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THREE DECADES OF REMOTE SENSING ANALYSIS ON FOREST DECLINE RELATED TO CLIMATE CHANGE: A BIBLIOMETRIC STUDY

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ABSTRACT. Climate change is predicted to lead to increasingly intense and hotter droughts, causing physiological weakness followed by forest decline in many regions of the world. Long- and short-range remote sensing (satellites and unmanned aerial vehicles, commonly called drones) can sense drought-induced changes in vegetation. Although several studies have addressed forest decline events, none have analyzed the forest decline attributable to climate change using remote sensing in a concise manner. A bibliometric analysis was carried out to characterize the scientific production reported in the Web of Science repository. The search descriptors were a combination of keywords related to forest decline and remote sensing. The results showed 278 articles published between 1989 and 2021 in 92 journals, with an average annual increase of 31%. A total of 29 nodes and 220 scientific collaboration links were located, mainly led by researchers from USA, Germany and China. Keyword analysis using World-TreeMap reflected the association of different key forest decline phenomena such as drought stress and climate change. Although the use of satellite information to study and understand forest decline has been reported for just over three decades, the most notable feature of the present research was the limited role of drones with only 5 studies. This reveals an area of opportunity to take advantage of the main strengths of drones, i.e., spatial and temporal resolution, low cost compared to manned flights, and centimeter accuracy. Therefore, it is strongly recommended to increase studies to improve the use of multispectral sensors, thermal and LiDAR technology for long-term monitoring of forest decline related to climate change.

Tres décadas de análisis de sensores remotos sobre la pérdida de bosques relacionada con el cambio climático: un estudio bibliométrico

RESUMEN. Se pronostica que el cambio climático conducirá a sequías cada vez más intensas y cálidas, que provocarán una debilidad fisiológica seguida de la disminución de los bosques en muchas regiones del mundo. La teledetección de largo y corto alcance (satélites y vehículos aéreos no tripulados, comúnmente llamados drones) puede detectar cambios en la vegetación inducidos por la sequía. Aunque varios estudios han abordado los eventos de pérdida forestal, ninguno ha analizado de manera concisa la pérdida forestal atribuible al cambio climático utilizando sensores remotos. En este trabajo se realizó un análisis bibliométrico para caracterizar la producción científica incluida en el repositorio Web of Science. Los descriptores de búsqueda fueron una combinación de palabras clave relacionadas con la disminución de los bosques y la teledetección. Los resultados arrojaron 278 artículos publicados entre 1989 y 2021 en 92 revistas, con un incremento anual promedio del 31%. Se localizaron un total de 29 nodos y 220 enlaces de colaboración científica, liderados principalmente por investigadores de EE.UU., Alemania y China. El análisis de palabras clave utilizando World-TreeMap reflejó la asociación de diferentes fenómenos clave del declive forestal, como el estrés por sequía y el cambio climático. Si bien el uso de información de satélites para estudiar y comprender la disminución de los bosques se ha reportado en las últimas tres décadas, el rasgo más notable de la presente investigación fue el papel limitado de los drones con solo 5 estudios. Esto revela un área de oportunidad para aprovechar las principales fortalezas de los drones, es decir, la resolución espacial y temporal, el bajo costo en comparación con los vuelos tripulados y la precisión centimétrica. Por lo tanto, se recomienda encarecidamente aumentar los estudios para mejorar el uso de sensores multiespectrales, tecnología térmica y LiDAR para el monitoreo a largo plazo de la disminución de los bosques relacionada con el cambio climático.

Keywords: Scientometrics, forest mortality, UAV, global warming, forest resources.

Palabras clave: Métrica científica, mortalidad forestal, vehículo aéreo no tripulado, calentamiento global, recursos forestales.

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1. Introduction

Future climate scenarios suggest major global changes with adverse impacts on food security and ecosystems (Pörtner *et al*., 2022). Therefore, the scientific community has clearly warned that we are facing a planetary climate emergency (Ripple *et al*., 2020). Consequently, a great threat is emerging for plant and animal species suffering changes in their distribution, abundance and dynamics, in addition to effects on nutrients cycles and many other environmental services (Fort, 2015; Sáenz-Romero *et al*., 2020).

Droughts related to climate change have caused widespread tree decline and mortality in many forest biomes (Allen *et al*., 2010, 2015), with severe effects on ecosystem function and terrestrial carbon fluxes in the biosphere (Anderegg *et al*., 2016). A cause for concern is that climate change is expected to lead to increasingly intense and hotter droughts (Hammond *et al*., 2022), causing physiological weakness in plants promoting pest and disease damage and the eventual occurrence of forest decline phenomena (Choat *et al*., 2018).

The scientific community has adopted a variety of approaches to study forest decline phenomena (Lu *et al*., 2019). An important part has analyzed the mechanisms of drought-induced tree mortality, specifically testing whether trees die due to hydraulic failure (Anderegg and Anderegg, 2013; Klein *et al*., 2022), reduced or no radial growth (Guada *et al*., 2016), biotic attacks, or the interaction of those factors (McDowell *et al*., 2008; Hajek *et al*., 2022). Unfortunately, predictions of forest mortality are not encouraging, even with active tree defense mechanisms against drought (e.g., leaf stomata closure) (Williams *et al*., 2013).

Therefore, for innovative analyses of forest decline symptoms, it is important to collect field observations on a consistent basis over the short, medium or long term (Hammond *et al*., 2022). However, given the massive number of forest decline events that are occurring and the high cost to assess them through field surveys with conventional technologies, it is necessary to rely on state-of-the-art technologies such as long- and short-range remote sensing. In this regard, Huang *et al*. (2019) carried out a comprehensive scientific review to analyze how remote sensing can help perceive drought-induced changes in plant physiology, biochemistry, and structure. The authors conclude that remote sensing techniques provide the opportunity and potential for large spatial scale observation and analysis and early detection of forest decline symptoms. Even though, Huang *et al.* (2019) study gives an overall view about the forest decline and forest die-off process, it is necessary analyzed systematic the scientific contributions to understand the different approaches with which this topic has been analyzed. Remote sensing has allowed us to monitor the spatial and temporal development of droughts at regional scales (Jiao *et al*., 2021), which is useful for accurate estimates of tree mortality in areas with forest decline symptoms (Meddens *et al*., 2013), and to describe the geographic extent, ecological patterns of tree loss and damage, and track ecosystems after tree mortality (Huang *et al*., 2019). As a result, the links between changes related to forest decline symptoms and remote sensing show exceptional promise for strategic and adaptive management of forest biomes to climate change.

Although there are several studies that address forest decline events on a regional or global scale (Allen *et al*., 2010, 2015; Huang *et al*., 2019; Hammond *et al*., 2022), no study has analyzed in a concise way the existing scientific publications on the following two topics (1) forest decline attributable to climate change and (2) remote sensing as a support to field observations for a better understanding of these phenomena. Under the hypothesis that scientific production on the topic (forest decline) is growing dramatically, a systematic analysis of these research studies is very important to understand the trends, the areas that have been little studied, and the areas of opportunity in the use of remote sensing information to study forest decline attributable to climate change. In this regard, scientific publications are a fundamental element in the process of socialization of advances, generation and application of knowledge and measurement of the impact of novel topics (Belter, 2015). The documentary method called bibliometric analysis has the potential to statistically study scientific production, growth and distribution. This method becomes important as it is a systematic, transparent and reproducible review process with the aim of assessing scientific activity and its impact on society (Hood and Wilson, 2001; Ellegaard and Wallin, 2015).

Therefore, broadly speaking, the objective of the present study was to characterize the scientific production of forest decline attributable to climate change studied with remote sensing by means of a bibliometric analysis. The specific objectives were: (1) to create a carefully selected bibliographic dataset that other researchers related to the topic can use for scientific research; (2) to analyze the general and recent trends in the analysis of forest decline attributable to climate change using remote sensing; and (3) to detect possible areas of opportunity where additional efforts are needed and to suggest possible alternatives. The bibliometric analysis included: dynamics of publications over time; most influential journals and articles on the topic; leading authors and countries; scientific collaboration networks; and thematic analysis i.e., types of satellite platforms or remote sensors most used in scientific contributions, types of vegetation and species most frequently analyzed, maps of keywords defined by the authors, and types of forest decline phenomena analyzed. The target audience for this research is represented mainly by forest decision-makers (forest owners, technicians, governmental authorities and entrepreneurs) and young researchers who want to get involved in the topic of forest decline related to climate change using remote sensing.

2. Survey methodology

This study is a systematic review and bibliometric analysis of scientific articles focused on the study of different symptoms of forest decline attributable to climate change by means of remote sensing.

Literature search was carried out using the scientific repository Web of Science (https://www.webofscience.com/wos/woscc/basic-search), because it is one of the most wide-ranging bibliographic databases in the world (Pranckutė, 2021) and over time has become one of the most influential databases used for journal selection, research evaluation, bibliometric analysis, and other tasks (Li *et al*., 2018a).

The search descriptors were a combination of keywords related to forest decline and the technical term related to satellite platforms. The search focused on the title, abstract and keywords of the manuscripts reported in Web of Science. Also, the search period comprised exclusively scientific contributions published until December 2021. Therefore, the search equation was as follows: "forest decline" or "forest mortality" or "forest die-off" or "tree mortality" (Topic) and "remote sensing" (Topic). In addition, papers belonging to the so-called "gray literature" (theses, conference proceedings, technical brochures, etc.) were excluded, since these are not subject to strict arbitration reviews, or do not meet bibliographic control standards and impact indexes.

Based on the database downloaded from Web of Science, a review process was carried out to exclude publications that were not directly related to the objective of this study. The name of those authors and journals that presented different formats in the database were also standardized. The final database was the starting point for the analysis. The analysis was performed with the free software R (RStudio, 2022), using the “bibliometrix” package (Aria and Cuccurullo, 2017). In addition, the analysis of keywords defined by the authors was performed using World-TreeMap, which allows identifying the main topics of scientific articles in a concise and intuitive way. The World-TreeMap consists of incorporating the most frequently mentioned defined keywords, i.e., the more times they appear, the larger the square area occupied by that word. This bibliometric technique has been widely used to study various scientific topics; for example, vegetation response to climate change (Afuye *et al*., 2022), carbon sequestration economics (Verma and Ghosh, 2022) and even medical studies (Youn *et al*., 2021) and recently COVID-19 (Queiroz *et al*., 2020).

Finally, a detailed review of each document was carried out to gather and systematize in a spreadsheet the following information field: type of vegetation and tree species studied, type of satellite platform or remote sensor used, type of ecological disturbance related to forest decline (i.e., drought stress, insect attacks, mortality of individual trees, impact of forest fires, changes in biomass production, forest diseases, land cover change, and pollution stress). This information was grouped and classified to facilitate the preparation of comparative tables and graphs for the purpose of this study.

3. Results and discussion

3.1. Publication dynamics

The Web of Science search revealed a final database with 278 scientific papers related to the central theme of this research (see supplementary material https://bit.ly/3KaomRB). The articles analyzed were published between 1989 and 2021. In other words, the use of satellite information, aerial photographs or some other type of remote technology to study and understand forest decline at different scales has been reported in Web of Science for a little more than three decades. Table 1 shows a summary of the final database of 278 scientific papers from the period 1989-2021, published in 92 journals. The papers were written by a total of 1174 authors (0.23 papers per author) and up to the present have obtained a mean of 29.4 total citations in Web of Science.

Table 1. Summary of the literature database

General Information	
Total number of documents	278
Period	1989-2021
Sources (Journals)	92
Average documents per year	8.68
Annual growth percent	31
Average citations per document	29.4
Annual average citation per document	4.22
Authors	
Total number of authors	1174
Authors of single-authored document	5
Authors per document	4.22
Documents per Author	0.23

As expected, the number of articles has varied over the years with a range of 0 to 42 articles per year. Especially, since the 2010 has been an exponential increased in the amount of articles published. The number of scientific articles published has increased by an average of 31% per year (Fig. 1). In other words, interest in this topic has grown and is growing steadily. This shows that remote sensing technologies used to analyze forest decline phenomena related to climate change have been developed for a little more than three decades. This trend could be explained by the launching of satellite platforms for earth observation such as Landsat (Wulder *et al*., 2019) and MODIS (Justice *et al*., 2002), which are freely available and accessible to the scientific community. Furthermore, in the last decade it is possible to manage a large amount of information from satellite platforms using Google Earth Engine. This cloud-based platform, focused for planetary-scale geospatial analysis, exploits Google's massive computing capabilities to address a variety of high-impact social and environmental problems, such as deforestation, drought, disasters, disease, food security, water management, climate control, and environmental protection (Gorelick *et al*., 2017).

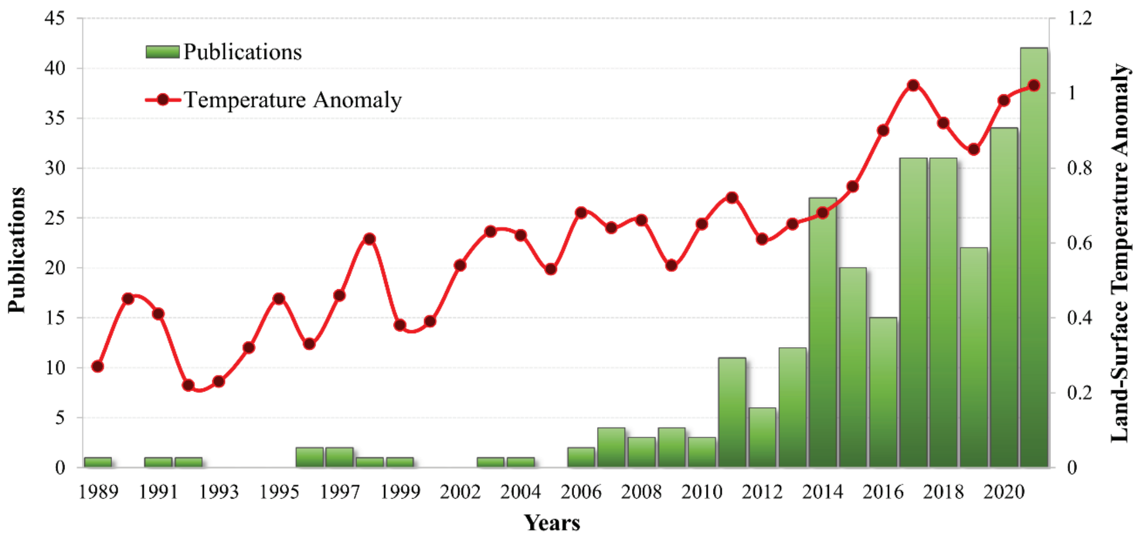

Figure 1. Number of publications and temperature anomaly (°C) regarding the reference period 1951-1980.

Figure 1 also shows that the increase in temperatures (Lenssen *et al*., 2019) and the greater frequency of drought events (Hammond *et al*., 2022) may be leading researchers to focus their studies on understanding the repercussions of these events on forest ecosystems (Allen *et al*., 2010). This could also be related to the publication of the United Nations Framework Convention on Climate Change, a document in which 10 commitments were written, including the promotion of scientific research on the effects of climate change (Breidenich *et al*., 1998). This may have led to an increase in the scientific community's interest in studying the processes of forest decline due to increased temperatures and changes in the rainfall regime, supported by complementary technologies such as remote sensing.

3.2. Most relevant sources and manuscripts

Of the total scientific production analyzed, 41% was concentrated in 5 journals. The following journals stand out for the number of papers published: Remote Sensing of Environment (34), Forest Ecology and Management (26), Remote Sensing (26), Global Change Biology (18) and Forests (11). Figure 2 shows the most relevant journals according to the number of publications and total citations (sphere size), which range between 1662 and 104 for the most and least cited journal respectively.

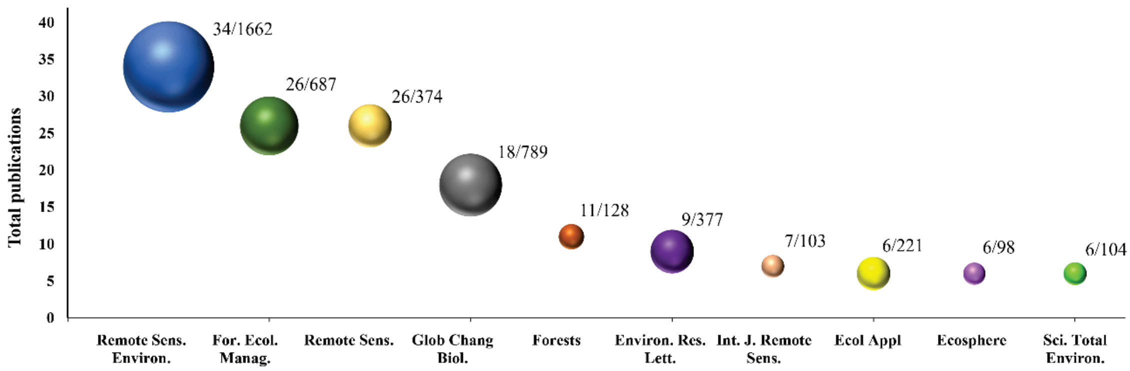

Figure 2. The 10 most relevant journals according to the number of articles published and total citations obtained (the latter indicated according to the size of the sphere).

Remote Sensing of Environment is published by the scientific publisher Elsevier and is considered the journal with the highest impact factor (10.16 by 2022) in the area of remote sensing (https://www.journals.elsevier.com/remote-sensing-of-environment), which explains the number of citations reported in the analysis and the preference of authors to publish in this journal. On the other hand, *Forest Ecology and Management* is a leading journal in the forestry sector with an impact factor of 3.55. *Remote Sensing* reports an impact factor of 4.8 and is a specialized journal that publishes the most cutting-edge advances in the field of remote sensing on a semi-monthly periodicity. Periodicity, high visibility and impact factor of these journals are attractive features for the scientific community.

Table 2 shows the articles with the highest number of citations. Total citations (TC) are a cumulative number over time, i.e., previously published articles have cumulative advantages. Therefore, a column of citations per year is shown to put into perspective the number of citations of each article regardless of the year in which they were published. The analysis on scientific articles regarding the topic with the highest number of citations allows elucidating the topics with the highest interest and characteristics that confer projection among the scientific community (Patience *et al*., 2017).

It was observed that 50% of the most cited articles analyze forest decline patterns regarding climate processes and the incidence of drought periods (Anderson *et al*., 2010; Hernández-Clemente *et al*., 2011; Michaelian *et al*., 2011; Chambers *et al*., 2013; Cohen *et al*., 2016). For example, the article with the highest number of citations is Wu *et al*. (2016) which analyzes nocturnal and diurnal climate variations and their response on plant growth with a multitemporal and regional (northern hemisphere) approach; in that study, a negative relationship was found between minimum values of mean autumn temperature with plant growth patterns. Collins and Woodcock (1996) conducted an analysis to evaluate different techniques to identify forest mortality using multi-temporal information from Landsat 5 TM. Finally, Michaelian *et al*. (2011) studied a specific period of drought that occurred in western Canada between 2001-2002, the objective was to count areas with a high percentage of dead trees and to geospatially interpolate this information.

Table 2. Top Manuscripts by Citations

Manuscripts	Total Citations (TC)	TC per Year
Wu *et al*. (2016)	342	48.8
Collins *et al*. (1996)	292	10.8
Michaelian *et al*. (2011)	266	22.1
Cohen *et al*. (2016)	159	22.7
Meigs *et al*. (2011)	158	13.1
Dash *et al*. (2017)	145	24.1
Hernández-Clemente *et al*. (2011)	144	12
Homer *et al*. (2020)	142	47.3
Chambers *et al*. (2013)	138	13.8
Anderson *et al*. (2010)	135	10.3

3.3. Most relevant authors, countries and collaboration network analysis

Table 3 shows the 10 authors with the highest number of publications related to the study of forest decline using remote sensing. Their contributions represent 18% of the total number of articles in the database. Nine of the authors are affiliated with institutions in the United States of America and one author is from Taiwan. The h-index, used to measure productivity and impact of the authors, is also reported, granting the value h to the author who has published h articles that have been cited at least h times (Hirsch, 2005). The authors with the highest h-index in this study are Asner Gregory P. (133), Cohen Warren B. (88) and Anderegg William R. L. (55).

Table 3. Most productive authors and affiliation

Authors	Affiliation	Country	Publications	H-index
Huang, Cho-Ying	National Taiwan University	Taiwan	7	23
Asner, Gregory P	Arizona State University	USA	6	133
Hicke, Jeffrey A	University of Idaho	USA	6	50
Anderegg, William R. L.	University of Utah	USA	5	55
Cohen, Warren B.	USDA Forest Service	USA	5	88
Negron-Juarez Ri	Lawrence Berkely National Laboratory	USA	5	30
Yang, Zhiqiang	Oregon State University	USA	5	25
Bright, Benjamin C	USDA Forest Service	USA	4	16
Buma B	University of Colorado	USA	4	21
Chambers JQ	Lawrence Berkeley National Laboratory	USA	4	49

Huang Cho-Ying (https://orcid.org/0000-0002-9174-7542), Asner Gregory P. (https://orcid.org/0000-0001-7893-6421) and Hicke Jeffrey A. (https://orcid.org/0000-0003-0494-2866) are the authors with the highest number of published papers, with seven, six and six papers, respectively. Huang Cho-Ying belongs to the National Taiwan University and his main contributions involve analyses of biomass and carbon loss in mountain ecosystems due to tree dieback (Huang *et al*., 2010; Huang and Anderegg, 2012). This same author has developed extensive analyses of scientific production related to forest decline, studying carbon fluxes in ecosystems (Anderegg *et al*., 2016), a problem that is emphasized by the influence of human activities (Huang *et al*., 2019). Asner Gregory P. has studied giant sequoias (*Sequoiadendron giganteum*) from different perspectives by applying diverse remote sensing techniques; to analyze canopy water content (Martin *et al*., 2018), responses to warmer droughts (Nydick *et al*., 2018) and vulnerability mapping (Baeza *et al*., 2021). Hicke Jeffrey A. has studied forest mortality related to insect attacks, using different remote sensing i.e., high resolution multispectral Quickbird images (Hicke and Logan, 2009), Landsat medium resolution images (Meddens *et al*., 2013) and LiDAR technology (Bright *et al*., 2012).

A total of 32 countries published scientific contributions on the study's subject. The USA is the country with the highest number of publications, followed by Germany and China with 133, 22 and 19 respectively. Figure 3 shows the map of the most relevant countries according to the number of papers published. This is consistent with the fact that, according to OECD data (2022), the countries with the greatest investment in research and development are the USA, China and some European Union countries. The USA alone contributed 48% of the total publications i.e., 133 out of 278, which is consistent with the fact that 9 of the most productive authors belong to institutions in that same country (Table 3) and one of the most cited papers addresses forest disturbance in the USA between 1985 and 2012 (Cohen *et al*., 2016). It is also important to mention that there are no studies at several countries including Mexico, Colombia, and someone of Africa.

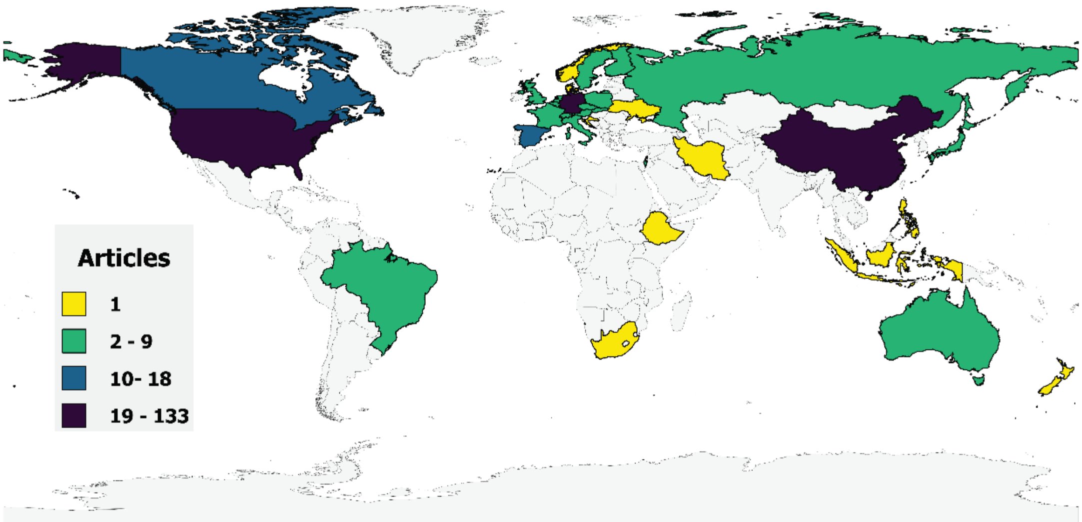

Figure 3. Number of papers published per country.

This trend could be partly explained by unprecedented levels of climate change-induced forest mortality documented in the USA due to increasingly intense and hotter droughts, especially in the southwestern of this country. For example, derived from the 2012 to 2016 drought in California, more than 100 million dead trees were reported (Stevens, 2016; Jay *et al*., 2018). Allen *et al*. (2010) mention that drought and heat in the western USA have caused extensive insect outbreaks and mortality in many forest types throughout the region, affecting 20 million hectares. Also, between California and Texas combined, half a billion trees have died since 2010 because of this phenomenon (Hammond *et al*., 2022). These facts have aroused the concern of the scientific community to the point that it has been identified as a global climate emergency (Ripple *et al*., 2020).

Another important issue to analyze, in addition to the quantity indicators, is the scientific collaboration networks (Glänzel, 2001). Figure 4 shows the links between each of the countries that published scientific articles related to the topic. The network has been built based on the citations between papers, i.e., the number of citations of papers from another country contained in a paper from a particular country. It is important to note that isolated nodes were removed, therefore, the network of collaborating countries consisted of 29 nodes and 220 links between 1989 and 2021.

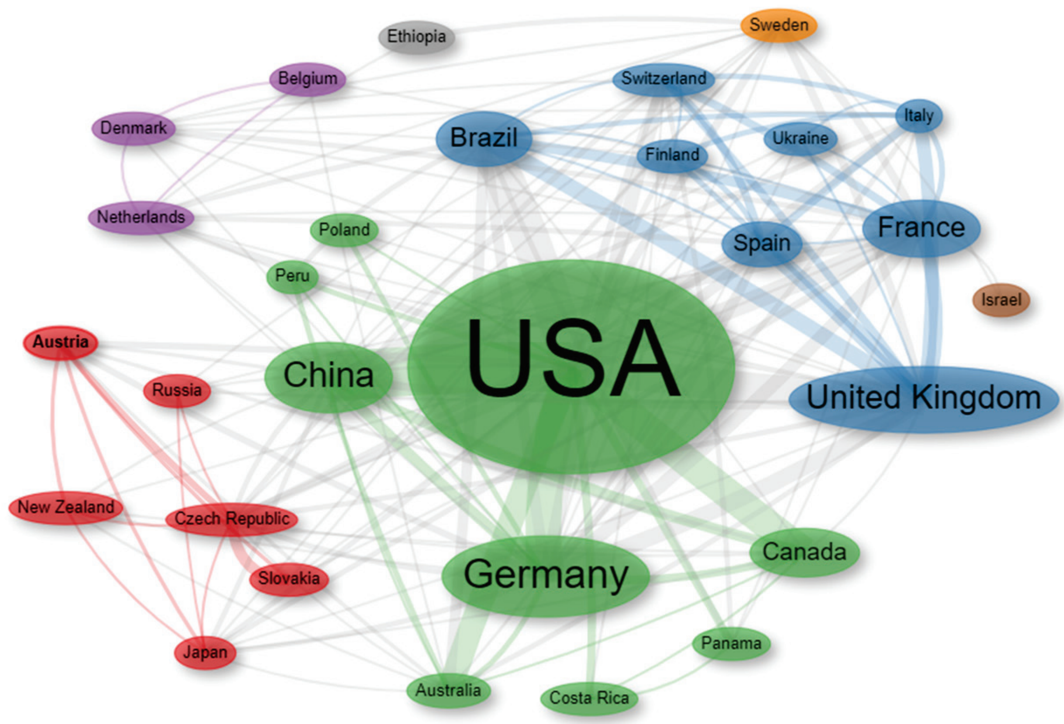

Figure 4. Countries' collaboration network.

Figure 4 shows that USA, Germany, China and UK have larger circles than other countries, indicating that they are more productive in this particular research area, which is consistent with the information in Figure 3. The thickness of the lines suggests strong ties between authors from the USA, Canada, Australia and Germany. The strongest USA relationships are with mainly Germany and Canada. It is important to note that weak ties imply a low level of cooperation. It is interesting to note that China, despite being the country with the third largest number of publications, appears to have few or weak collaborations with other countries. This could be explained due to the language barrier in which it publishes. Li *et al*. (2018b) mention that it was not until the 2000's that the Chinese scientific community had a growing interest in publishing in English, skills that are still developing in this community. So, we can expect that in the coming years collaborative networks between China and other countries will strengthen considerably. Although international collaborative networks are extremely important, there are countries with strong and productive internal scientific production networks, as is the case of China.

3.4. Thematic Analysis

The analysis of keywords defined by the authors using World-TreeMap (Fig. 5), showed that the most used words (excluding the words that were criteria of the initial search i.e. "forest decline", "forest mortality", "forest die-off", "tree mortality" and "remote sensing") are: Landsat (19%), Drought (17%), Climate Change (14%), Forest Disturbance (9%), Change Detection (7%), Time Series (7%), LiDAR (6%), MODIS (5%), NDVI (5), Bark Beetle (5%) and Fire (5%).

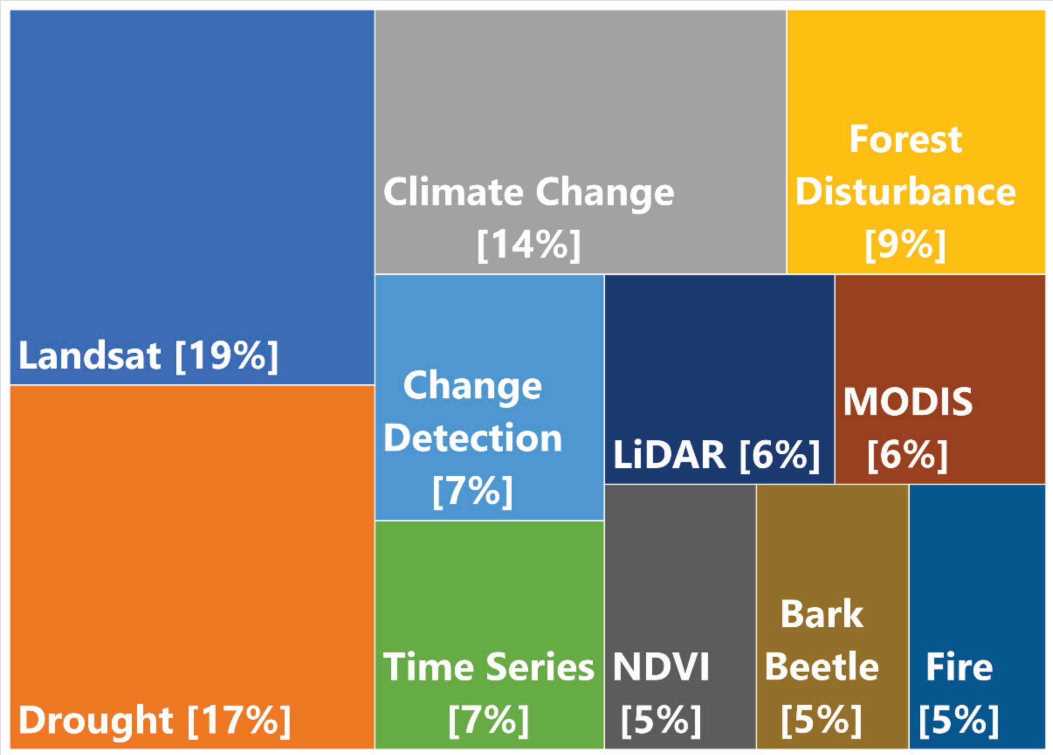

Figure 5. Word-TreeMap of high-frequency keywords in the field of forest decline and remote sensing. The size of the square or rectangles indicate the papers frequency of keywords.

It is important to note that, although the words “Climate Change” or “Drought” were not included in the search equation, these are some of the keywords defined by the authors as being the most frequent in the articles (Fig. 5). This shows that forest decline phenomena are frequently analyzed with a focus on climate change. It is also important to highlight the relationship of forest decline (or homonymous forms) with words such as "Drought", "Climate Change" and "Forest disturbance". This indicates that the authors give them a direct or causal relationship in their research. Their presence as keywords defined by the authors could imply that there is a scientific consensus on the main catalysts of forest decline. That is, climate change will lead to increasingly intense and hotter droughts, which will directly impact forest ecosystems (Hammond *et al*., 2022). For example, Ogaya *et al*. (2020) found higher forest mortality when mean annual temperature was higher and precipitation was lower, especially during spring and summer. Gheitury *et al*. (2020) mentioned that reductions in winter precipitation of approximately 37 mm and adverse increase in air temperature by 0.14°C corresponded with a 20% reduction in tree density. They concluded that drought stress caused physiological weakness in plants promoting pest and disease damage and the eventual onset of a forest decline phenomenon, with severity related to both climate factors and human activities (Huang *et al*., 2019).

On the other hand, derived from the individual analysis and classification of the 278 scientific articles, we found the approaches used by the authors to address the phenomena of forest decline in their research. The classifications turned out to be drought stress, insect attacks, forest disturbances, individual tree death, fire impact, forest dieback, changes in biomass production, forest diseases, land cover changes and pollution stress (Fig. 6).

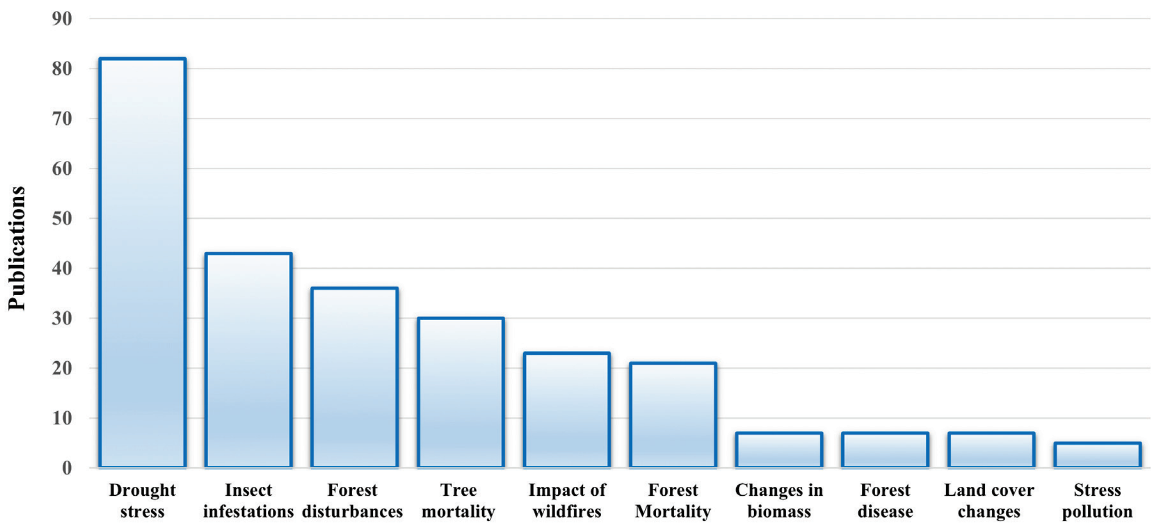

Figure 6. Forest decline phenomena in the articles studied.

Based on the individual analysis of the 278 scientific articles, it was possible to identify the most frequent types of vegetation used to study the phenomena of forest decline. Figure 7a shows that almost half of the research was carried out in temperate forests. This type of forest is the most vulnerable to increasingly intense and hotter droughts, especially in mountain ecosystems (Hammond *et al*., 2022). These ecosystems are characterized by high altitudes and show climate and environmental heterogeneity within their altitudinal gradient (Naud *et al*., 2019; Peng *et al*., 2020). Additionally, they are considered highly sensitive to climate change (Beniston, 2003) and represent priority conservation areas due to the high biodiversity and environmental services they provide (Liu *et al*., 2019).

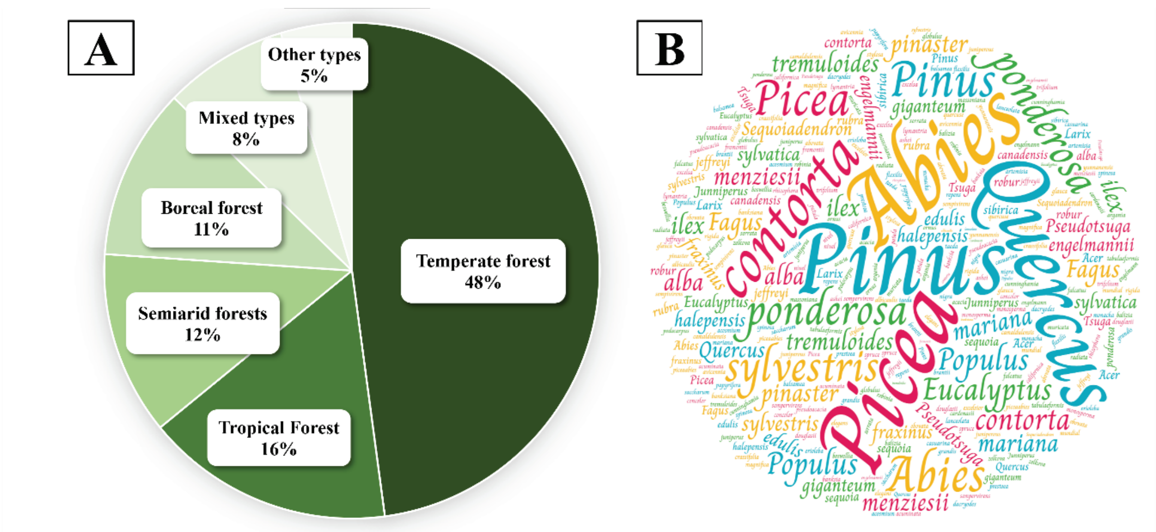

Figure 7. Types of vegetation (A) and species (B) most frequent in forest decline studies using remote sensing. The size of the letters in (B) indicates the number of publications.

In accordance with the vegetation types, the most frequently studied tree genera or species were extracted. Figure 7b is a word cloud showing *Pinus*, *Picea*, and *Quercus* as the genera with the highest representation in studies related to forest decline phenomena studied with remote sensing. *Pinus ponderosa* is representative of temperate forests in USA and has been widely studied. For example, Furniss *et al*. (2020) used Landsat images to predict the number of dead trees after a fire. *Pinus contorta* has been a species of interest due to its great impact caused by the outbreaks of bark beetles; derived from this, Bright *et al*. (2020) conducted an analysis with time series of Landsat images using the Google Earth Enginne platform, to estimate tree mortality in affected areas. Furthermore, *Picea abies*, a species found in temperate and boreal forests, whose populations have suffered many attacks by bark beetles, was studied by Stereńczak *et al*. (2020) to analyze the influence of severe droughts on forests in Poland and Belarus. The authors used information from multispectral aerial imagery and LiDAR, finding that drought conditions are related to the spread of pest and increased forest mortality.

Regarding keyword “Landsat” refers to the most ambitious and consistent earth observation satellite system program ever (Wulder *et al*., 2019). Landsat has captured land surface information consistently since 1972. Going through Landsat 1 ERTS (Earth Resources Technology Satellite), Landsat 4 TM (Thematic Mapper) and later with Landsat 5 TM, Landsat 7 ETM (Enhance Thematic Mapper), Landsat 8 OLI/TIRS (Thermal Infrared Sensor) and the recently launched Landsat 9. This research shows that the scientific community has studied and reported in journals which belong to Web of Science data base the phenomena of forest decline related to climate change with the help of the Landsat program since 1989 (Fig. 1).

On the other hand, the word MODIS refers to the platform described as Moderate-Resolution Imaging Spectroradiometer, which serves as the key instrument for NASA's Earth Observing System (EOS) and is being used for global change research and natural resource management (Justice *et al*., 2002). Together the Landsat program, MODIS and several other satellites offer the scientific community unprecedented volumes of remotely sensed data for research and natural resource management applications. NDVI (normalized difference vegetation index) and Change Detection, refer to specific techniques that use products derived from remote sensing as inputs. The NDVI is the most widely used vegetation index as a proxy of vegetation vigor and productivity, this is because there is easily accessible and freely downloadable information on the spectral bands for their estimation (Huang *et al*., 2021). On the other hand, the Change Detection technique is the process of identifying differences between images at different times. Several novel algorithms based on Landsat time series, including frequencies, preprocessing and applications, have been developed with this technique (Zhu, 2017).

These results are consistent with Figure 8, which shows the types of satellite platforms or remote sensors used in the research analyzed. Landsat was the preferred satellite according to the researchers, followed by the MODIS platform, images captured with aircraft, airborne LiDAR and Sentinel platforms with 99, 47, 17, 16 and 12 documents, respectively.

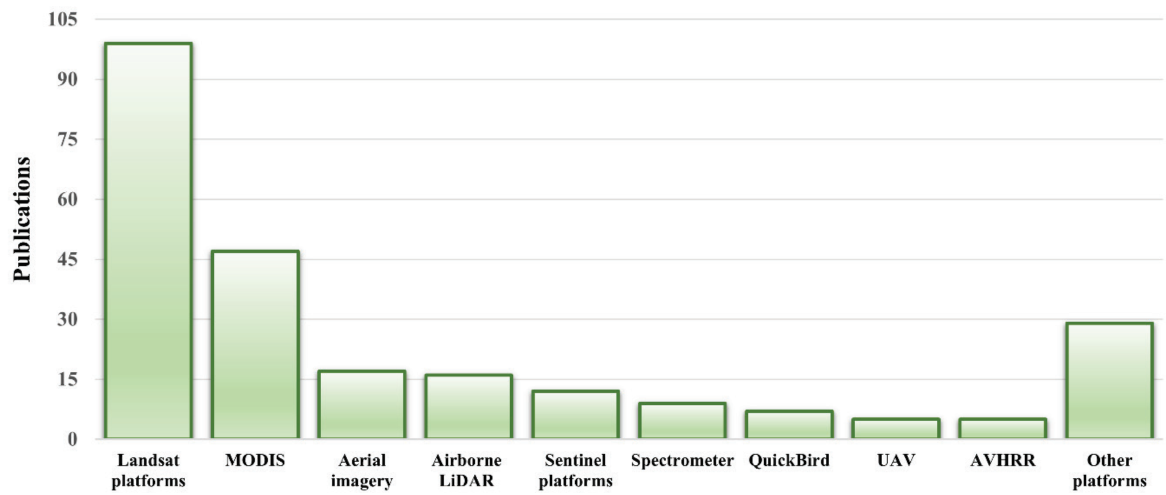

Figure 8. Number of articles published according to the type of satellite platform or remote sensor used.

The most remarkable thing about this research was to detect that despite the recent boom of unmanned aerial vehicles (UAV), commonly called drones (Colomina and Molina, 2014), they were used in only 5 studies. Therefore, it is extremely important to recognize that this fact reveals an area of opportunity to take advantage of drones' main benefits i.e., spatial and temporal resolution and centimeter accuracy to generate high quality information (Yao *et al*., 2019) and help study the different symptoms of forest decline attributable to climate change. UAV provide high-resolution information with analysis capabilities on an individual tree level (Gallardo-Salazar and Pompa-García, 2020). And thereby, recognize ecological parameters for early detection of phytosanitary problems, determination of plant phenology conditions and symptoms of forest decline and mortality attributable to climate change (Dash *et al*., 2017; Brovkina *et al*., 2018; Lin *et al*., 2019).

The cost of UAV technology is significantly higher than conventional satellite sources like Landsat, Sentinel, and MODIS. However, UAV data offers several advantages, including the periodicity of data collection, the ability to capture data under cloud cover, and the potential for 3D reconstruction of forest communities. UAV data are more accessible than other methods with similar characteristics, such as aircraft data. Despite the cost limitations of obtaining remote sensing high-resolution data, the development of open-source communities and open-data policies could improve accessibility to this kind of data, ultimately benefiting forest well-being. Additionally, Dash *et al*. (2018) demonstrated that the UAV data were more sensitive to changes at a finer spatial resolution and could detect stress down to the level of individual trees. The satellite data could only detect physiological stress in clusters of four or more trees.

In fact, the limited use of UAV for climate change-related forest decline analysis (Fig. 8), is consistent with that reported by Dainelli *et al*. (2021) who conclude that currently, most UAV applications in the forestry sector are focused on the calculation of forest structure attributes, and not on more complex applications such as monitoring forest health, fires or symptoms of forest decline. Moreover, Gallardo-Salazar *et al*. (2020) mention there are still challenges concerning the development of UAV in specific parts of the world, mainly in tropical and equatorial forests. The current interest in conducting exploratory studies on the use of UAV probably responds to the learning curve of new technologies and the need to generate proposals on the use of such devices (Iglhaut *et al*., 2019). In the following years, it is possible that studies on specific applications such as forest management, pest and disease monitoring, post-fire monitoring, and symptoms of forest decline will increase. In addition, a lot of complementary research is required for the better use of multispectral, hyperspectral and thermal sensors for long-term monitoring in forest ecosystems.

4. Conclusions

This study reviewed the scientific publications reported in Web of Science on forest decline supported by remote sensing. This resulted in a bibliographic dataset available to researchers interested in this topic (see supplementary material https://bit.ly/3KaomRB). Keyword analysis of the manuscripts revealed the relationship between the different phenomena of forest decline with drought stress and climate change (see Figure 6). The bibliometric analysis method was extremely useful for understanding the characteristics and evolution of scientific production on the subject. The results show that the use of satellite information, aerial photographs or some other type of remote technology to study and understand forest decline at different scales has been reported in the Web of Science for a little more than three decades. Furthermore, scientific production on this topic is growing exponentially and seems to respond to the increase in temperatures and the greater frequency of drought events, which in turn, is inducing forest decline events in many regions of the world.

However, satellite platforms (Landsat, MODIS and Sentinel) were the most widely used for the analysis of forest decline processes. The most remarkable aspect of this research was to detect the lack of prominence of unmanned aerial vehicles (UAV; commonly known as drones). This reveals an area of opportunity to take advantage of the main benefits of UAV, i.e., spatial and temporal resolution and centimeter accuracy to generate high quality information.

Therefore, it is expected that in the following years there will be an increase in studies on specific applications of UAV in forest management, pest and disease monitoring, post-fire monitoring and symptoms of forest decline related to climate change. However, since the most worrying aspect of climate change is not only its magnitude, but the speed at which it is occurring, it is essential to develop tools to address it and achieve strategic and adaptive management of forest ecosystems. For this reason, it is strongly recommended to increase studies to improve the use of multispectral, hyperspectral, thermal and LiDAR sensors assembled in UAV for long-term monitoring of forest decline related to climate change.

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