c). Under the simulation model, planned burning is theoretically efective. Burning all the flammable material in the forest that needs to be removed, regardless of any restrictions, is efective in reducing the occurrence of wildfires (Wang et al., 2014; Taresh et al., 2021). However, there are also problems in the simulation such as uncertainty of future severe fire weather. For example, the simulation model showed that on average, prescribed burning reduces wildfire extent in dry forested grasslands by only 1 ha per 3 ha. This suggests that it is almost impossible to reduce the occurrence of forest wildfires by prescribed burning alone, but such planned burning has been proven by many studies to be one of the important and useful disturbance methods to effectively reduce forest wildfires and manage forest ecosystems (Davis et al., 2022). However, if planned burns are used blindly to remove, it may also bring negative effects such as damage to young forests on forest land. Henceforth, upcoming research endeavors should align with the proposed burn management strategy, necessitating additional focus on enhancing simulation accuracy and scale. In a prolonged unburned region of northeastern Washington State, USA, the most substantial impact on fire intensity was observed across a broad bioclimatic gradient. Findings indicated that factors such as previous fire events, harvesting, clear-cutting, and particularly planned burning could mitigate fire intensity in subsequent forest fires (Cansler et al., 2022). The comprehensive analysis presented here not only offers a snapshot of the current state of forest and wildfire studies but also provides valuable insights into the historical evolution, collaborative dynamics, and emerging trends within this critical field. The global nature of contributions, interdisciplinary approaches, and the infusion of technological advancements underscore the collective efforts aimed at mitigating the impact of forest fires on our ecosystems and communities. Through collective and innovative efforts, we can effectively address this urgent and important issue and safeguard the invaluable ecosystems and resources provided by nature.

Conclusion

Forest fires have been integral to Earth's history for over 400 million years. This study represents a pioneering effort in employing bibliometrics and terminology analysis to offer a consolidated and comprehensive examination of the literature pertaining to forest fires/wildfires within the SCOPUS database. A significant rise in forest fire occurrences persists despite ample scientific research publications. Valuable scientific insights from diverse global regions continue to accumulate, with active participation from the international scientific community. Noteworthy contributors include the United States, China, Canada, Spain, Australia, and India, with funding primarily sourced from organizations like the National Science Foundation, National Natural Science Foundation, U.S. Forest Service, and National Aeronautics and Space Administration.

The study reveals an exponential surge in publications after 2000, particularly in the last 20 years, indicating growing academic interest.

Despite these advancements, challenges persist. Wildfire research remains compartmentalized in disciplines like forestry and atmospheric chemistry. Improved accuracy in wildfire model simulations is essential, necessitating advancements in numerical simulations considering factors like climate, hydrology, atmosphere, soil, and topography. Developing coupled models incorporating human dimensions is crucial for predicting future fire activity and effects accurately. However more focused and in-depth studies by the scientific community in the future are required, recognizing its pivotal role as a driver and key disturbance factor in global climate change and forest ecosystem succession.

Declaration of funding

This research did not receive any specific funding.

CRediT authorship contribution statement

Himanshu Bargali: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Aseesh Pandey:** Writing – review & editing, Supervision, Data curation. **Dinesh Bhatt:** Writing – review & editing, Supervision. **R.C. Sundriyal:** Writing – review & editing, Supervision, Conceptualization. **V.P. Uniyal:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank the Director G.B. Pant National Institute of Himalayan Environment (NIHE'), Almora for providing institutional support to conduct this study. Authors express sincere thanks to Dr. G.C. S. Negi, former Scientist G, NIHE for his encouragement and anonymous reviewers for proving valuable inputs. HB and AP acknowledge the partial funding support from Department of Science and Technology, Govt of India under NMSHE-Task Force-3 Phase II (Forest Resources & Plant Biodiversity).

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