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Causes and Effects of Forest Fires in Tropical Rainforests: A Bibliometric Approach

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Abstract

Despite their humid environment, tropical rainforests are threatened by fires that negatively impact their ecological and economic value. However, fires in these ecosystems have been investigated to a far lesser degree compared with temperate or seasonally dry forests. We performed a bibliometric analysis to identify knowledge gaps in rainforest fire studies from 1981 to 2015. Through an analysis of the temporal and spatial research trends, we aimed to evaluate the main drivers that motivate investigations in this field of study. In total, we recorded 366 publications in indexed journals. Approximately 60% of these studies were conducted in four countries. The number of publications tended to increase after El Niño years. A word co-occurrence network revealed a strong relationship between land use change and fires and the role of fire in agricultural and ecosystem traits. We conclude that socioeconomic drivers, deforestation, and global climate change should be considered to gain a better understanding of the occurrence of forest fires. Further studies should include the cause, intensity, and recurrence of fires, since they determine the effects of fire on the soil and biota (fire severity). The spatiotemporal patterns of forest fires require further study to develop strategies for good agricultural production and to predict successional routes after fires. These identified gaps in the research on forest fires could guide decision-making toward the prevention of further fire expansion or at least to reduce its negative effects in tropical rain forests.

Keywords

data mining, indexed journals, knowledge fields, publication temporality, geographic analysis

Introduction

Rainforests are the terrestrial systems with the highest species diversity on the planet, and they provide important services to the ecosystem (Lewis, Edwards, & Galbraith, 2015; Rodríguez-Trejo, Ramírez-Maldonado, Tchikoué, & Santillan-Pérez, 2008). Their natural fire regime is characterized by a low frequency of fires, but these tend to be intense when they occur (Bowman et al., 2011). Rainforests are vulnerable because a great majority of their species lacks the ability to adapt in order to cope with fire (Cochrane & Schulze, 1999). In recent decades, forest fires have been increasing (Cochrane, 2001), mainly caused by human activities (Lewis et al., 2015); they represent a threat to the remaining tropical forests around the world (48.84%, a mere 3.6 billion hectares of their initial coverage area, International Sustainability Unit, 2015). This current increase is related to global warming and the alarming global deforestation rate (5.2×10^6 ha yr^{-1}; Food and Agriculture Organization of the United Nations [FAO], 2012a). In fact, deforestation and forest fires act in synergy to reduce and fragment tropical rainforests (Cochrane, 2001). Furthermore, surge in droughts and temperature associated with global climate change (GCC) will promote an increased

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frequency of fire occurrence in the near future (Abeli, Jäkäläniemi, & Gentili, 2014).

Despite the absence of precise figures that reflect the loss of tropical rainforests, it is well established that broad areas of tropical forests have diminished in spite of conservation efforts over the last 25 years (Keenan et al., 2015). Rainforests are critically threatened by agricultural expansion, cattle ranching, logging, mining, road construction, and the cultivation of biofuel plants (International Sustainability Unit, 2015). It should be emphasized that the main activities associated with forest fires are agriculture and ranching (van Vliet et al., 2012). These human activities have played an important role, inducing legal and illegal land use changes (Jakovac, Peña-Claros, Mesquita, Bongers, & Kuyper, 2016; Zhang & Pearse, 2011). Low-income farmers in many places around the world practice slash-and-burn agriculture in small areas, while intensive agriculture and extensive farming usually expand over several hectares.

Forest fires extensively affect vegetation cover, density, structure, composition, diversity, and productivity. They result in deforestation, reduction in population sizes, forest edge effects, changes in the community structure, and the immigration of exotic species (Cochrane & Laurance, 2002; Laurance et al., 2012; Turner, 1996). The fire may also generate critical changes in soil properties, depending on the type of soil, the amount and quality of fuel, the duration of the fire, and the temperature attained (Badía & Martí, 2003). Fire affects the soil chemistry, altering the concentration of nutrients such as C, P, Ca, Mg, Na, K, ON, NO_3, and NH_4 (Knicker, 2007).

Bibliometrics comprises a set of quantitative methods currently employed to analyze the published literature on a specific topic (Broadus, 1987; Hull, Pettifer, & Kell, 2008; Tanev, 2014; Thanuskodi & Venkatalakshmi, 2010). Through specific searches in the literature, it is possible to identify certain tendencies in the development of research on forest fires (Thanuskodi & Venkatalakshmi, 2010). Bibliometric studies have been utilized to follow the course of several ecological phenomena such as changes in diversity and the impact of conservation strategies (Song & Zhao, 2013) or the impacts of shifting cultivation (Mukul & Herbohn, 2016; Ribeiro Filho, Manfredini, Aguilar, & Neves, 2013) through an examination of information provided in publications on the subject and its evolution over time (Stork & Astrin, 2014; Young & Wolf, 2006).

The increase in the frequency of fires has been widely explored in fire-prone temperate and Mediterranean forests, where the plants are adapted to fire (Ganteaume et al., 2013), but the research on tropical forests fires is not sufficient. Ecologists and foresters are currently interested in exploring the causes and effects of forest fires in tropical rainforests. Therefore, the objective of this study is to analyze the trends in the research on tropical rainforest fires employing bibliometrics and basic data mining tools. We also identified the main causes and effects of forest fires in this ecosystem, the major research areas addressed by the scientific community, and the temporal and spatial distribution of publications around the world.

Methods

Object of Study Definition

Tropical rainforests are described in the literature under different names (Simons, Singh, Zhu, & Davis, 1999). The usage of different terminology hinders the compilation and synthesis of new information. This vegetation type appears in publications as evergreen tropical rainforests (FAO, 1998), evergreen and semi-evergreen rainforests (FAO, 2012b), lowland rainforests, and tropical and subtropical moist broadleaf forests (World Wildlife Fund [WWF], 2015). Similarly, other authors employ the term rainforest to refer to other types of vegetation located in areas with different climates, edaphic conditions, and other physiognomic characteristics. This is the case with moist deciduous tropical rainforests, montane rainforests, subtropical and temperate rainforests, and other deciduous forests such as monsoon forests (Richards, 1996). In this work, we adopt the FAO (1998) definition of tropical rainforests as the type of vegetation distributed in areas with more than 2,500 mm of annual precipitation with a dry period that commonly does not exceed 3 months. This research is an attempt to explore the maximum possible number of academic publications regarding tropical rainforests, taking into account all the variant terms employed in the current academic literature. In the case of forest fires and burns, we also tried to include all kinds of variation in terms, such as fire, wildfire, burn, ignition, shifting agriculture or cultivation, slash and burn, and swidden cultivation.

Data Collection

After defining the study object, we proceeded with bibliometrics and basic data mining analysis (Figure 1). First, we performed an advanced search of all the articles in indexed journals related to forest fires and agricultural burns in tropical rainforests between 1981 and 2015. The journals covered environmental, agronomic, and geographic information. In this search, we considered only papers with a title that was focused on forest fires in tropical rainforests. We retrieved publications from the following bibliographic databases: ISI Web of Science, Scopus, ScienceDirect, BIOSIS, and Zoological Abstracts. For the advanced search, we employed the

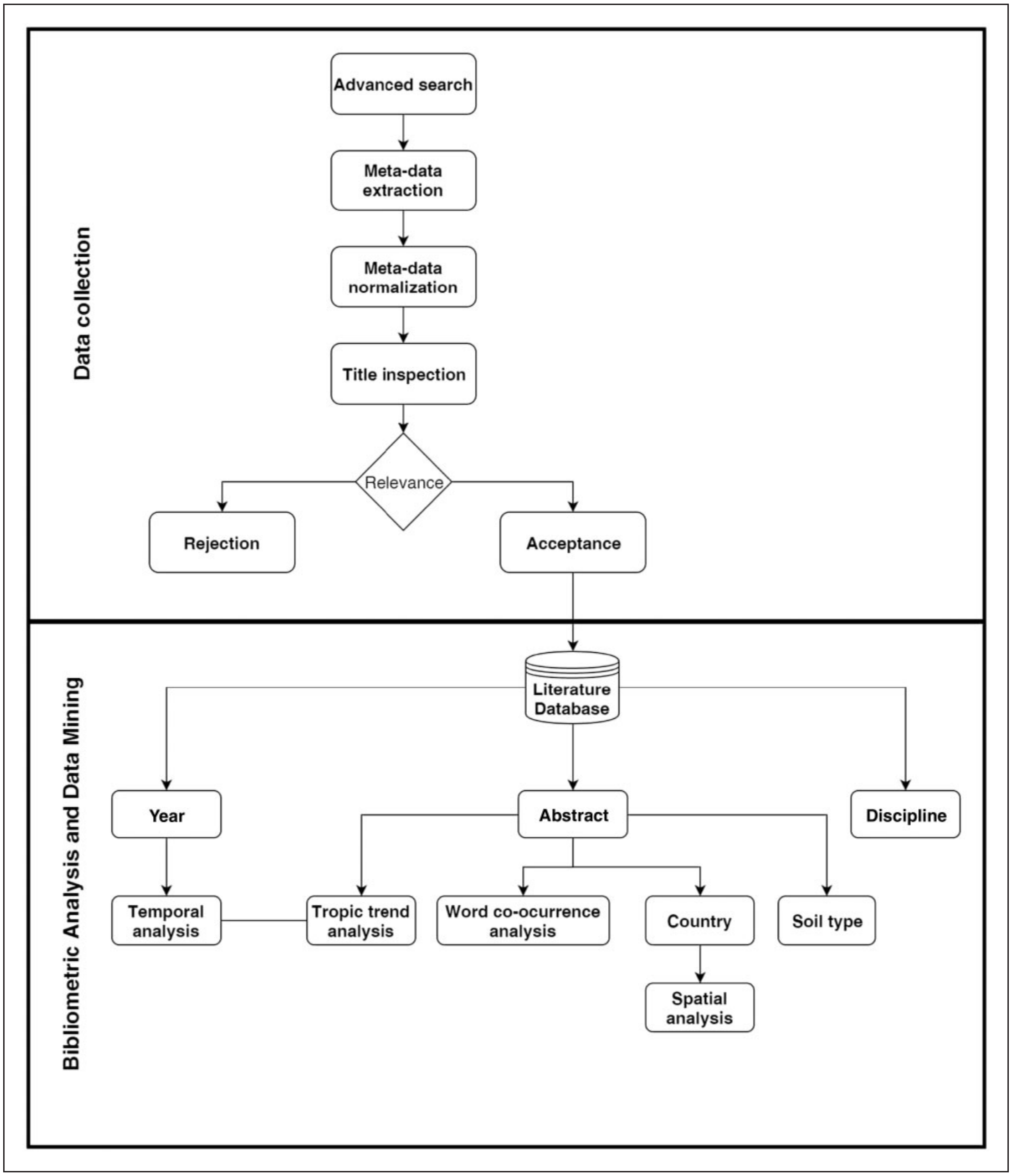

Figure 1. Methodological approach.

logic and Boolean operators AND, OR, NOT, ?, * and '' to extract all the publications related to forest fires and tropical rainforests. From this search, we created a database with the following fields: (a) publication title, (b) publication year, (c) abstract, (d) keywords and descriptors, and (e) discipline. Each record was normalized and carefully reviewed to exclude those items that were not accordance with the objective of this work. The papers included were restricted to those belonging to the environmental disciplines. Utilizing the information contained in the title, abstract, keywords, and descriptors, we extracted specific data regarding the publications, such as the country where the study was performed, the type of soil, and the objectives of each work analyzed. The different types of soils were normalized based on the World Reference Base soil classification (FAO, 2014).

Bibliometric Analysis and Data Mining

To identify the trends in the scientific literature on tropical rainforest forest fires, we employed a word co-occurrence analysis that combines bibliometrics and

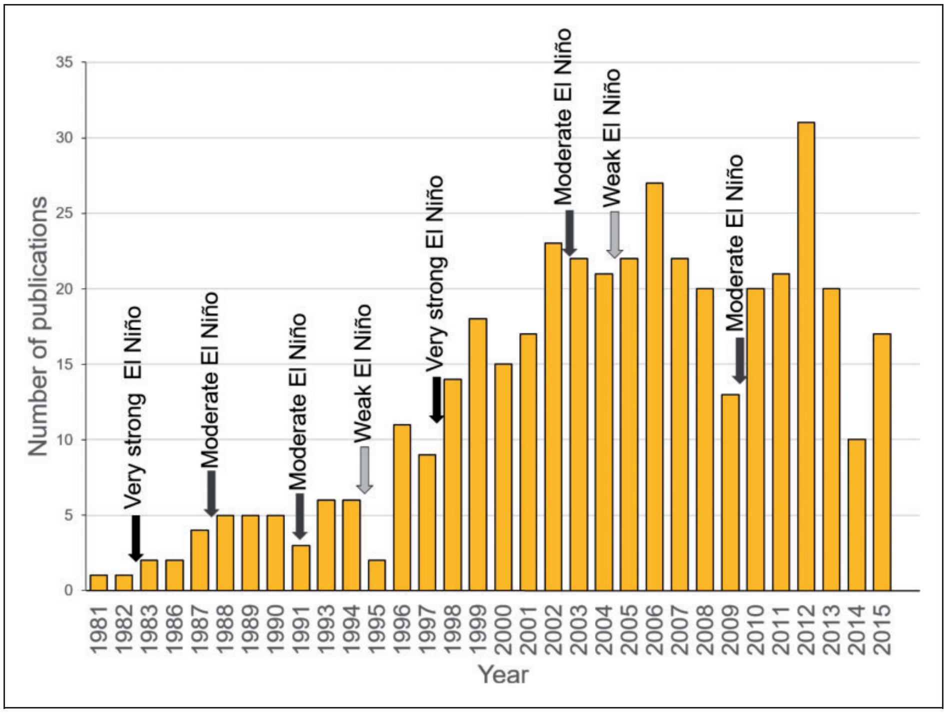

Figure 2. Temporal and spatial variation in the number of publications. Arrows represent very strong, moderate, and weak El Niño years (black, dark gray, and light gray arrows correspondingly where $N = 365$).

text mining techniques to demonstrate the associations between terms in a network (An & Wu, 2011). To perform this analysis, we employed 365 publications with abstracts, as the abstract contains relevant information about the content of each work. The preprocessing of these data included stop word removal and word stemming that implies the elimination of common words unrelated to the research objective, such as ''for,'' ''the,'' and ''and,'' among others. In addition, word stemming entails the reduction in the number of morphological variants of words by the removal of word endings. Subsequently, we obtained a term-document matrix from which we extracted word frequencies. Based on this information, we conducted a word co-occurrence network employing R (v. 3.2.2) and Sci2 (v. 1.2b). In the word co-occurrence network, each node represents a word, whereas the edges symbolize the connections between them. The strength of each connection depends on the frequency of the two words appearing together, and it is symbolized by the width of the line in the network. The edges represent co-occurrences. In this graph, words are connected to one or more words (Tanev, 2014). The maximum value of the strength is one, and this occurs when two words always appear together, whereas the minimum value is 0, when two words never appear together. In this case, we constructed the network including the 100 strongest relationships among words or edges. Finally, we also generated a topic model in R that classifies sets of documents into themes employing the frequency of the terms in a probabilistic framework.

Results

Spatiotemporal Analysis

In total, we analyzed 365 publications (S-1) in the period from 1981 to 2015. The following results were obtained from the analysis of these records. Over the period of time covered by this study, the number of articles on fire in tropical rainforests was found to be growing, with some fluctuations. The maximum number of publications on this theme was recorded in 2012, while the least number of publications was observed in 1995. Figure 2 displays that the number of publications has increased over time with peaks occurring around the years with very strong and moderate ENSO (El Niño-Southern Oscillation) effects (National Oceanic and Atmospheric Administration and National Weather Service, 2016).

The publications analyzed belonged to 45 countries from around the world (Figure 3). Most of the studies were concentrated in the continent of South America followed by Asia, Australia, and Africa. From these regions, Brazil (119) and Indonesia (52) recorded the highest number of publications. Two major tropical rainforests of the world are located in these countries, the Amazon

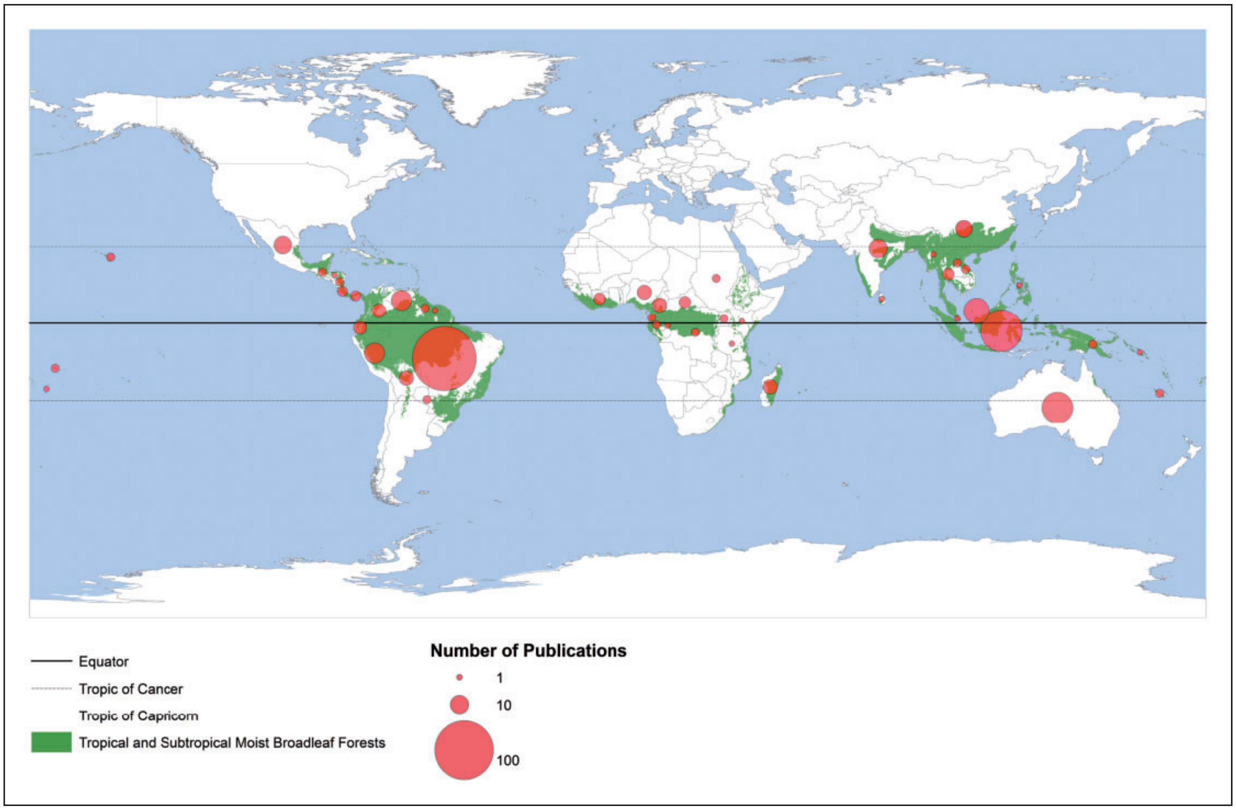

Figure 3. Spatial distribution of publications at the global scale that are focused on fires in tropical rainforests. The green areas represent the principal remnants of tropical rainforests (The Nature Conservancy, 2009). The red dots represent the number of publications.

and the Borneo. The Amazon is the largest rainforest in the world and it is also one of the most highly researched regions in terms of forest fires. However, other countries with large rainforests, such as the Democratic Republic of the Congo, only had three publications on this theme.

Word Co-Occurrence Analysis

To obtain a word co-occurrence network, we analyzed the abstract of 365 documents. Subsequent to the stop word removal and word stemming, we found 4,489 different terms in the 365 documents that contained an abstract. The term-document matrix obtained from the complete abstracts revealed that most of the terms did not appear frequently (sparsity = 98%). However, the most frequent terms were *forest* (term frequency = 1,542; number of documents in which it appears = 300), *fire* (1,428; 161), and *burn* (602; 196), which was expected, as they were the central objects of this study. Some frequently occurring terms were associated with ecological terminology such as *species* (558; 140), *tree* (304; 100), *biomass* (198; 74), *disturbance* (148; 82), *community* (162; 80), *diversity* (136; 59), and *severity* (116; 55). On the other hand, the terms associated with conservation and management were *use* (303; 203), *shifting cultivation* (150; 70), *deforestation* (164; 58), *agriculture* (156; 89), *fallow* (185; 60), and *log* (143; 35). The themes pertaining to the word frequency coincided with the main disciplines that are related to the study of forest fires, which were environmental sciences and ecology (36%), biodiversity and conservation (10%), and agriculture (9%).

Of the 365 publications, 129 were articles that focused on ecology and 39 focused on soil. The ecological variables that were most often reported in the abstracts were those concentrating on the community level, with composition and diversity being the terms with the highest frequencies. On the other hand, the variables that were the least reported were decomposition and productivity, both of which belong to the level of ecosystem (Figure 4). Of the ecological studies, 72 were conducted on plants, 53 on animals, and 4 on fungi. The most frequently reported chemical soil variables in the abstracts were nitrogen and carbon followed by other nutrients such as phosphorus and potassium (Figure 5). Of the total publications analyzed, only 76 reported the type of soil. The reported soil types were acrisol (43%), ferralsol (34%), and podzol (7%; $n = 76$).

Two networks of terms were generated based on analysis of the abstracts of the publications. The selection of terms in the networks was performed based on two criteria: the terms with highest frequency (Figure 6) and the most co-occurrence words (Figure 7). The network of

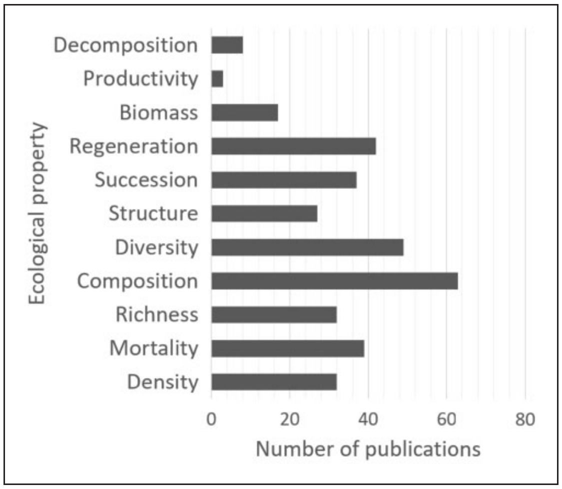

Figure 4. Number of publications reporting ecological properties ($N = 129$) and frequency of the analyzed properties.

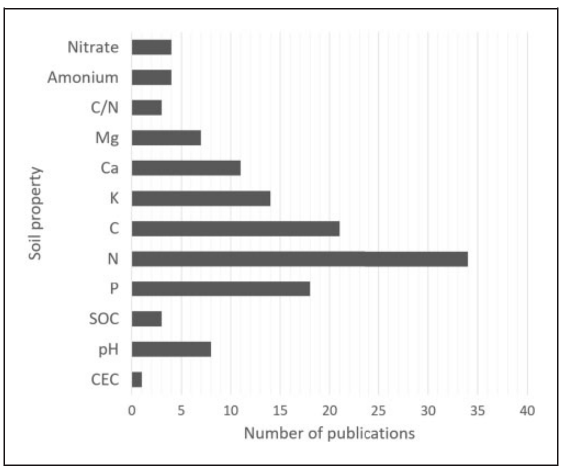

Figure 5. Number of publications that evaluated chemical soil properties ($N = 39$) and frequency of the analyzed properties.

word co-occurrence of the most frequent terms revealed associations among the most frequently employed terms across all abstracts (Figure 6). In Figure 6, *agriculture* appears as the leading cause of *fires* with *fallow* as one of its attributes, since this is frequently utilized in *shifting cultivation* systems. *Soil* is also revealed as important after agricultural burns. The term *community* is also prominent, since it is related to the effect of fire on *rainforest species*. A strong relationship is also revealed between *forest logging* as a *disturbance* related to fire. At the scale of *region*, we found a prevalence of certain terms such as *biomass burning* and *burned area calculation*. Many regional studies address the Amazon forest; therefore, words such as *deforestation* and *fire* are extremely prevalent in the literature.

Figure 7 shows the co-occurrence network of the 100 most prominent relationships among the terms in the abstracts of the publications about fires in tropical rainforests around the world. The node size represents the number of articles or references and the thickness of the lines connecting them represent the corresponding co-occurrence values. The pairs of words with the highest co-occurrence were *tropic-forest*, *burn-forest*, *forest-use*, and *forest-area*. However, it is important to consider that the most significant associations in this research were *land-use*, *increase-area*, *increase-burn*, *studies-effect*, *studies-change*, *burn-effect*, *burn-compare*, *burn-use*, *change-land*, *change-area,* and *fire-impact*, among others.

The topic analysis identified five main topics through the categorization of the terms in the abstracts based on their frequency (Figure 8). The first group evidently indicates that agriculture was one of the primary areas addressed by the scientific community and the interest in this topic (reflected in the number of publications) remained steady throughout the study period. The terms in the second group refer to the narrow relationship that exists between forest fires and deforestation. This theme has been addressed since the 1990s till the present time and attracts the attention of scientists and decision makers. Management was the third subject, and it is closely related to deforestation. However, publications on this theme commenced in the beginning of the 1980s. The last two subjects include the effects of fire on ecological variables and are related to the research on soil and biomass and tree species. The topic related to soil and biomass was less frequently reported, while studies on the relationship between fire and tree species drew the attention of researchers in late 90s and the first decade of the millennium. Finally, an increase in the occurrence of all of these themes was noted in 2003, which was a year with a high number of publications.

Discussion

Temporal Trends Displayed in Publications

The research interest in forest fires in tropical rainforests occurred simultaneously with the loss of these ecosystems. Despite their ecological and economic value, rainforests represent 32% of the total global forest loss (Hansen et al., 2013). The trend regarding the increase in publications in this specific theme (Figure 2) coincides with an increment of articles in other fields. However, this tendency reflects a concern about fire recurrence in tropical rain forests that is expected to worsen under a GCC scenario (Seiler, Hutjes, Kruijt, & Hickler, 2015).

The El Niño phenomenon has a strong relation with forest fires. Since several decades, the interest in this relationship has been published with regard to several vegetation types from differing perspectives. In relation to this, we found that the periodic increase in the research on forest fires is influenced by the El Niño years.

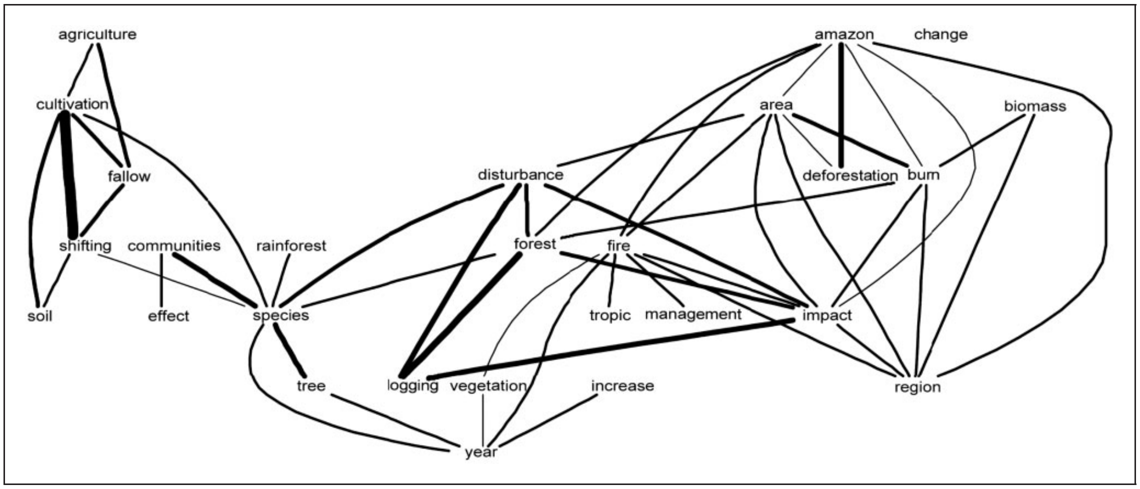

Figure 6. Word co-occurrence network. Lines represent co-occurrences of the terms and thick lines represent a strong relationship between two terms. Network terms are presented as lexemes or lexical units with a basic meaning.

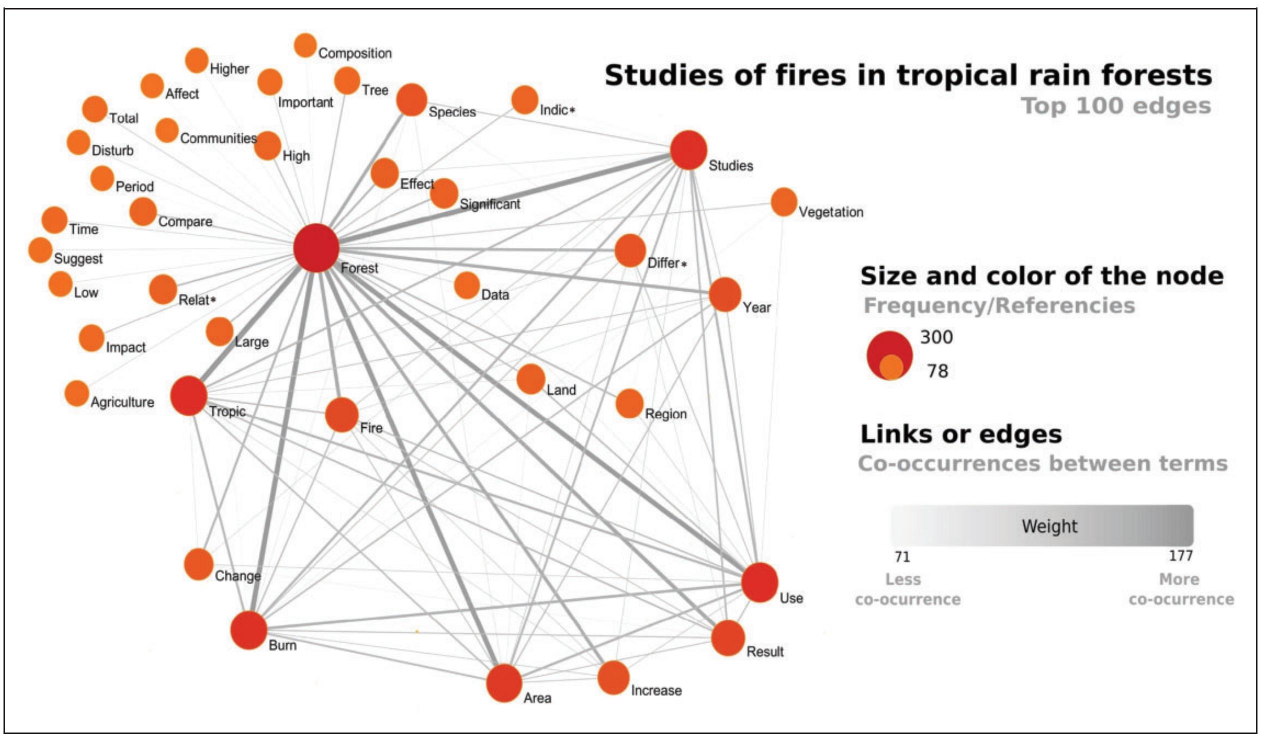

Figure 7. Co-occurrence network of the 100 terms that appeared more frequently together (links or edges). The degree of co-occurrence between two words is indicated by the thickness of the line, while the size and color of the nodes refer to the number of times the terms appear in documents. Network terms with an asterisk are presented as its lexical root, since they include words with substantially more than one implication (land: land, landscape, landholder; relat: relate, relation, relationship, relative and LandSat; indic: indicate, indicator, and indices).

Our analysis revealed that publications increased after very strong (1982–1983 and 1997–1998), moderate (1987–1988, 1991–1992, and 2009–2010), and weak (2004–2005) El Niño years, except for the period 2002–2003 (Figure 2). This tendency appears to be a reaction to the increase in fires that occurred in rainforests (favored by the high temperatures and drought that characterize El Niño years), rather than a prevention strategy to address the actual high deforestation rates and GCC. In spite of this, few of the published papers (13.11%)

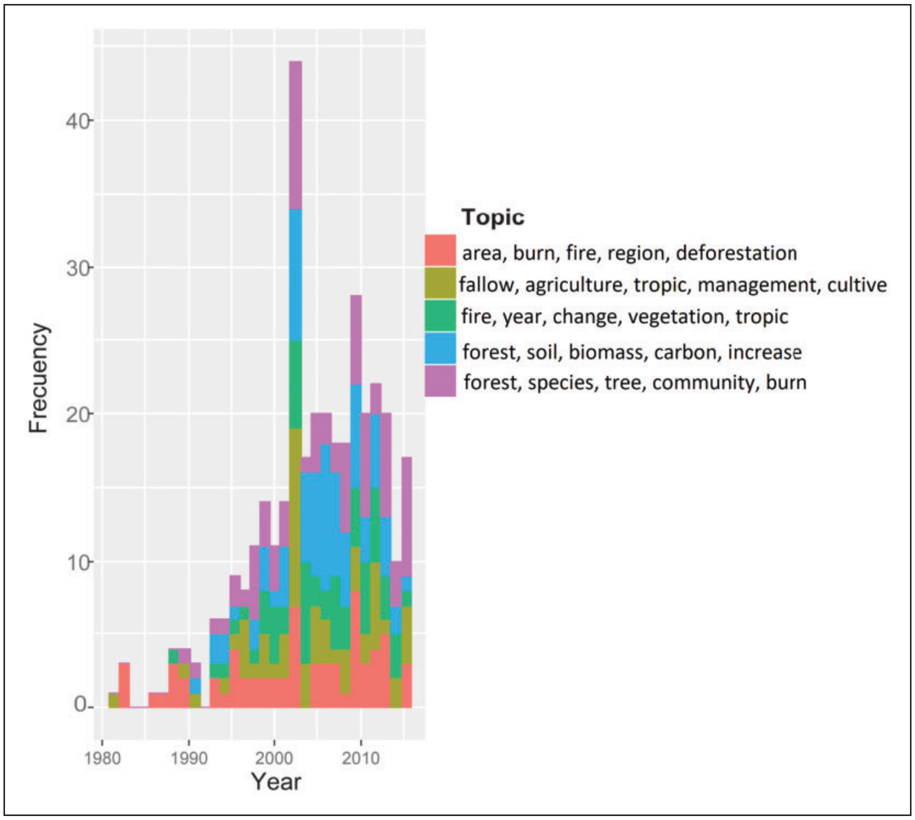

Figure 8. Topic analysis from 1981 to 2015.

mentioned this climatic phenomenon in their abstracts. On the other hand, the cause of these peaks in the research might have a relation with the global trend in research funding that is mainly concerned with issues that attract worldwide attention. In particular, Brazil has been interested in studying the effects of ENSO on fire occurrence (Alencar, Nepstad, & Diaz, 2006).

Spatial Distribution of Publications

Approximately 60% of the studies on rainforest fires were mainly concentrated in four countries: Brazil (32.62%), Indonesia (14.25%), Australia (7.67%), and Malaysia (5.48%). The high number of publications from these countries is related to the surface area covered by rainforests, their economic value, and their conservation. The Amazon forest in Brazil (3,300,000 km^2) and the Borneo forest in Malaysia and Indonesia (220, 000 km^2) are the largest remaining rainforests in the world (Fearnside, 1997; WWF, 2016a). Both Brazil and Indonesia exhibit high deforestation rates that contributes to rainforests vulnerability to fires (Barni, Pereira, Manzi, & Barbosa, 2015; Fanin & Van Der Werf, 2015; Margono et al., 2012; Margono, Potapov, Turubanova, Stolle, & Hansen, 2014). For instance, between 1985 and 2001, 56% of the Kalimantan rainforest was deforested to fulfill global timber demands (WWF, 2016b). Under these circumstances, disturbed rainforests are more susceptible to fires and their regeneration capacity is greatly diminished (WWF, 2016b).

An expansive forested area does not necessarily translate into an extensive number of articles. According to the World Bank (2016), most countries in the tropics have a sizeable rural population and a low gross domestic product per capita, except Australia, which was third in terms of the maximum number of publications. Central Africa, with the second largest expanse of contiguous rainforest (1.7 million km^2; Mayaux, Achard, & Malingreau, 1998) had the least number of publications on forest fires. Madagascar and Cameroon, the countries with the highest publications in Africa, only contributed six publications each over a period of 33 years. The tropical rainforest of Congo Basin is bordered by savannahs and deforested areas due to logging and land clearing activities (Bucini & Lambin, 2002) that heighten the risk of fires, especially under GCC. This limited number of publications contrasts the well-documented phenomenon of deforestation in the Congo Basin (Ernst et al., 2013; Mayaux et al., 2013) and the registered forest fires in its rainforest (Bucini & Lambin, 2002; Global Forest Watch, 2016; Schmaltz, 2004; University of Maryland Global Land Analysis and Discovery Team, 2016).

However, in some of these countries, the small number of publications on forest fires could be due to the limited strength of scientific research (Scimago Lab, 2016). Consequently, since fires are a serious problem for this ecosystem, the research subject deserves more attention. In addition, other countries in Southeast Asia and Central America displayed low productivity in terms of articles focused on fires. The underlying causes of deforestation in these areas are mainly associated with agricultural expansion, fuel wood and timber extraction, and infrastructure development but also with areas of high population density, poor governance, and war-related conflicts (Ernst et al., 2013).

Main Fire Causes Reported

We found that the main interests of researchers regarding tropical rainforest fires continues to be in the close relationship between deforestation, agriculture (slash/burn), cattle ranching activities, and fires. The fact that most of these practices are ancestral cultural activities might explain the reason behind most studies being based on an ecological, conservation, or agricultural approach (Figure 3). Currently, the causes of fires are anthropic in origin, with agriculture displaying the maximum level of association with forest fires (Cochrane, 2013). Thus, considering the current consequences of human activities in global deforestation and GCC, further in-depth research at several temporal and spatial scales appears to be extremely pertinent.

Word Co-Occurrence Network

Biotic responses after fire reported in the literature. In the environmental and ecological research areas, we found a distinctive interest in the changes in the plant and animal communities (in terms of richness, composition, and diversity) after a single or multiple forest fires. Rainforest species recovery was evaluated for insects, amphibians, birds, mammals, and plants (mainly trees). Resprouting is considered to be the central mechanism of vegetation recovery after a fire; however, the vegetation resprouting capacity diminishes after recurrent fires (Clarke et al., 2015). This may influence plant diversity, since seed regeneration is greatly affected by fires. It has also been exhibited that after a fire, plant species richness and diversity increase due to immediate changes in species composition induced by an increment in the number of herbs, vines, and ferns (Randrianarison et al., 2015). On the other hand, the recovery of tree species takes place over decades. The vegetation biomass and structure of forests affected by fires change over ecological succession. It appears that at the initial successional stages, trees with small diametric classes possess more biomass compared with those with wider trunks (Omeja, Lwanga, Obua, & Chapman, 2011).

Abundant precipitation and high humidity levels limit the frequency of fires in tropical rainforests (Cochrane, 2003). However, under different disturbance regimes such as deforestation, the frequency experiences a surge (Xaud, Martins, & Dos Santos, 2013; Cochrane, 2001). A relationship between canopy openness and fire susceptibility has been reported after a fire (Ray, Nepstad, & Brando, 2010; Ray, Nepstad, & Moutinho, 2005), partially because canopy openness is associated with the moisture present in the understory fuels. However, the traits of soil and plant debris (insulation, moisture content, and others) prior to fire are rarely reported.

Even low-intensity fires may affect tropical forests, since plants do not possess the adaptability to tolerate high temperatures (Pivello, 2011). Depending on the size class, these fires can kill trees and thus lead to a reduction in the forest biomass. Low-intensity fires can further lead to the destruction of the seed bank and alteration off the microclimatic conditions that favors the growth of ruderal plants and lianas. The greater the frequency and intensity of the fires, the more significant and evident are the changes in diversity, composition, and structure (Xaud et al., 2013).

Fire: Underlying Causes and Effects

In tropical rainforests, human activities such as agriculture and ranching constitute the direct underlying causes of fires (Butler, 2012). Logging impacts this ecosystem, increasing the number of fires through agricultural activities and modifying the microclimatic conditions and plant composition that create a positive feedback with fire. However, further, other socioeconomically driven forces are associated with conflicts pertaining to land tenure and land-use allocation (Dennis et al., 2005). Therefore, the role of human beings in the matter is unquestionable. Based on the causes of fire, three pathways have been identified in the Brazilian Amazon that may decrease fire incidence: (a) restriction of human activities restriction, (b) reduction in slashing and burning of secondary forests, and (c) change in the land-use methods of agriculture from extensive (unmanaged) to intensive (managed) (Aragao & Shimabukuro, 2010).

The effects of shifting cultivation are extensively argued in the literature. For several years, policy makers consider it to be a system of low productivity with important environmental repercussions. The studies on this practice are focused mainly on soil nutrients and chemistry followed by plant ecology and agricultural production or management (Mukul & Herbohn, 2016). On the one hand, shifting cultivation is an agricultural practice associated with large-scale deforestation and degradation. However, a recent meta-analysis (Ribeiro Filho, Adams, Manfredini, Aguilar, & Neves, 2015) reinforces the fact that traditional shifting cultivation is a sustainable practice wherein the main effects on soil consist of an increased pH level and a reduction in the N and C contents. Changes in fertility after shifting cultivation are moderate, since changes in cation exchange capacity, base cations, or exchangeable phosphorus are minor or not significant (Béliveau et al., 2014). Regardless, the effect of fire on soil depends on the attained temperatures that are influenced by microsite quality, plant coverage at the burning site or around it (Ray et al., 2010), and previously prevalent climatic conditions (Ghuman & Lal, 1989). However, the negative effects of shifting cultivation, such as soil erosion, are less severe than those of modern agriculture.

However, proper fire management during shifting cultivation can result in low-intensity burns (Nigh & Diemont, 2013). After land abandonment, the capacity of forest and soil regeneration depends on the number and frequency of cultivation cycles (Dutrieux, Jakovac, Latifah, & Kooistra, 2016). Under large resting periods, soil recovers better than under modern intensive agriculture. Therefore, agricultural management determines the main effects of fire on soils. Currently, socioeconomic drivers induce changes in agricultural management. Nevertheless, an increase in swidden-fallow cycles and a decrease in the fallow length could have counter-productive results for farmers, such as a decrease in the yield or an increase in weed cover (Jakovac et al., 2016).

We expected that the close relationship between management, land use, and fires would favor concomitant studies of soil, but we found only a weak relationship between these variables (Figure 5) and relatively few investigations focused on soils or the relationship between soil properties and fires (39/365 studies, soil/use). Interestingly, studies which report that fires occur on several soil types, but spatial or temporal sampling series are rarely reported as well as the relation of soil temperatures during fires to soil properties. The main effect of fire on soil is a tremendous loss of nutrients stored in the aboveground biomass, particularly if fires are related to land-use change (Certini, 2005). In these studies, the release of nutrients is the most commonly addressed issue. However, the subsequent nutrient leaching and erosion are still undeveloped themes in the literature of tropical rainforests as well as the measurement of changes in physical soil properties. Aspects such as the formation of a water-repellent soil layer induced by high temperatures during burns are also subjects that are scantily included in the literature. In spite of the fact that there is some information about the changes in soil during agricultural burns, the documentation of the effects of fire on tropical rainforests soils is limited. It is important to seek strategies to maintain good agricultural production or to predict the successional route that will be taken after consecutive or recurrent fires, both in agricultural plots and in zones with different degrees of conservation. This action is urgent because the expected effects of GCC and the associated increased forest fire occurrence on soil water infiltration, nutrient loss, erosion, floods, and landslides are real threats to food and human security.

In the last 25 years, Brazil, Indonesia, Mexico, Peru, and Venezuela have lost a significant portion of their forest cover and have increased their agricultural land area (World Bank, 2016). In most of these countries, people have migrated to the forest frontier in search of economic opportunities (Bryant, Nielsen, & Tangley, 1997). In Southeast Asia, Indonesia has the largest economy, although 28.6 million of its inhabitants live in poverty (World Bank, 2016); while in Latin America, Brazil achieved economic and social progress between 2003 and 2014, which has allowed it to bring down the number of population living in poverty. However, due to an economic recession, this trend has been slowed down. Brazil has demonstrated notable leadership in international negotiations on GCC, promising to reduce its greenhouse gas emissions in the future (World Bank, 2016).

Remote Sensing in Fire Studies

In the case of the remote sensing studies included in this study, the principal interests were focused on the detection of forest fires, the calculation of burned areas, and the determination of changes in land use. Forest fire risk models usually consider multiple variables such as road proximity, distance to urban areas, geographic barriers, topography, and weather variables, among others (Little, Prior, Williamson, Williams, & Bowman, 2012; Monzón-Alvarado et al., 2012; Silvestrini, Soares-Filho, Nepstad, Coe, Rodrigues, & Assunção, 2011). However, the calculation of biomass was rarely directly included in fire studies, despite the fact that biomass is important in the creation of risk models in remote sensing studies. These calculations are also necessary in ecosystem level studies that aim to explain a huge part of the fire dynamics and improve fire management and prevention programs. In recent decades, global fires have been monitored by NASA's satellites and by FIRMS (Fire Information for Resources System, University of Maryland; Justice et al., 2013). These registers demonstrate the incidence of fires in diverse parts of the world. Based on identified hotspots, some authors have discussed the main causes of fires in countries with rainforests, such as Malaysia (Page, Rieley, Hoscilo, Spessa, & Weber, 2013) and Brazil (Cochrane, 2013). However, this bibliometric study shows the urgent necessity to increase research on regional patterns of greater fire frequency and on the damage to tropical rainforests. Remote sensing systems are an excellent tool for the focal localization of fires. The landscape approach has been previously suggested by

Cochrane (2013), but remote sensing tools are underused as the few papers that employ them to study tropical rainforest fires demonstrate. Additionally, we ought to report fire occurrence with its intensity and the damage caused to tropical rainforests more closely. Papers that use remote sensing tools that were included in this study associate fires with human activities but do not mention their causes. Therefore, it is necessary to complement all of the information obtained from satellites with field work. Pivello (2011), interestingly, compares fire occurrence in Cerrado communities and surrounding tropical rainforests that differ in the moisture content of biomass and in their adaptations to fires.

Implications for Conservation

We consider that this bibliometric review will help in decision-making, understanding the importance of approaches at different scales, and identifying the gaps in fire ecology research. This information will be useful in evaluating both the effects of climatic change and the true relevance of shifting cultivation and other anthropogenic activities on fire dynamics, its consequences, management, and prevention. Forest fires related to human activities represent a threat for the relicts of tropical forests around the world, even in protected areas. Despite this, almost half of the studies have been conducted in only two countries (Brazil and Indonesia). This fact reveals that there have not been enough studies to reflect the problem around the world. It is necessary to know with precision the number of fires occurring in tropical rainforests around the world and the extent of such events. Future studies ought to also reveal the causes of fires; this has been done in some studies, indicating that the conversion of land to agriculture or pasture is the dominant driver factor. However, the proximity to roads, the densities of rural roads or populations, or climatological causes such as long periods of dryness related to GCC have been scantily mentioned. Social and economic factors should be studied at all scales to reduce the increased frequency of fires that accompanies deforestation and contributes to the impoverishment of the soil, greenhouse gas emissions in the atmosphere, and consequent GCC affecting people quality life.

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