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Trends in Global and Mexico Research in Wildfires: A Bibliometric Perspective

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Abstract

In the last two decades, unprecedented changes have taken place in the frequency and severity of wildfires; in different regions of the world, some fires were even classified as megafires. Although there are studies about the diverse effects of fire, which have made significant theoretical contributions, a comprehensive review of the changes in fire research is required to understand worldwide patterns, particularly in those countries where fire activity is on the rise, such is the case of Mexico. The objective of this study was to analyze the trends in the research on wildfires published in Mexico and worldwide over a 40-year timescale. For this purpose, the Web of Science database, bibliometric tools, and the keywords TI = Forest fire* OR TI = Wildfire* were used to extract as many articles as possible related to fires from 1980 to 2020, without being restricted to those studies whose title included any of the variants of the keywords. There were 8458 publications about fires in the vegetation cover, with a notable increase in the frequency of studies in the previous decade; 52% of the studies were concentrated in five countries and 20% of the articles focused on the study of different aspects of the soil. Mexico ranks thirteenth in volume of scientific production and studies in the country have focused mainly on the description of the quantitative relationship between the size of the affected area and the number of occurrences in the landscape, meanwhile, studies on fires and the consequences on the biotic interactions have been little explored.

Keywords

Global Warming, Fire Regime, Forest Ecosystems, Biotic Interactions, Anthropogenic Activities

1. Introduction

Wildfires are one of the most important natural disturbance processes in the world (He et al., 2019). In geological time terms, fire is considered a determining factor in climatic regimes; it is also a factor in the diversification of plants, since they colonized terrestrial environments, approximately 350 - 410 million years ago, during the Devonian-Silurian period (Scott, 2018). In the ecological context, fire plays an important role in the maintenance of biodiversity and in the regeneration dynamics of savannahs, scrublands, temperate forests (where oaks and pines predominate), and boreal forest (characterized by the presence of various conifers), among other environments. However, this natural phenomenon is now considered a destructive disturbance, because of the increase in the frequency and severity of fires in recent decades (Fidelis, 2020).

In the mid-20th century, the frequency and severity of fire regimes increased considerably, because of human activities related to industrialization, land use change, and urban sprawl (Pausas & Keeley, 2009). The last two decades have seen unprecedented changes in fire regimes because of climate change. The increase in the concentration of greenhouse gases in the Earth's atmosphere contributes to the increase in global temperature, which is 0.85˚C ± 1.2˚C higher than in the 20th century (Gen-Suo, 2020). Although this increase seems marginal, on a global scale, heat waves and prolonged droughts have been reported, which—associated with an abundant load of dry fuel in natural and anthropogenic systems—cause more fires (Attri et al., 2020). Currently, the average annual duration of the wildfire season in the world is 20% higher than the percent recorded ten years ago; this phenomenon has caused an increase in the extent of fires (Jones et al., 2020).

The 2019 megafires coincide with above-average record temperatures for the 1981-2010 period (Di Virgilio et al., 2019). In Australia, more than 12 million hectares burned, causing the death of dozens of people (Abram et al., 2021). In the Amazon rainforest, fires consumed almost 5.9 million hectares, releasing 969 million tons of CO_2 into the atmosphere (Dong et al., 2021). In California, USA, a state of emergency was declared as the flames consumed close to 100,000 hectares (Li et al., 2021). In Chile, the number of fires doubled compared to 2018, while Central Africa and the Mediterranean basin registered the highest number of fire sources (Abatzoglou et al., 2019). This increase in fire activity does not only take place in areas historically affected by fire; however, large-scale wildfires have been reported with increasing frequency in areas where those events rarely took place.

This increase in temperature intensifies atmospheric oscillations in the whole world. Specifically, as a consequence of the South Pacific oscillation known as El Niño/La Niña, periods of heavy rainfall—which favor high primary productivity—are interspersed with periods of prolonged drought—in which there is a rapid accumulation of flammable material, which can catch fire spontaneously. However, most of the fires are related to anthropic activities, such as deforestation, agriculture, and livestock, as well as to intentional/accidental burnings (Flores-Garnica, 2009; Juárez-Orozco et al., 2017).

In Mexico, the number of fires has also increased in the last decade. More fire events took place in 2011 (12,113 fires), 2013 (10,406), 2016 (8422), 2017 (8896), 2019 (7410), and 2021 (7337) than in other years, except for 1998, when a record figure of 14,315 disasters was recorded (CONAFOR, 2022; SEMARNAT, 2022a). The severity of wildfires in Mexico has also been increasing. They were once of low and moderate severity, but now they have reached the "very high" severity category in some areas in central and northern Mexico (CONAFOR, 2022). Overall, the frequency and severity of wildfires have intensified along with the global temperature increase (global climate change).

Faced with this scenario, the national community has researched fire and its severity, promoting the development of studies aimed at understanding core aspects, such as fuels, distribution, behavior, and its modeling in various ecosystems (Rodríguez-Trejo et al., 2011). In addition, given the negative effect of fires on ecosystems and human communities, priority should be given to further research about the trends of wildfires and their consequences at the national level (Robinne et al., 2018). Likewise, the lack of systematization and analysis of knowledge about wildfires in Mexico contrasts with the work done in other countries and regions (United States, Australia, Central Africa, the Amazon rainforest, and Mediterranean Europe) where wildfires have traditionally been the subject of scientific research (Abatzoglou et al., 2019). Therefore, reviewing published works is a starting point to detect general patterns and design future research as conservation and management programs.

In this context, the objective of this study was to analyze the trends in the research in wildfires global scale with emphasis in the Mexican situation over a 40-year timescale. This work seeks to understand the space-time patterns of the study of wildfires and the topics addressed. A bibliometric approach (comprising a set of quantitative methods) was used to analyze the published literature, in order to identify trends in research development (Broadus, 1987; Zhang et al., 2019; Santos et al., 2021). This methodology was used to answer the following questions: 1) What is the temporal and spatial distribution of studies on wildfires? 2) What countries have done more research about wildfires? 3) What wildfire topics are most frequently addressed? 4) Which are the most evaluated ecological variables in studies on wildfires? 5) In which ecosystems have most of the researches been carried out? and 6) What is the status of studies about biotic interactions and fires?

2. Materials and Methods

Data Collection

An advanced search of the articles about wildfires published during the last 40 years (1980-2020) was carried out in the Web of Science database. The TI = Forest fire* or TI = Wildfire* logical operators were used to extract all possible publications related to wildfires, where "TI=" restricts the search to those studies whose title includes any of the variants of the keywords. All the resulting publications were exported in the BibTeX format, with their full record and cited references. The information was classified according to its ID, author, year, title, journal, abstract, and keywords. The R 3.3.1 software (R Core Team, 2020) was used to create a database with the following fields: 1) year of publication, 2) articles by country, 3) topics, 4) ecological variables, 5) ecosystems, and 6) biotic interactions. Each record was carefully reviewed to exclude those items that did not agree with the objective of the work. To be included in the review, the publications had to meet the following criteria: 1) they were articles published in English or Spanish, and 2) the articles belonged to environmental disciplines (environmental, agronomic, geographical, ecological, etc.). Reviews, book chapters, and conference proceedings were not considered, because they can be published more than once in different media and be subsets of primary sources (Vasconcelos et al., 2020).

3. Results

3.1. Spatiotemporal Analysis

In total, 8458 publications related to wildfires were found for the 1980-2020 period. The number of publications has geometrically increased worldwide. Starting from an approximate annual rate of 100 articles in the year 2000, an annual rate of 400 articles was reached in 2010 and almost 700 articles were published in 2019. The production of research papers in this last period (2013-2019) accounts for the 46.7% (3957 studies) of the total publications analyzed (**Figure 1(a)**). In the case of Mexico, 118 publications were registered: a noticeable lag in publications from 1980 to 1997, with only one article published (**Figure 1(b)**). From 1998, the number of articles showed an erratic pattern of increase. However, the numbers of articles published (78) underwent a sustained growth (66.1%) from 2006 to 2015; most of the articles (13) were published in 2015 (11%) (**Figure 1(b)**).

3.2. Countries

The articles were published in 128 countries (**Figure 2**). Most of the studies were concentrated in the United States (1020), Canada (654), Australia (576), Spain (466), Mali (373), Portugal (223), Brazil (205), China (201), and the United Kingdom (198). Mexico ranked thirteenth in the world (118), behind India and Greece, which have 121 and 150 publications, respectively (**Figure 2**).

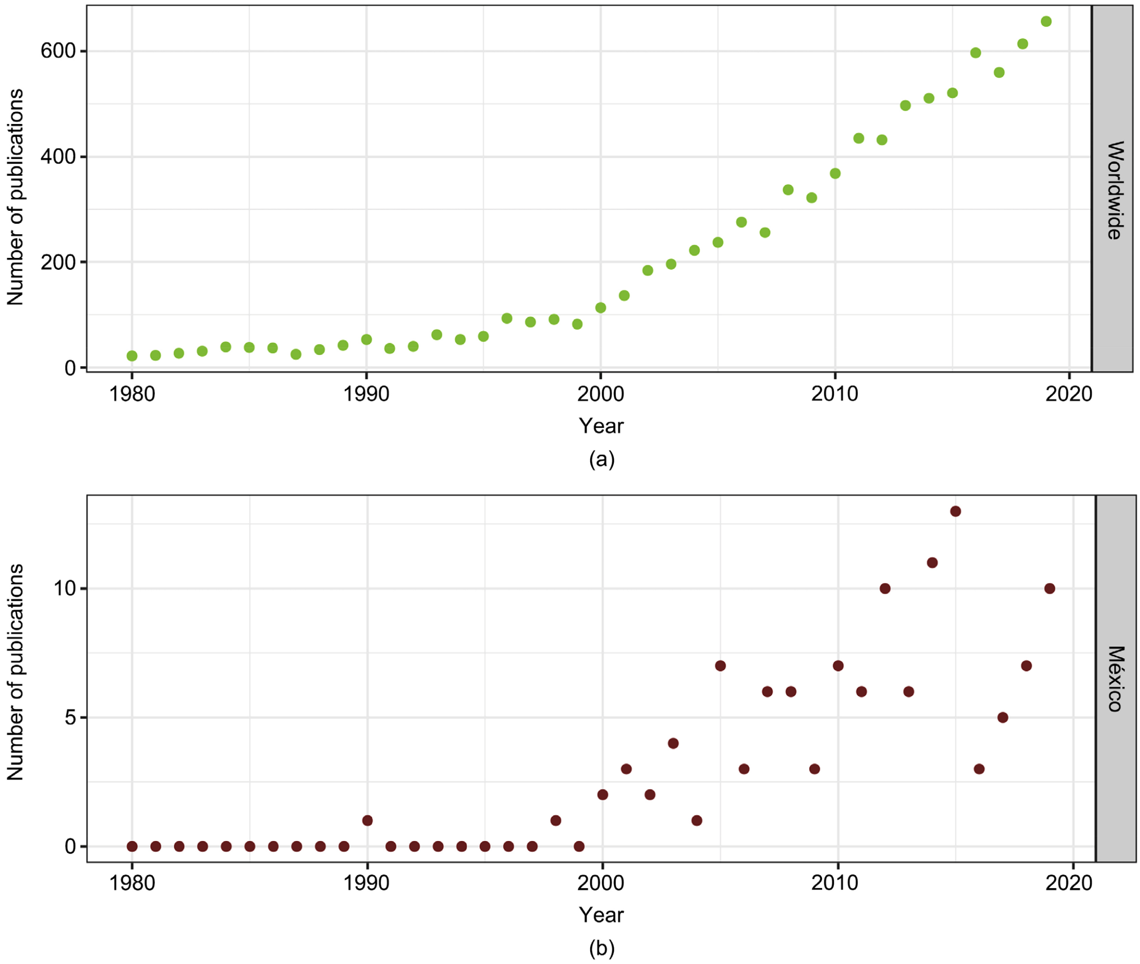

Figure 1. Temporal variation in the number of publications about wildfires: (a) worldwide (N = 8458), and (b) Mexico (N = 118). The dots indicate the number of publications per year.

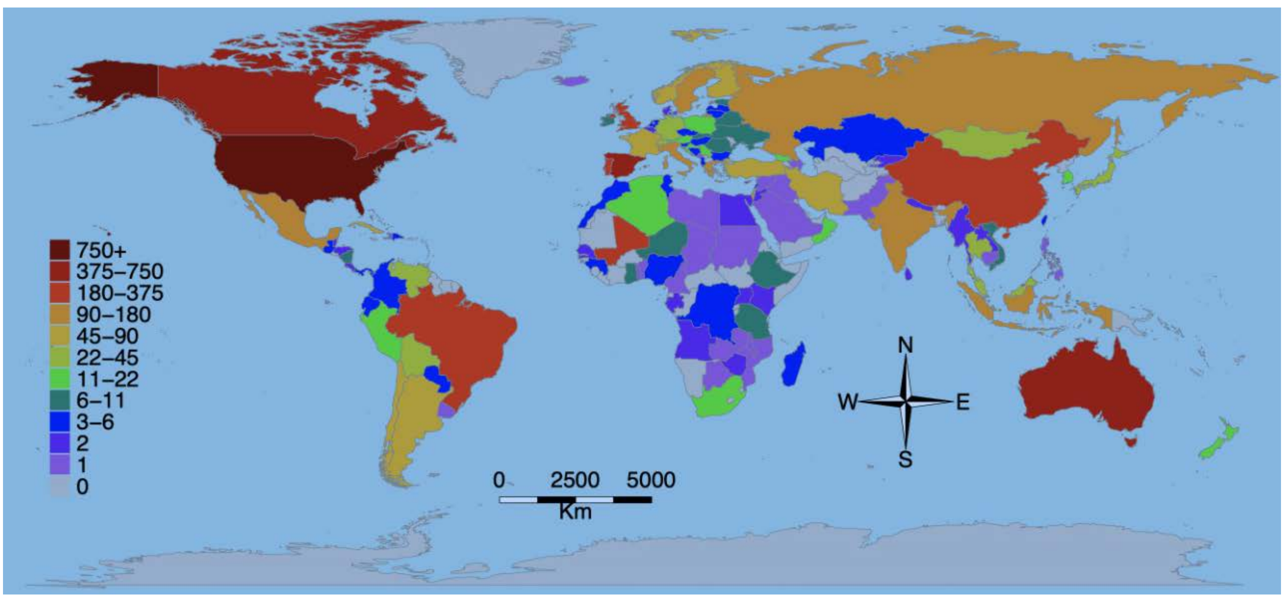

Figure 2. Spatial distribution of the number of publications related to wildfires in the world. The color scheme represents the number of articles per country.

3.3. Topics

Worldwide, 70 research topics were detected in articles about wildfires (Figure 3(a)). The topics with the highest recurrence (almost 20% of the publications) were different aspects of the soil (1694) and anthropic disturbances (1672). The composition and structure of the vegetation was the focus of 15.4% of the analyzed publications (1310). In the case of Mexico, the main topics were the spatial distribution of wildfires (24), the anthropic disturbance associated with fires (21) and the regeneration of vegetation (20). Wildfire studies account for 20.3% of the publications registered in Mexico, while anthropic disturbance and the regeneration of forest vegetation each account for 17% of the publications (Figure 3(b)).

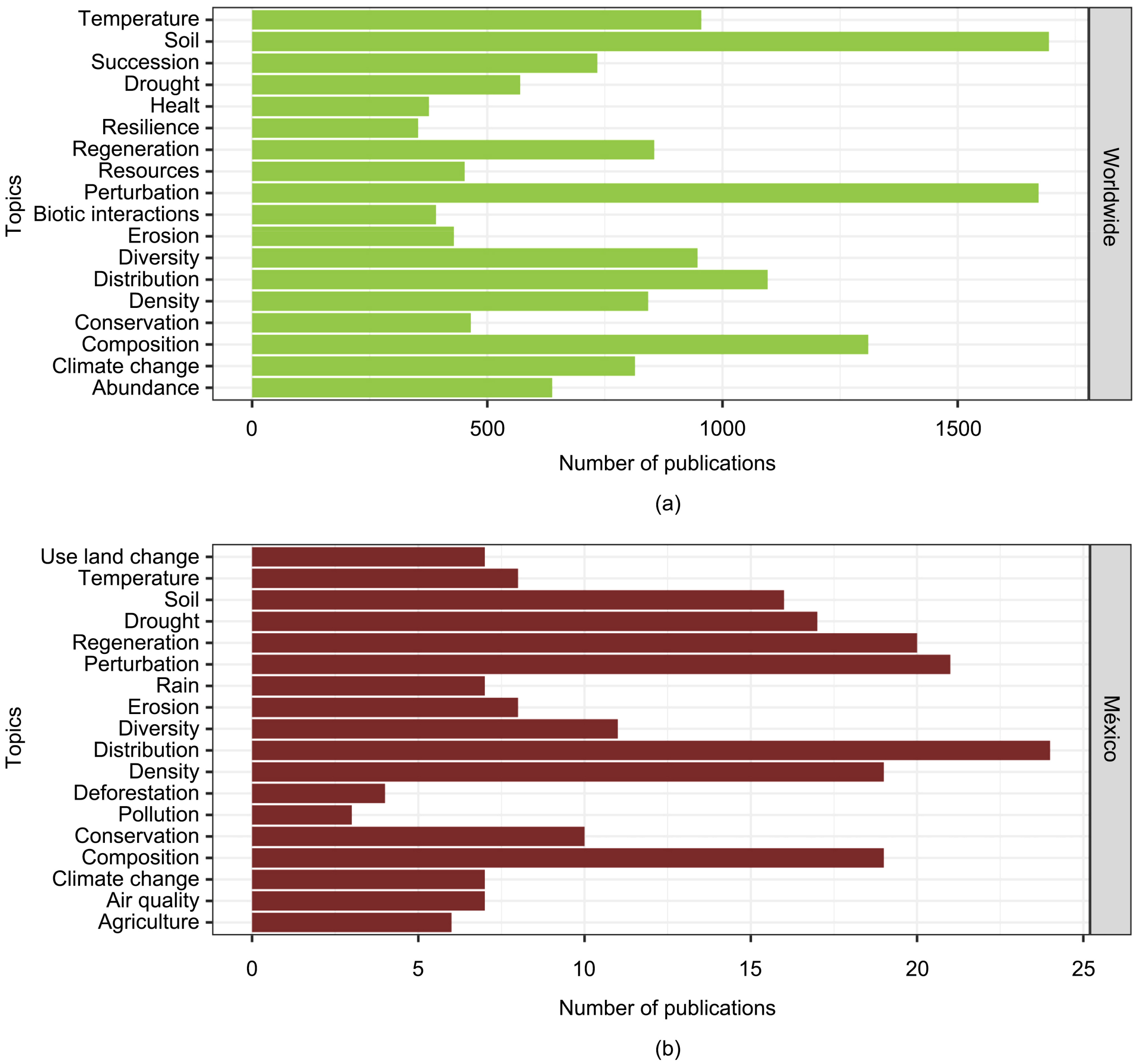

Figure 3. Number of publications that evaluated different topics related to wildfires: (a) worldwide, and (b) Mexico.

3.4. Ecological Variables

Out of the 8458 publications, 4369 focused on ecological studies. The most frequently studied variables were those focused on the community and environment level. The most frequently recorded terms were species diversity and regeneration of vegetation with 947 and 855 articles, respectively (Figure 4(a)). For Mexico, 69 articles were related to ecological studies, mainly focusing on the regeneration of vegetation and the population density of species in ecosystems, with 20 and 19 articles, respectively (Figure 4(b)).

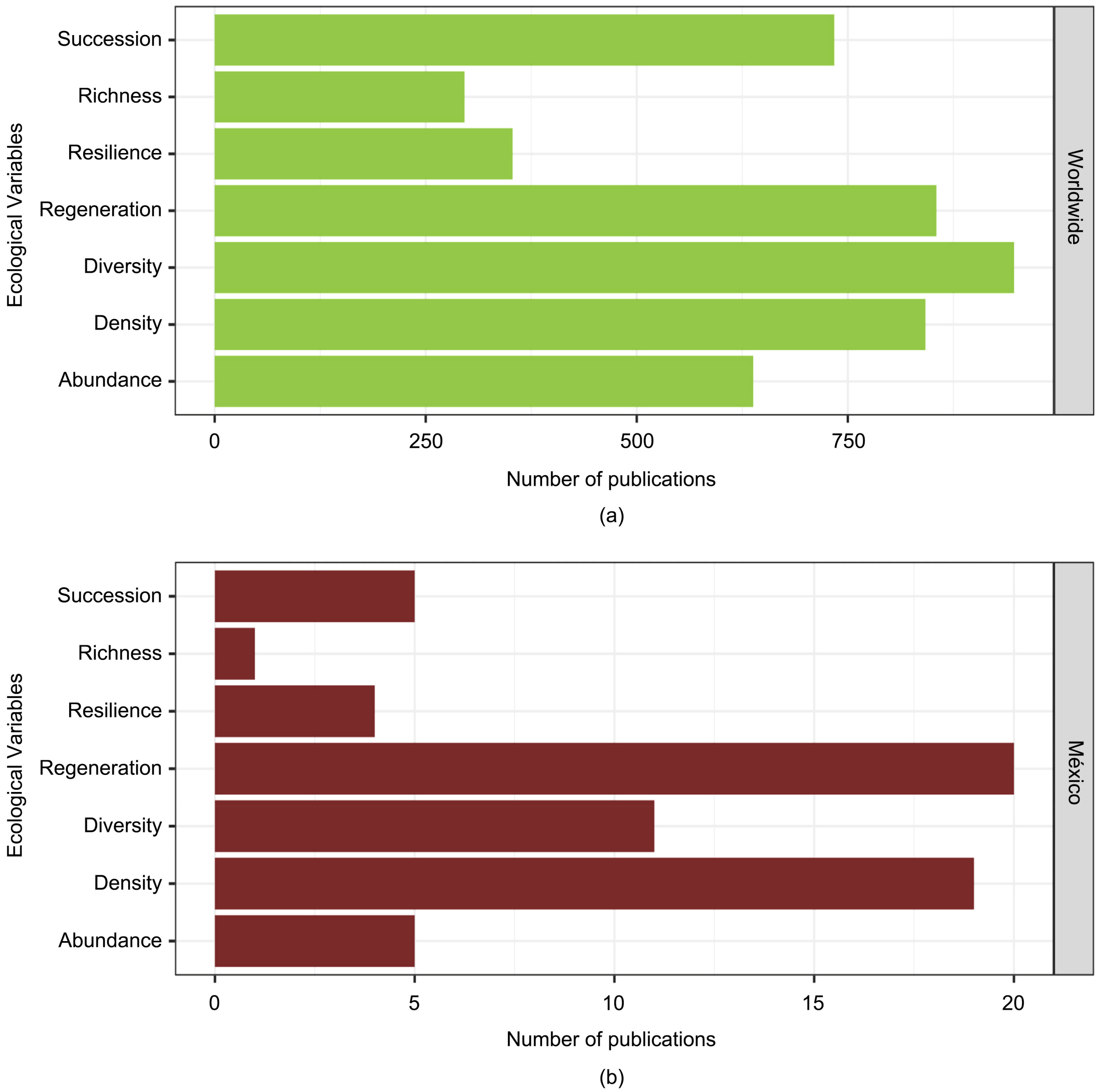

Figure 4. Temporal variation in the number of publications about wildfires: (a) worldwide (N = 8458), and (b) Mexico (N = 118). The dots indicate the number of publications per year.

3.5. Ecosystems

In total, 65 nominations were registered for the types of vegetation, which were grouped into four main biomes (temperate forests, arid zones, aquatic ecosystems, and tropical forests) as urban areas and crops. Figure 5 shows that most of the studies about wildfires were carried out on the temperate forest biome (3617 publications: 42.2%). Out of those publications, 1118 (30%) were carried out in the boreal forest and 893 (24%) in the pine forest. The second most studied biome (877 articles; 10.3%) were the aquatic ecosystems, focusing on the effects of fires on water bodies—such as sediment and ash pollution that modify the pH level—, as well as on the carbon released into the underground layer. In Mexico, 81 studies (71.2%) have been carried out in temperate forests, including 21 articles about pine forests (25%) and 13 articles about other conifers (15%) (Figure 5).

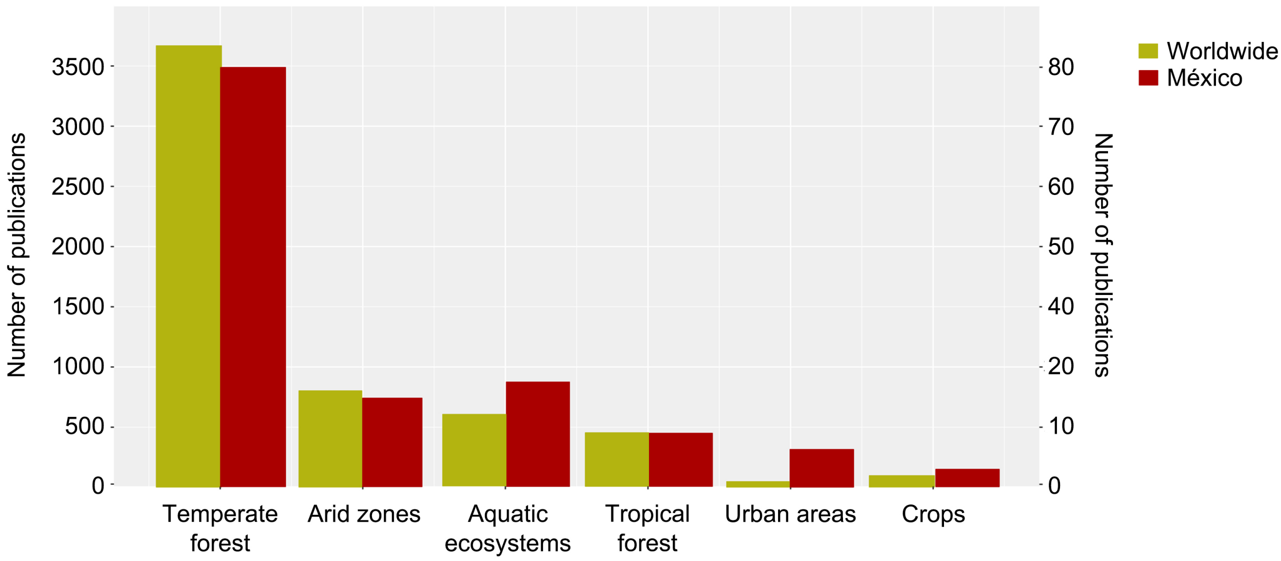

Figure 5. Number of publications in the different ecosystems of worldwide. The green bars represent the number of articles worldwide, while the red bars represent Mexico (right-side axis).

3.6. Biotic Interactions

Eight biotic interactions were taken into consideration in this field. The two most evaluated subjects related to wildfires were predation (predator-prey) and mycorrhizae, with 99 and 91 mentions, respectively, which account for 50% of all publications (Figure 6). Parasitism and frugivores were the least studied interactions (<5%). In the case of Mexico, two studies evaluated the effects of fires on mycorrhizae and lichens over a 40-year timescale.

4. Discussion

4.1. Temporal Trends of Publications

The worldwide interest in scientific research about wildfires has increased remarkably in the last 20 years. From 2013 to 2019, 3957 publications were produced: 46.7% of the total articles analyzed. This trend coincides with the increase

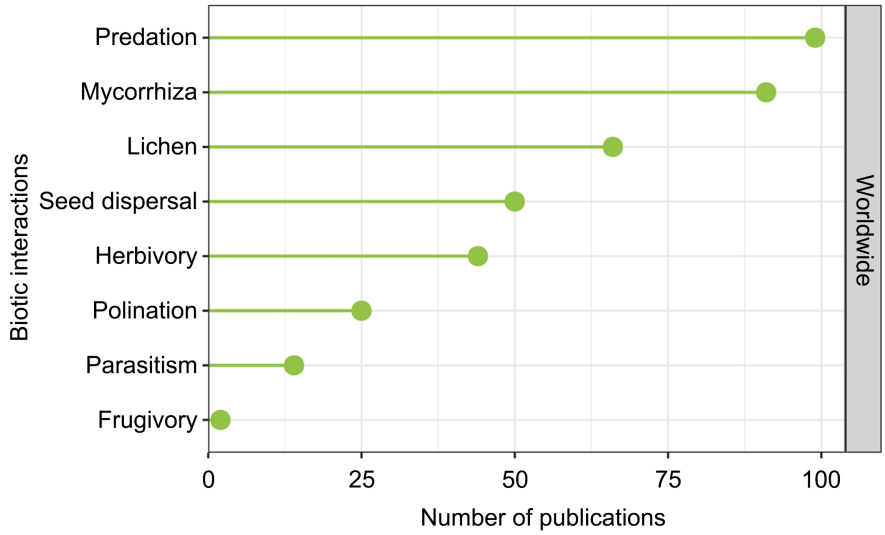

Figure 6. Number of articles on fires and their effects on biotic interactions (N = 391).

in global temperature and its effects on climate regimes in recent years (Rebecca & Luann, 2021). The increase in scientific research in recent years could be related to the ecological, economic, and social impacts generated by wildfires in the world (Doerr & Santín, 2016). For example, more than 350 million hectares of vegetation are affected by fire each year; this phenomenon causes economic losses of ~100 million dollars (Attri et al., 2020). Similarly, indirect health impacts attributed to smoke exposure include loss of human life and post-traumatic stress disorders in populations affected by the event (Abram et al., 2021).

In Mexico, extreme weather events associated with global climate change have also undergone a significant increase in the last decade (Bautista Vicente, 2015). Yearly climate variations have been largely influenced by the El Niño Southern Oscillation (ENSO) (Pompa-García & Sensibaugh, 2014). Specifically, this phenomenon—which favors high temperatures and droughts—has a strong relationship with wildfires (Juárez-Orozco et al., 2017). This study identified an increase in the number of studies on wildfires in Mexico from the 2000s, which probably responds to the record number of wildfires that took place in 1998 (Jiménez & Mendoza, 2019). Prior to the year 2000, a lag in the scientific production of wildfires studies was detected; only one article was detected during that period. This could be related to the fact that before the year 2000, information related to fires or prescribed burning was not documented in indexed articles, only in technical reports (Flores-Garnica, 2021). However, the 1998 fire season made visible the impact of wildfires in Mexico and brought about changes in fire management policies and practices (Rodríguez-Trejo et al., 2011). By the year 2000, government agencies, universities, and institutes—such as the Comisión Nacional Forestal (CONAFOR), Secretaría de Medio Ambiente (SEMARNAT), Comisión Nacional de Áreas Naturales Protegidas (CONANP), Instituto Nacional de Investigaciones Forestales Agrícolas (INIFAP), Universidad Autónoma Chapingo (UACh), and Colegio de Postgraduados (CP)—began to lay the foundations for fire ecology research and practice, and integrated community management in rural areas, as well as fire prevention and combat (Domínguez & Rodríguez-Trejo, 2008).

4.2. Spatial Distribution of Publications

Approximately 52% of the publications on wildfires worldwide were concentrated in five countries. The high number of publications is related to technological advances. For example, the technological development that they have generated in recent years has allowed the United States and Canada to become world leaders in fire research. Their technological development includes sensor systems that have allowed them to determine data in time series and to make advances in satellite image processing techniques (Chuvieco et al., 2019). The United States Forest Service (USFS-USDA) is the institute that has published more articles in the world and more than 15 editors work in the main fire-related magazines of the country.

Some countries in Southeast Asia and North America have showed a low productivity in terms of wildfire studies. In most tropical countries (such as India and Mexico), the percentage of the gross domestic product allocated to environmental problems is low. Unlike infrastructure development and agricultural expansion, the environment is not considered a priority (Juárez-Orozco et al., 2017). Similarly, poverty, lack of forest management, and poor governance hinder the development of the issue (Domínguez & Rodríguez-Trejo, 2008).

4.3. Main Reported Topics

The main topic were the effects of wildfires on the ground, perhaps as a result of the fact that soils are subject matter in which forest succession and its impact on biodiversity can be rapidly evaluated (Erickson & White, 2008).

The impact of fires on soils can be both beneficial and detrimental, depending on their frequency and severity (Mataix-Solera et al., 2011). For example, various studies have shown a decrease in the colonization of mycorrhizae and microorganisms, when the frequency and severity of fires increase (Certini, 2005). Other authors mention that low-impact fires positively affect the diversity of the soil mesofauna (Certini et al., 2021). For their part, moderate impacts lead to an increase in soil fertility and the establishment of various plant species (Cadena-Zamudio et al., 2020), while high severities have negative effects on vegetation and soil, mainly related to the loss of carbon and nitrogen (Girona-García et al., 2021). Drawing general conclusions about the possible links between fire, soil, and ecosystem functioning is hindered by the still incipient knowledge about the responses of biodiversity to the different fire severities, as well as about the seasonal and spatial variations in the distribution of biological diversity and its physiological capacities. Therefore, government bodies and other funding agencies should prioritize the promotion of an ongoing research in the area (Pressler et al., 2019).

Prescribed burning has been the focus of much research worldwide. The main objective of this activity is to eliminate the excess fuel that could generate a high intensity fire; additionally, it promotes some ecological processes (Doerr & Santín, 2016). Similarly, prescribed burning is used to increase soil fertility by accelerating the decomposition of organic matter. This practice increases the concentration of nutrients in the soil, including carbon, nitrogen, phosphorus, and calcium. These procedures are also used for the regeneration of grazing grasslands (Williams et al., 2012), but often at the expense of xerophytic shrublands and grasslands.

Land use change and the transformation of forests to productive agricultural systems are known to be closely related to the increase in the frequency of wildfires (SEMARNAT, 2022b); however, in Mexico these issues have seldom been addressed in the literature. The most studied topic in Mexico related to wildfires was their distribution. Specifically, the main subject has been the distribution of the size of fires (Schoenberg et al., 2003)—i.e., the quantitative relationship between the size of the fire and the number of occurrences in a forest landscape or region during a given period (Cui & Perera, 2008). The interest of researchers in the distribution of the size of fires has extended beyond forest management; they also have sought to understand the factors that influence the distribution of fires (Cruz-Espíndola et al., 2017). For example, emphasis has been placed on the consequences of fires, taking into consideration the spatial heterogeneity of the habitat (Flores-Garnica & Omi, 2003) and space-time analysis (Cruz-López et al., 2019).

4.4. Post-Fire Ecological Variables Reported in the Literature

The greatest interest was placed on changes in plant, animal, and soil communities after one or more wildfires. In particular, diversity, density, and regeneration were the ecological variables evaluated: mainly, vegetation (Mexico) and soil and its organisms (globally) (Certini et al., 2021).

The severity and intensity of a wildfire modify the physical and chemical properties of the soil. For example, the soil keeps its water retention capacity, low erosion is recorded, and nutrient (phosphorus, nitrogen, and potassium) storages are maintained, facilitating the recovery of vegetation through the regeneration of shoots (Clarke et al., 2015). These processes can influence plant diversity in the early post-fire stages where the number of herbaceous and shrub species increases (Pressler et al., 2019). Meanwhile, changes in diversity can take more years for tree species (Randrianarison et al., 2015). After a fire, the richness and abundance of the species of soil organisms increase when the severity of the said fire is moderate, while the recovery is considerably slower in high severity cases (Cadena-Zamudio et al., 2022). These effects also have short-, medium-, and long-term implications for the dynamics of the soil food web and the resilience of ecosystem communities (Certini et al., 2021).

4.5. Most Impacted Ecosystems as a Consequence of Wildfires

Worldwide, temperate forests are one of the most studied ecosystems in relation to wildfires. The boreal forests stand out among these ecosystems, covering 1.3 million km^2 of the northern circumpolar areas of Earth: vast areas of Canada, the United States (Alaska), Scandinavia, Russia, and northern China (Irannezhad et al., 2020). These forests are characterized by long, cold, and dry winters that limit the decomposition of organic matter; therefore, fire constitutes a natural mechanism that completes forest regeneration and other ecological processes and is essential for the maintenance of soil biogeochemical cycles (Scholten et al., 2021).

The North American boreal forest is characterized by high frequency fires with great intensity and severity. In contrast, the boreal region of northeastern Asia experiences moderate fires of low to moderate intensity and severity. This dichotomy in boreal fire regimes is seemingly related to type (crown *vs* surface fires) and tree species morphology (fire-sensitive broadleaved *vs.* thick bark), as well as continental differences (Scholten et al., 2021). In the case of North America, demographic trends, industrial development, and urban sprawl have increased fires in recent years (Irannezhad et al., 2020).

In Mexico, just like in the rest of the world, temperate forests (mainly pine and other coniferous forests) dominated the trend among biomes with the highest number of studies about fires. Temperate forests account for 17.4% of the total area of Mexico. They are considered centers of diversity for pines and oaks, with 50% (50) and 33% (200) of the total worldwide species, respectively (Challenger & Soberón, 2009). Fire is a key component of the ecological dynamics of these ecosystems. For example, fire is an element that guarantees the survival of the species of the genus *Pinus* spp., such as *P. douglasiana*, *P. durangensis*, *P. oocarpa*, and *P. devoniana*, (Rodríguez-Trejo & Fulé, 2003), while it promotes the opening of the serotinous cones of *P. greggii*, *P. attenuate*, and *P. patula*, which release their seeds, favoring natural regeneration (Flores Rodríguez et al., 2021). It is important to point out that agricultural activities and prescribed burning cause 90% of the fires in Mexico; therefore, most of the studies have been based on these activities (Flores-Garnica, 2009).

4.6. Post-Fire Biotic Interactions

In the case of research on biotic interactions, the effects of fire on predation (predator-prey) and their responses to this disturbance have received the most attention. This phenomenon can be attributed to the fact that fire can directly kill predators or preys (Geary et al., 2020), affecting the availability of food or other habitat components, which ultimately influence the abundance and/or behavior of preys (Hradsky et al., 2017). In addition, changes in the structure and composition of the vegetation caused by fires can favor invasive predators, because fires cause a decrease in the populations of native predators (Banks, 2011).

In Mexico, only two studies evaluated the effects of fires on mycorrhizae and lichens in 40 years of research. This highlights the scarce interest in the topic of the impact of fires on biodiversity and the dynamics in the resilience of biotic groups (Koltz et al., 2018). In particular, it accentuates the information gap regarding the effects of fires on biotic interactions such as competition, facilitation, herbivory, pollination, seed dispersal by frugivorous and granivorous animals, interaction between fungi and plants, and their functioning in ecosystems (Pausas & Parr, 2018).

Overall, fire studies in Mexico have focused on other aspects. Specifically, studies have been carried out about the following subjects: the evaluation and characterization of forest fuels and the estimation of fire behavior (Flores-Garnica, 2021); the smoke generated by wildfires in central Mexico (Jardel-Pelaez et al., 2009); the modeling of fuels through geographic information systems (Flores-Garnica & Omi, 2003); and the effect of fire in reducing the species diversity and its role in the morphological and phenological characteristics of trees and forests (Rodríguez-Trejo & Myers, 2010). Therefore, the inclusion of new ecological approaches (such as fauna, soil, insects, hydrology, and biotic interactions) will generate a different perspective on the ecology of fire.

5. Closing Remarks

Climate warming will cause more fires in many regions of the world; fires will be more frequent and extreme, putting lives, economies, and ecosystems at risk (Jones et al., 2020). Therefore, understanding fire regimes is a priority for the short-, medium-, and long-term mitigation of risk situations in areas prone to these events. These studies will provide a better understanding of the relationship between fire and human societies, reconsidering the former as a natural ecological agent that is essential in many ecosystems and not as a destructive disturbance.

The observation of fires by remote sensing, the characterization of space-time patterns, and the simulation of the risk of wildfires will provide early warning that will enhance pre-fire prevention. In the case of Mexico, a reference framework for fires and climate change—that includes a diagnosis of those regions that require an immediate response—must be developed.

6. Conclusion

The number of publications increased during the analyzed period. Five countries concentrated 52% of the total articles published (Mexico ranked thirteenth). Different aspects of the soil were the focus of 20% of the studies, while in Mexico the focus was the distribution of the size of the fire. The most frequently recorded ecological variables were species diversity and regeneration of vegetation. Temperate forest was the biome where most of the studies on wildfires have been conducted. Finally, studies on biotic interactions focused on predation (predator-prey) responses to fires. In Mexico, a gap was found in scientific research related to biotic interactions and wildfires.

This work faced certain limitations, some of which will serve as a basis for future research on wildfire issues. For example, future studies should integrate experiments that incorporate temporal and spatial variability considering the resilience of biotic communities to changes in fire regimes to improve understanding of post-fire feedbacks between plant recovery and soil arthropod-driven ecosystem services, herbivory and pollination through experimental manipulations. Further studies are also needed on seed dispersal and its contribution to forest species succession through post-fire seedling recruitment and to determine changes in species composition patterns in temperate forests. This will help to better understand the functioning of ecosystems and generate restoration strategies based on the functionality of their communities.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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