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A Spatio-Temporal Analysis of the Frequency of Droughts in Mexico's Forest Ecosystems

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Abstract: Droughts can affect forest ecosystems and lead to soil degradation, biodiversity loss, and desertification. Not all regions of Mexico are affected in the same way, as some areas are naturally more prone to drought due to their geographical location. Therefore, the objective of this work was to carry out a spatio-temporal analysis of the occurrence of droughts (severe and extreme) in Mexican forest systems, covering the period 2000–2021, and to study the area covered by these events in Mexican forest systems. This analysis was divided into three stages: the classification of land use and vegetation, spatial mapping and the classification of drought intensity, and an analysis of drought frequency and probability in forest systems. The results show that more than 46% of Mexico's forest area experienced severe and extreme droughts during the 21-year period studied. Broadleaved forests were most affected by severe and extreme droughts, with a frequency of 6 years. The increasing frequency of droughts poses a major challenge to the resilience of forest ecosystems in Mexico, highlighting the need to implement climate change adaptation and forest management measures to protect the country's biodiversity and natural resources.

Keywords: standardised precipitation index; climate exposure; drought intensity; spatio-temporal analysis; Mexico; forest

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1. Introduction

Drought can have devastating effects. Drought, a global problem exacerbated by climate change and anthropogenic factors, has far-reaching effects on various aspects of society [1,2]. It affects environmental components such as soil processes, vegetation growth, and aquatic ecosystems, leading to water scarcity and stress for one third of the world's population [3]. The health impacts of drought are significant, threatening physical, mental, and social well-being, particularly in regions such as Iran where poor water resource management exacerbates the effects [4]. Economically, droughts reduce per capita GDP growth by 0.39 to 0.85 percentage points, with low- and middle-income countries in drylands experiencing the greatest losses, highlighting the need for adaptation investments and changes in water management practices [5,6]. Drought can lead to economic losses affecting agriculture and other sectors, with the magnitude of the impact depending on water allocation policies [7].

Understanding the multiple impacts of drought is crucial for effective mitigation and preparedness measures worldwide [8]. Therefore, some researchers have analysed different methods for quantifying drought and its potential impacts.

Globally, droughts have reduced global crop production by about 10% [9]. In regions such as the Loess Plateau and the Qinling Mountains in China, the resilience of vegetation is gradually decreasing, and productivity takes longer to recover than canopy structure [10]. In addition, the sensitivity of global vegetation productivity to drought has increased over time [11].

Historical droughts such as the European drought of 1540 and the US Dust Bowl of the 1930s illustrate the severity of such events in Europe and North America [12]. The extreme drought of 1842 affected a broad zonal belt from France to eastern central Europe, resulting in significant agricultural, hydrological, and socio-economic impacts [13]. An analysis of severe droughts from 1970 to 2020 shows that Eastern Europe, western Russia, and North America have experienced extreme droughts associated with specific atmospheric conditions and circulation patterns [14]. South Korea has identified periods of extreme drought, the most severe of which occurred from 2014 to 2016 [15].

Internationally, several methods are commonly used to quantify drought. These methods include the Standardised Precipitation Index (SPI) [16], the Standardised Precipitation Evapotranspiration Index (SPEI) [17], the Palmer Drought Severity Index (PDSI) [18], the Keetch–Byram Drought Index (KBDI) [19], the Standardised Aridity Index (SAI) [20], and the Effective Drought Index (EDI) [21]. The use of composite hydrometeorological indices such as JDHMI-CCA, JDHMI-PCA, and JDHMI-Copula, which incorporate canonical correlation analysis, principal component analysis, and copula-based methods, has been explored to provide a more comprehensive assessment of drought conditions [22]. While the SPEI is particularly useful for characterising drought in agricultural settings [23,24], the SPI remains widely accepted due to its simplicity and reliance on precipitation data only [25,26].

In Mexico, significant efforts have been made in recent years to understand the impact of drought on the agricultural sector using the SPI. These studies have analysed various aspects such as the reduction in maize grain yields and livestock production [27,28], soil moisture deficits and plant water stress that threaten both crop yields and livestock productivity [29], and the economic value of agricultural water under drought conditions [30]. In addition, a 40% reduction in national maize production and agribusiness due to drought has been documented [31]. Questions remain, however, about the effects of drought on forest ecosystems.

For example, prolonged extreme drought causes significant stress to trees, resulting in reduced growth and significant leaf loss [32,33]. This decline in growth is closely linked to water availability and can lead to physiological changes that may ultimately result in tree death. In the tropical montane cloud forests of Mexico, the vulnerability of tree species to extreme drought has been highlighted, affecting their physiological and phenological processes and ultimately the resilience of the ecosystem [34].

In addition, increased water stress may influence how forests interact with climate change, potentially exacerbating its effects. For example, in semi-arid areas, tree mortality could increase the rate of soil evaporation, leading to warmer microclimatic conditions [32]. As climate change leads to increases in temperature and variations in precipitation, water availability and vegetation patterns in forests may be significantly altered [35]. A prominent example of the relationship between drought and extreme events is the occurrence of forest fires in the state of Chihuahua in the 1990s, to which drought events contributed significantly [36]. In northern Mexico, in mountainous regions, species such as *Yucca carnerosana*, *Pinus cembroides*, and *Larrea tridentata* show differential mortality across stress gradients [37].

Remote sensing studies have highlighted the phenological effects of drought on vegetation cover, emphasising the need to understand how drought affects landscapes [38,39]. A spatio-temporal analysis of severe and extreme droughts is critical for understanding climate patterns and making decisions related to natural resource management and climate change adaptation [40].

Therefore, the objective of this work was to carry out a spatio-temporal analysis of the occurrence of severe and extreme droughts and to study the area covered by these events in Mexican forest systems. In this study, we focus on assessing the probability and frequency of such events, recognising that both are key components of risk analysis studies. Previous research has shown that understanding the probability of severe and extreme droughts is crucial for assessing potential future risks to these ecosystems [41,42]. This assessment will

provide important information for both government agencies and local communities, and contribute to planning for and mitigating the adverse effects of drought in a country facing unique and changing climatic challenges.

2. Materials and Methods

The spatio-temporal analysis of drought in forest systems was carried out in three stages: the classification of forest land use and vegetation, spatial mapping and classification of drought intensity, and an analysis of drought frequency in forest systems (Figure 1). Each step is described below:

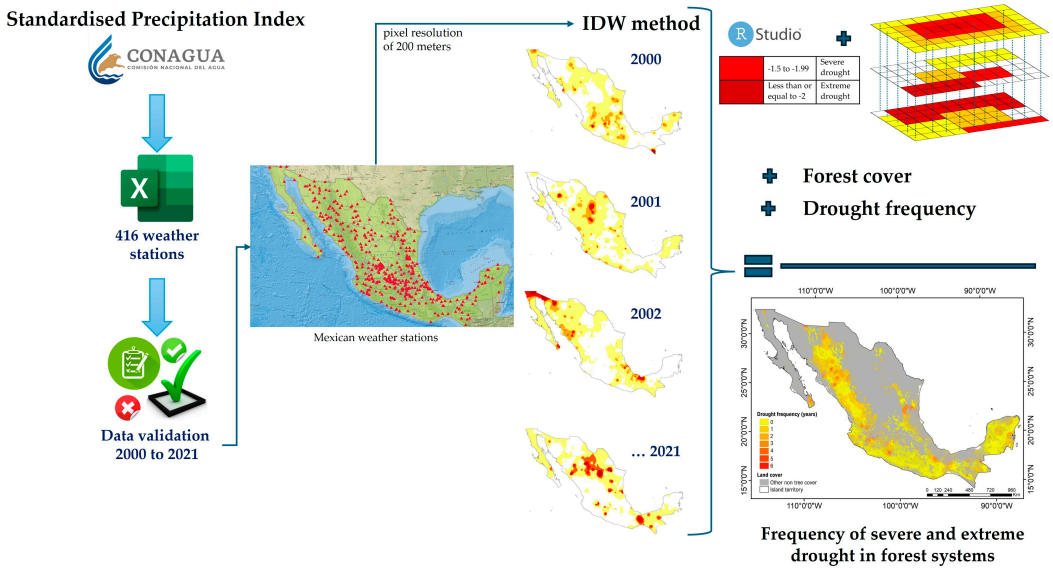

Figure 1. Flow chart to determine the area affected by severe and extreme drought in forest systems in Mexico for the period 2000–2021.

2.1. Delineation of Forest Systems

The study area corresponds to the forested areas of Mexico, delimited on the basis of the latest 1:250,000 scale land use and vegetation map of Mexico, provided by the National Institute of Statistics, Geography and Informatics (INEGI) [43]. It should be noted that this map reflects the situation in 2018. The mapping of vegetation and forest use included nine categories, following CONAZA [44]: coniferous, coniferous and broadleaved, broadleaved, cloud forest, highland and midland tropical forests, lowland tropical forests, other wooded areas, secondary forest vegetation, and secondary rainforest vegetation.

2.2. Spatial Mapping and Classification of Drought Intensity

The SPI is calculated by fitting a gamma distribution to the historical rainfall data and transforming the cumulative probabilities to a standard normal distribution according to Equation (1) [45].

$$SPI_{12} = \sum_{i=1}^{12} \frac{P - \mu}{\sigma} \quad (1)$$

where P is the observed precipitation, μ is the precipitation distribution mean, and σ is the precipitation distribution standard deviation.

The calculated 12-month SPI (SPI-12), or annual drought summary, was downloaded from the National Weather Service [46] in an Excel file. In order to reduce the error in interpolation and the quality of the information, a thorough check of the data was carried out to identify any missing data or anomalies so that each point had data for all 21 years. It consisted of 415 points or meteorological stations distributed throughout the Mexican territory for the period 2000–2021 (see Supplementary Material S1 for more

information). From the grid of points, a map of the spatial distribution of drought was obtained for each of the years of the period, using the IDW method with a pixel resolution of 200 m. Any interpolation method introduces an inherent error. To minimise this error, an interpolation method that has been shown to be effective in similar studies was selected, and its parameters were adjusted to optimise its performance [47–49]. Twenty-two maps were obtained in raster format. Each map was classified into five drought intensity classes according to Barker et al. [50] (Table 1).

Table 1. Standardised Precipitation Index (SPI) drought intensity classes.

SPI Value	Drought Intensity Class
Greater than 0	No drought
0 to −0.99	Mild drought
−1.0 to −1.49	Moderate drought
−1.5 to −1.99	Severe drought
Less than or equal to −2	Extreme drought

Source: Barker et al. [50].

2.3. Drought Frequency and Probability in Forest Systems

For the drought analysis, in addition to counting frequency, a crosswalk with the 9 previously defined forest categories was carried out. This crosswalk made it possible to assess how severe and extreme droughts specifically affected each type of forest cover in the study area. It should be noted that attention was focused on severe and extreme droughts because they are the most drastic, and their recurrence reflects the climatic exposure of forest ecosystems. The calculation of frequencies was carried out using RStudio 2023.06.0 Build 421 [51], counting pixels with SPI-12 values less than or equal to −1.5, corresponding to severe and extreme intensity. Identifying and quantifying the frequency of such events is essential to fully understand their impacts in different regions and over time [32]. The identification of severe and extreme drought events allows decision makers in risk and natural resource management to implement appropriate adaptation and mitigation measures. It also provides critical information for planning drought management strategies and efficient resource allocation [52].

A probability analysis was performed to assess the potential occurrence of drought according to Equation (2).

$$P(D) = \frac{F}{T} \quad (2)$$

where $P(D)$ is the probability of occurrence of severe and extreme droughts based on 2000–2021 data, F is the number of years with severe and extreme droughts in the studied period, and T is the number of years, in this case 21.

3. Results

3.1. Subsection Distribution of Forest Ecosystems in Mexico

Forest ecosystems in Mexico are very diverse throughout the country. In summary, the results show that 71% of the country's surface area is covered by primary vegetation, of which 33% corresponds to coniferous, coniferous and broadleaved, broadleaved, cloud forest, highland and midland tropical forests, lowland tropical forests, and other wooded areas (Figure 2). In contrast, 29% of the area has been converted for agricultural, urban, or other human uses, of which 36% corresponds to secondary forest vegetation and secondary rainforest vegetation. In terms of forest cover, the states with more than 50% of their territory covered by forest are, from largest to smallest, as follows: Quintana Roo > Oaxaca > Campeche > Guerrero > Yucatán > Nayarit > Michoacán de Ocampo > Jalisco > Colima > Sinaloa.

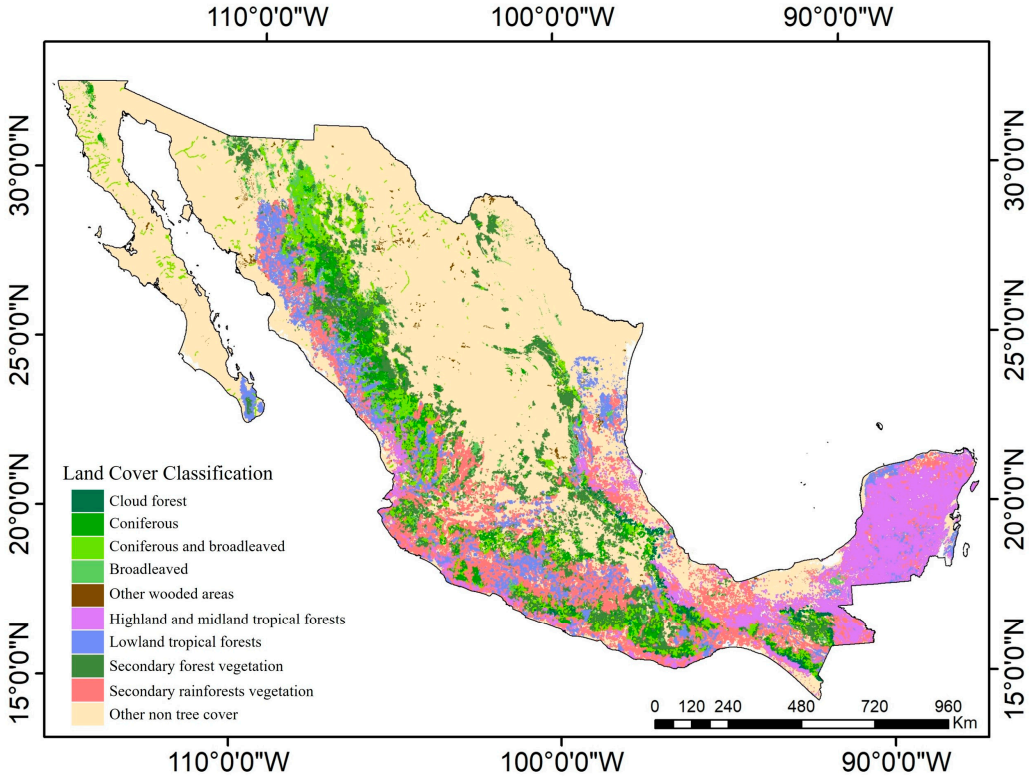

Figure 2. Mexico's forest ecosystems. Source: Author's elaboration based on INEGI [43].

3.2. Drought Intensity in Mexico

Figure 3 shows the temporal and spatial variations of the SPI-12 in Mexico during the period 2000–2021. The entire national territory is plotted on the x-axis according to its longitudinal orientation (from the Greenwich meridian).

It can be observed that at least half of the period studied has SPI-12 values corresponding to droughts between longitudes 110° and 100° W of the country, corresponding mainly to the states of Chihuahua, Durango, Sinaloa, Zacatecas, Jalisco, Guanajuato, and Michoacán. A similar situation is observed in the areas between 100° and 88° W, corresponding to the states of Veracruz, Tabasco, Puebla, Oaxaca, Chiapas, and the Yucatan Peninsula. Drought has affected between 30 and 50% of the national territory in 2003, 2004, 2006, 2007, 2017, and 2018, between 50 and 70% in 2000, 2001, 2003, 2003, 2016, 2019, and 2021, and between 70 and 77% in 2009, 2011, 2012, and 2020.

In practically all the studied years, the threshold of severe and extreme intensity was exceeded, the difference being the national area covered (Figure 4). In 2011 and 2020, both intensities covered the largest national area, 27.16% and 13.17% respectively.

3.3. Drought Frequency Analysis in Forest Systems

The results of this study show that severe and extreme droughts have been distributed throughout the country and have significantly affected different regions of Mexico. In particular, the years 2011, 2020, and 2021 stand out as the periods in which the area affected by these droughts reached its greatest extent (see Supplementary Material S2 for more information).

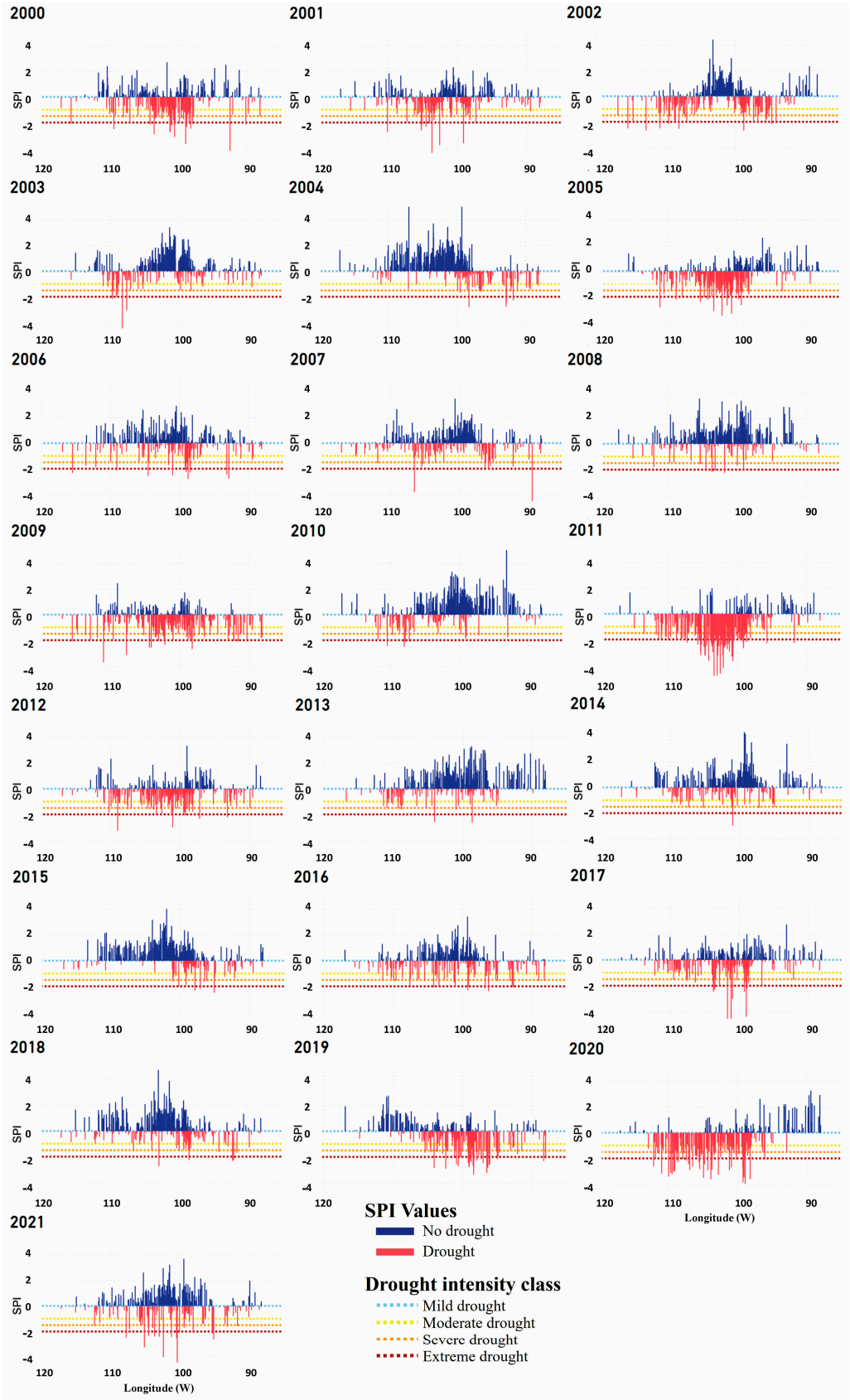

Figure 3. Temporal and spatial pattern of drought in Mexico.

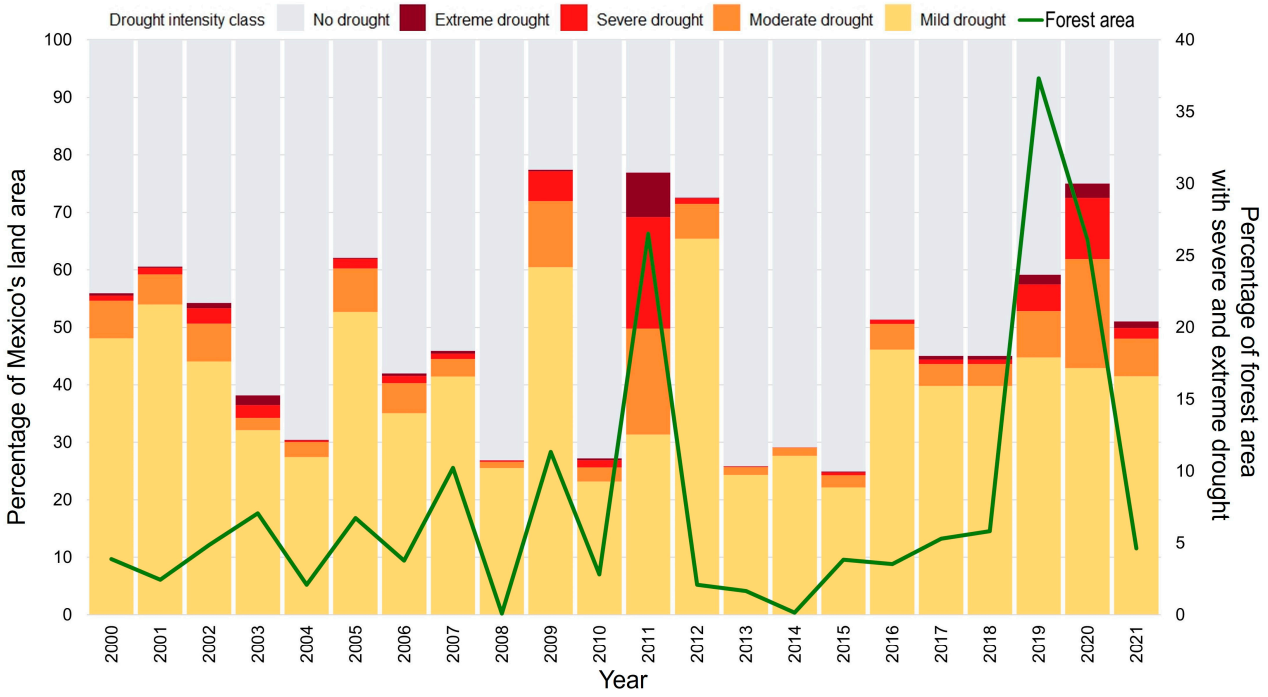

Figure 4. Percentage of Mexico's land area under some form of drought and forest area under severe and extreme drought.

The frequency analysis resulted in a colour map where darker shades indicate a higher frequency of severe and extreme droughts in the different forest categories, allowing a clear and comparative visualisation of the spatial distribution of these events (Figure 5a). The results show that 46% of the forest area has experienced severe and extreme drought during the study period. Categories such as other wooded areas have experienced both types of drought over 70% of their area, while coniferous, broadleaved, and lowland tropical forests have experienced similar conditions over 55% of their area, and the remaining categories have been affected by these climatic conditions over 30%–40% of their area (see Supplementary Material S3 for more information).

In 2011, the severe drought had a significant impact on the forest cover of different forest types. Coniferous, coniferous and broadleaved, broadleaved, lowland tropical forests, and secondary forest vegetation were affected by 10%–20% of their area and other forest areas by 30% of their area. In 2019, cloud forests were affected by 20% of their area, followed by other wooded areas and highland and midland tropical forests, which were affected by 10% of their area. In 2020, coniferous forests were affected on 20% of their area, followed by coniferous and broadleaved, other wooded areas, and lowland tropical forests with 10%. The extreme drought, although affecting a smaller area, had a significant impact. In 2011, coniferous, broadleaved, and secondary forest vegetation were affected by 5%–10% of their area. In 2020, other wooded areas were affected by this catastrophic event covering over 20% of their area (see Supplementary Material S4 and S5 for more information).

According to the probability map (Figure 5b), 90% of the forest area has a 6% probability of experiencing severe and extreme drought. Lowland forests, deciduous forests, and other wooded areas, including coniferous forests, account for 40% of this area with such a probability. On the other hand, 7% of the forest area has a 10% probability of severe and extreme droughts, of which wooded areas and broadleaved forests account for 10% of the area. The forest area with the highest probability of occurrence, reaching 30%, is only 1%, although it is the broadleaved forests that are most affected by these severe and extreme droughts.

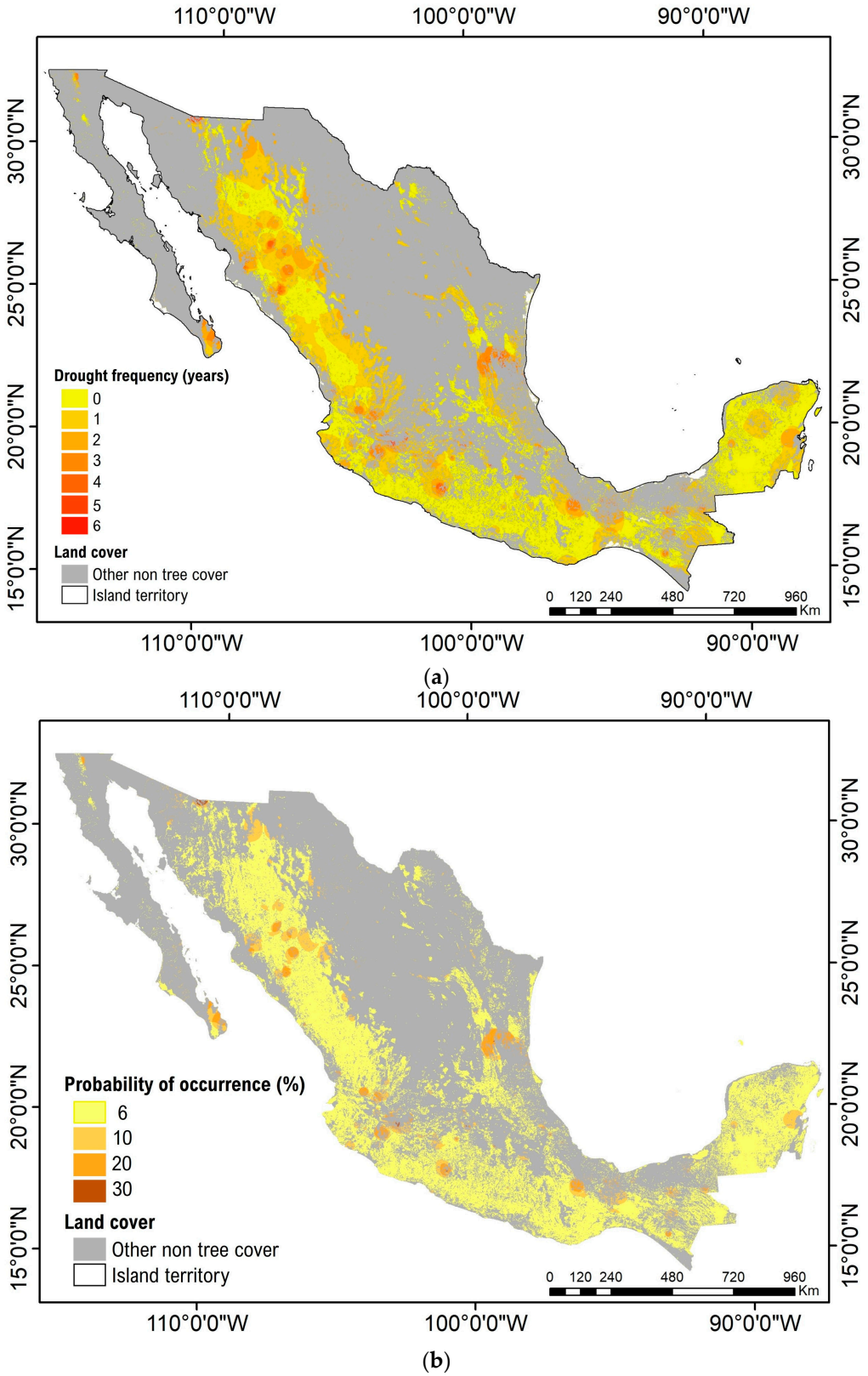

Figure 5. (**a**) Frequency of severe and extreme droughts in forest systems. (**b**) Probability of occurrence of severe and extreme droughts in forest systems.

4. Discussion

4.1. Forest Area Affected by Severe and Extreme Drought

Drought, a phenomenon that tests the resilience of forests and their ability to cope with these challenges [38], has a variable impact depending on its duration and severity. Understanding the resilience of forests to drought is critical at a global scale. Studies suggest that species interactions are beneficial during mild droughts, but negative effects such as competition dominate during extreme droughts [53]. The effects of drought severity and fire frequency on juvenile mortality and forest regeneration have been assessed, and they indicate that severe drought can reduce regeneration and the replacement of juvenile trees [54,55]. Severe droughts and heat waves have highlighted the danger to temperate forest ecosystems [56], highlighting their vulnerability to increased drought severity and the urgent need for further research to improve their resilience [57].

Mexico is a country that experiences drought practically every year, with the main differences being in the magnitude, duration, and distribution over the territory [58]. According to the data analysed, there is considerable variability in these aspects across the different forest areas studied. These results suggest that a significant part of the forest area has experienced drought at different times, which is a relevant concern for the health and resilience of forest ecosystems. Of these, secondary forest vegetation covers 9 and 10% of the national territory [59]. Other wooded areas account for 6%, the categories of coniferous with deciduous and lowland forests for 4% each, deciduous and coniferous forests for 3% each, high and medium forests for 2%, and mesophyll forests for less than 1%.

Mexico's forest cover has been significantly affected by severe and extreme drought events, as shown in Figure 4 and Table 2. It should be noted that for the purpose of sizing the forest systems' problem, Table 2 groups the different categories used in this paper into temperate forest, tropical forest, and cloud forest. In 2019, the percentage of affected forest area reached a significant 37%, compared to 26% in 2011 and 2020. Temperate forests have been most affected by these climatic events, with around 60% of their area affected by drought, closely followed by tropical forests at 58% and cloud forests at 53%. According to CONAGUA data, 2020 was the second most severe year on record for the Drought Monitor, and was slightly less severe than 2011 [58,60].

Some authors agree that not only the duration but also the severity of drought plays a crucial role in determining the impacts on forests [58,61]. These severe conditions can lead to increased tree mortality and reduce forest resilience to future stress events [62]. The information obtained in this study on the areas most affected by severe and extreme drought reinforces the need to implement forest management measures to improve forest resilience to extreme climate variability, such as drought [63]. Furthermore, it is essential to continue monitoring and assessing these conditions in order to anticipate and mitigate them.

Forest ecosystems play a critical role in the ecological balance and biodiversity not only in Mexico, but also internationally [64–66]. Forests located in southern Mexico are more resilient to temperature changes, but variations in the seasonality of future temperature is a factor that will determine the distribution of vegetation [63].

Globally, tropical forests have faced severe droughts in the last decade, particularly in the Amazon basin and western Amazonia, which have affected forest dynamics and carbon balance [67,68]. In contrast, forests in West and Central Africa have shown resilience to extreme drought, possibly due to their historical adaptation [69]. Tropical forests, which are highly sensitive to drought, show differential responses to seasonal and meteorological drought, affecting gross primary production and evapotranspiration [70,71].

In temperate forests, about 65% have experienced drought episodes, affecting their vitality and species distribution [72]. Extreme droughts lead to negative leaf water potentials, significant tree mortality, and changes in vegetation composition [73]. Severe droughts, which are becoming more frequent due to climate change, are altering the structure and function of forests worldwide [74]. In Europe, extreme droughts threaten the sustainability of semi-arid and temperate forests [55]. Temperate forests, such as broadleaved forests, are affected by structural overstory, which contributes to more rapid declines during extreme

droughts [75]. However, these forests show greater stability compared to other biomes under increasingly extreme droughts, highlighting the critical role of conserving these ecosystems for global vegetation productivity and carbon sink stability [76].

Table 2. Area affected by drought in forest ecosystems in Mexico (km^2) for the period studied.

Forest System *	Total Area	Area Affected by Drought (km^2)							
		2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Temperate forests	336,589	3773	1349	7581	21,932	614	8066	4098	5137
Tropical forests	302,603	2724	1939	4118	1675	1367	10,800	5404	10,155
Cloud forests	12,921	239	182	162	0	189	99	98	691
Total drought affected area (km^2)		6736	3470	11,861	23,607	2,170	18,965	9600	15,983
%		3.87	2.45	4.87	7.07	2.10	6.73	3.76	10.23
		2008	2009	2010	2011	2012	2013	2014	2015
Temperate forests	336,589	124	6805	4458	61,254	5084	834	10	899
Tropical forests	302,603	169	17,610	3321	20,718	270	662	418	6295
Cloud forests	12,921	0	451	50	193	63	153	2	192
Total drought affected area (km^2)		293	24,866	7829	82,165	5417	1649	430	7386
%		0.09	11.33	2.81	26.54	2.09	1.65	0.16	3.83
		2016	2017	2018	2019	2020	2021		
Temperate forests	336,589	912	6338	3243	9993	48,754	4071		
Tropical forests	302,603	5452	9194	3745	31,188	32,058	7410		
Cloud forests	12,921	189	48	469	3106	126	124		
Total drought affected area (km^2)		6553	15,580	7457	44,287	80,938	11,605		
%		3.54	5.29	5.83	37.31	26.05	4.62		

* Temperate forests = coniferous, coniferous and broadleaved, broadleaved, and secondary forest vegetation; tropical forests = highland and midland tropical forests, lowland tropical forests, and secondary rainforests vegetation; and cloud forest = cloud forest.

In cloud forests, drought affects biodiversity, especially endemic species, and reduces tree characteristics such as growth rings [77]. Species diversity can mitigate these effects by improving productivity and carbon sequestration [78]. Epiphyte responses to drought vary, with some being more resilient due to water storage structures [79]. West African tropical forests experience changes in taxonomic, functional, and phylogenetic diversity, with less stability and diversity in drier areas [80]. In summary, drought is having a profound impact on the biodiversity and functioning of forest ecosystems worldwide.

4.2. Persistence of Severe and Extreme Droughts in Forest Areas

A probability analysis provided a clearer understanding of the possible scenarios associated with environmental risks in the forest ecosystem. Probability is used as a key component in understanding and quantifying potential risks associated with environmental factors and human activities in urban settings [81]. Drought frequency is also a key component of risk analysis. It allows the identification of patterns and trends that can inform forest management strategies [82]. By combining drought probability and frequency, it is possible to develop a more robust and accurate risk assessment, allowing more effective adaptation measures to be designed and implemented to mitigate the impacts of extreme climate variability on Mexico's forests.

The probability of drought occurrence varies globally, depending on the type of drought. Studies have shown that the average probability of the co-occurrence of meteorological, agricultural, and hydrological droughts in a single event is around 30%, with individual drought types having probabilities ranging from 61% to 69% of all single drought events [83]. However, this specific work shows that over a 21-year period, the probability of occurrence is 30%. Furthermore, research focused on Central Iran indicates that more severe and longer droughts are expected in the future, especially under certain emission scenarios, highlighting an increased probability of drought events [84]. Understanding

these probabilities is crucial for early warning systems, drought management planning, and the development of effective strategies to mitigate the impacts of drought on agriculture, natural resources, and society [85,86].

It can be observed that 39.74% of the forest area has been affected by drought at least once during the year. Although this is a significant proportion, what is even more alarming is that 16.4% have been affected for 2 to 3 years. This prolonged drought can have devastating long-term effects on forest health. In contrast, a small proportion, 0.56%, have experienced drought for 4 to 7 years. While this amount may seem insignificant, even on a small scale these droughts can have significant impacts on the structure and functioning of these forest ecosystems, affecting biodiversity, reducing carbon sequestration, and altering ecosystem services.

Coniferous, broadleaved, cloud forest, and highland and midland tropical forests are among the vegetation cover types that have experienced at least one year of drought on 90% of their area. In contrast, broadleaved forest, other woodland, lowland forest, and secondary rainforest vegetation have experienced between 2 and 3 years of drought on at least 5% of their area. Most worryingly, these same areas have experienced between 4 and 6 years of drought in at least 0.5% of their area, as shown in Figure 6. However, Mexico has experienced droughts with a frequency of 4 to 10 years (Dobler-Morales and Bocco, 2021). This situation makes vegetation vulnerable. A specific example of this situation is observed in Douglas fir growing in northern Mexico, which requires 6–10 years to fully recover growth rates after extreme drought events [87]. The idea that a forest will always fully recover after disturbance may not always be correct, as multiple droughts may affect its ability to recover to its previous condition. In other words, it is difficult to assess the response of a forest to a single drought without considering the cumulative effects of repeated droughts [38].

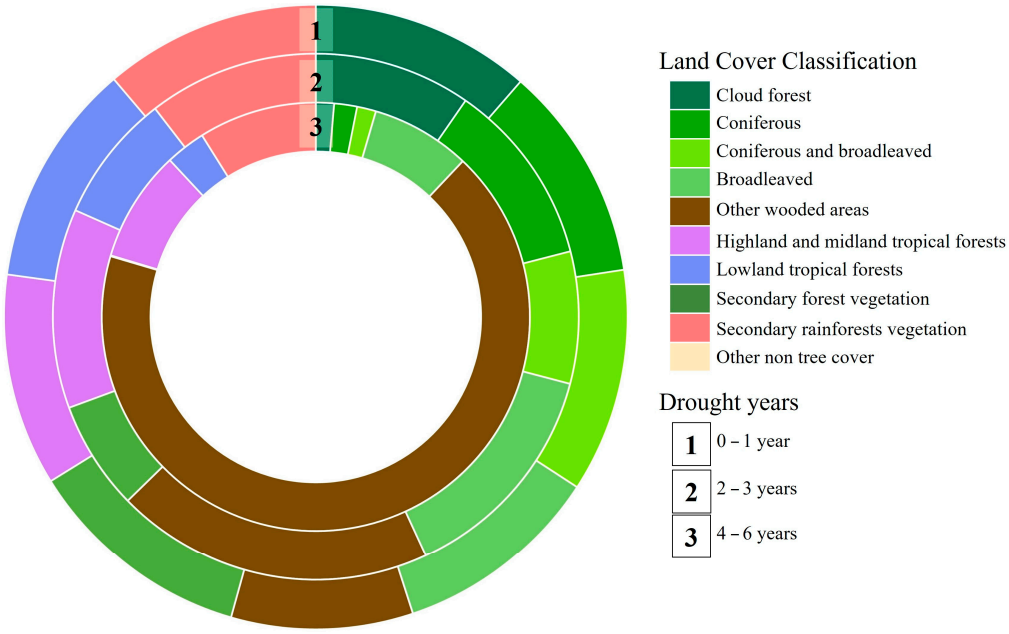

Figure 6. Cumulative frequency of severe and extreme droughts in forest systems.

In addition, water shortages due to drought events can negatively affect tree growth and development, which can have a negative impact on the productivity of forest resources [88]. This can affect the timber industry and the economy of the communities that depend on it, as reported by Rubio-Camacho et al. [89], who found that tree mortality in a forest dominated by *Pinus montezumae* and *Alnus firmifolia* was mainly due to drought events. Similarly, it can also have indirect effects on forest cover, such as the increased presence of pests and diseases that attack trees weakened by water scarcity [90].

Other authors, such as Tran et al. [91] and Calama et al. [92], claim that drought stress in *Pinus massoniana* and *Pinus pinaster* ssp. *mesogeensis* leads to reduced stomatal conductance, increased superoxide dismutase activity, and altered gene expression, thereby increasing drought tolerance. In studies of *Pinus ponderosa* in the western United States [93], more recurrent drought conditions were found to result in additional reductions in growth and changes in growth-climate sensitivity. Specifically, triple drought events were found to be particularly detrimental to growth in this species. In addition, a multi-decadal study conducted in mountainous areas of the southwestern United States highlighted that increased drought frequency alone is a contributing factor to the long-term growth effects observed in *Pinus ponderosa* populations [94].

4.3. Critical Analysis and Future Prospects

This study provides a detailed overview of the frequency of droughts in forest ecosystems in Mexico, providing valuable information for forest management and biodiversity conservation. It uses a spatio-temporal approach to analyse the evolution of droughts over time, providing a broad perspective on the situation. It is also based on hard data and established methodologies, such as the Standardised Precipitation Index, which gives validity and reliability to the results.

However, this study focuses mainly on the frequency of droughts and their impact on forests, without considering other possible factors that may influence ecosystem health. In addition, the delineation of forest areas and the classification of forest categories may introduce some subjectivity into the interpretation of the data. In addition, there is no explicit mention of analysing the possible causes of droughts, which may limit the full understanding of the factors contributing to these events. Finally, the representativeness of the data may be limited if not all relevant variables are considered in the study of droughts in forest ecosystems.

To address these limitations and to improve knowledge, it would be important to investigate the specific effects of drought on different tree species and their long-term adaptive capacity. It would also be possible to analyse how extreme droughts affect the dynamics of forest ecosystems, including changes in species composition and forest structure. It would also be important to study the interaction between droughts and other environmental stressors, such as forest fires, to better understand the combined effects on ecosystems. It would also be important to assess the effectiveness of forest restoration and management measures in mitigating the effects of drought on forests. Finally, it would be crucial to investigate the influence of climate variability and climate change on the frequency and intensity of droughts in forest ecosystems in Mexico.

5. Conclusions

In recent years, drought has significantly affected Mexico's forest ecosystems. In terms of severe and extreme drought, the years 2011, 2020, and 2021 showed the highest intensity, duration, and area affected. The analysis of frequency and probability of droughts showed that more than 46% of Mexico's forest area has experienced severe and extreme droughts. Although further damage studies are required to complete the risk approach, the inclusion of frequency and probability in the analysis provides insight into possible risk scenarios.

The increasing frequency of severe and extreme droughts in Mexico poses a significant challenge to the sustainability of forest ecosystems. Adaptation to these changing conditions is essential to ensure the conservation of biodiversity, the provision of ecosystem services, and the protection of the country's natural resources.

The variability in the geographical distribution and intensity of droughts in different types of Mexican forests highlights the diversity of forest ecosystems present in the country. Temperate forest ecosystems were most affected by drought, with drought affecting 60% of their area, followed by tropical rainforest, with drought affecting 58% of their area. In addition, montane cloud forests were affected in 53% of their area. More than half of Mexico's forest area has been affected by drought in the last 21 years, highlighting the

vulnerability of these ecosystems to drought. This diversity requires adaptive and specific management approaches for each forest type, considering the particularities of each region and its response to droughts.

Concerns about the persistence of prolonged droughts lasting 2–6 years underscore the importance of assessing the long-term resilience of Mexican forests. These prolonged events need to be studied, as they can have devastating impacts on biodiversity, tree growth, and the provision of ecosystem services, highlighting the need to strengthen forest resilience to these climate challenges.

The 30% probability of drought over a 21-year period highlights the ongoing threat that these climate events pose to Mexico's forest ecosystems. This finding underscores the importance of developing early warning systems, drought management plans, and adaptation strategies to mitigate the negative impacts of drought on biodiversity, natural resources, and Mexican society.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15071241/s1. Supplementary Material S1—Mexican weather stations. Supplementary Material S2—Annual mapping of severe and extreme droughts from 2000 to 2021. Supplementary Material S3—Severe and extreme drought area by category and frequency. Supplementary Material S4—Annual area affected by severe drought by category, in km^2. Supplementary Material S5—Annual area affected by extreme drought by category, in km^2.

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