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Article

Impact of Fire History on the Structure of a Temperate Forest in Northern Mexico

José M. Zúñiga-Vásquez [1], José Villanueva-Díaz [2,*], Julián Cerano-Paredes [2] and Gerónimo Quiñonez-Barraza [3]

[1] Unidad Regional Universitaria de Zonas Áridas, Universidad Autónoma Chapingo, Carretera Gómez Palacio-Ciudad Juárez, km 40, Bermejillo 35230, Mexico
[2] Centro Nacional de Investigación Disciplinaria Relación Agua-Suelo-Planta Atmósfera (CENID-RASPA), Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Margen derecha del Canal Sacramento km 6.5, Gómez Palacio 35140, Mexico
[3] Campo Experimental Valle del Guadiana (CEVAG), Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP), Carretera Durango-Mezquital, km 4.5, Durango 34170, Mexico
* Correspondence: villanueva.jose@inifap.gob.mx

Abstract: Understanding the ecological role of fire in forests is essential for proper management and conservation programs. The objectives of this study were: (1) to reconstruct the history of fires in a temperate forest in Sierra Madre Occidental; and (2) to interpret the impacts of fire and climate on forest structure. Sixty tree cross-sections with fire scars were analyzed, and descriptive statistics of fire history were generated. Additionally, growth cores were analyzed, and the ages of trees of different diameter categories were calculated. The synchrony between fire history and tree establishment was determined, and precipitation and Palmer Drought Severity Index (PDSI) values were correlated with the number of trees established per year. The presence of 137 fire scars was determined, which allowed the reconstruction of 41 fire events over the period 1855–2019; however, only the period 1940–2015 was used to compare tree recruitment, as tree establishment was detected in this period. The mean fire interval (MFI) was 2.28 years in general, and 12.17 years for extensive fires. As regards vegetation, a continuous recruitment pattern was observed, typical of a frequent low-intensity fire regime, although peak regeneration occurred after extensive fires. The correlation analysis showed that the number of trees established per year was influenced by the wet conditions that occurred in December of the previous year and the dry conditions in September and October of the previous year. This finding demonstrates the historical influence of fire and climate on the structure of the current stand in the study area. Therefore, the present study highlights the importance of including fire in forest management programs, considering the natural fire regime to which the species in this ecosystem are already adapted.

Keywords: age structure; fire regimes; fire scars; tree recruitment; fire reconstruction

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1. Introduction

Fire has played a major role in the evolution of global ecosystems [1] and is a key ecological process in conifer forests in the Western North American Mountain Range (WNAMR), where the environment is influenced by multiple factors, such as high rainfall variability and a 4- to 6-month annual drought, which favor frequent fires [2,3].

The Sierra Madre Occidental (SMO) of Mexico, belonging to the WNAMR, supports a mosaic of diverse ecosystems of great environmental and economic importance [4], reflected in a complex mixture of fire regimes [2]. These ecosystems include mixed pine–oak forests, which harbor a high floristic diversity [5]. Historically, surface fires were frequent in these forests, which may have contributed to the maintenance of their biodiversity [6].

Wood production is one of the main economic factors in SMO, highlighting the need to develop sustainable forest management plans based on the understanding of natural fire regimes [7]. Therefore, the analysis of fire regimes is highly important for ensuring the integrity of forest ecosystems [8].

The reconstruction of fire history using tree rings to determine spatial and temporal patterns of previous and contemporary fires (dendropyrochronology) allows understanding of the fire regime [9,10]. Knowing the history of fires in a certain area allows for understanding forest dynamics and its effect on vegetation structure [11].

In this sense, the presence of groups of trees of the same age has been used as compelling evidence of the occurrence of past disturbances [12], since age distribution results from tree mortality and the emergence of new cohorts after disturbance [13]. Among ecosystem disturbances, fire is considered a key disturbance that influences forest age structure [14]. In this way, the combination of fire history and tree age can help us to understand the patterns of tree age structure and their underlying processes, which are essential to sustainable ecosystem management [15].

In Mexico, several studies have reported the influence of fire history and climate on tree age structure in the SMO [6,16–19]. Since the effects of fire vary according to the natural fire regime under which the species evolved [20], it is relevant to study the fire history at small spatial scales to determine the disturbance regime in a particular area [21].

Based on the above, the objectives of this study were (1) to reconstruct the history of fires in a temperate forest in SMO; and (2) to interpret the impacts of fire and climate on tree age structure. We hypothesized that dates of tree recruitment in the current stand are attributed to a combined effect of past fires and prevailing climatic conditions following those fires. The results of this work contribute information about the effects of fire on the dynamics of temperate forest ecosystems in SMO.

2. Materials and Methods

2.1. Study Area

The study was carried out in the ejido El Brillante, located in the southwestern region of the state of Durango, Mexico (extreme coordinates 23°37′12.9″–23°50′55.76″ N, and 105°18′56.23″–105°31′9.84″ W) (Figure 1a), in the mountainous region of the Sierra Madre Occidental (SMO) (Figure 1b). The average elevation of the study area was 2480 m above sea level, and the local climates are semi-cold humid C(E)(m) and temperate subhumid C(w), both with summer rains [22]. The mean annual temperature ranges from 10 °C to 18 °C, and the mean annual rainfall is 1000 mm [23]. The main soil types in the area are morphologically classified as Luvisol and Regosol [23]. The dominant vegetation was a mixed conifer forest, mainly *Pinus* sp., occasionally mixed with broad-leaved vegetation (mainly *Quercus* sp. [24]). The sampling site included an area of approximately 100 ha (Figure 1c).

2.2. Data Collection

Following a selective sampling strategy, we selected the oldest trees with specific characteristics, including evidence of fire scars and number of scars [25]. Subsequently, we obtained cross-sections of both living and dead trees (including fallen logs, standing logs, and stumps (Figure 2a–d) with fire scars) (Table 1) [26].

Table 1. Number and percentage of fire-scarred cross-sections collected.

Collected Samples	Dated Samples	Live	Dead	Stumps	Species
60	58	19	11	28	Pd, Pt, Ax
%	96.67	31.67	18.33	46.67	

Pd: Pinus durangensis Martínez, Pt: Pinus teocote Schiede ex Schltdl, Ax: Arbutus xalapensis Kunth.

Additionally, using a Pressler borer, increment cores were obtained from trees of different diameter classes (5.0 cm classes) to estimate their age. Cores were extracted at a height as close to the ground as possible to obtain the inner growth [15].

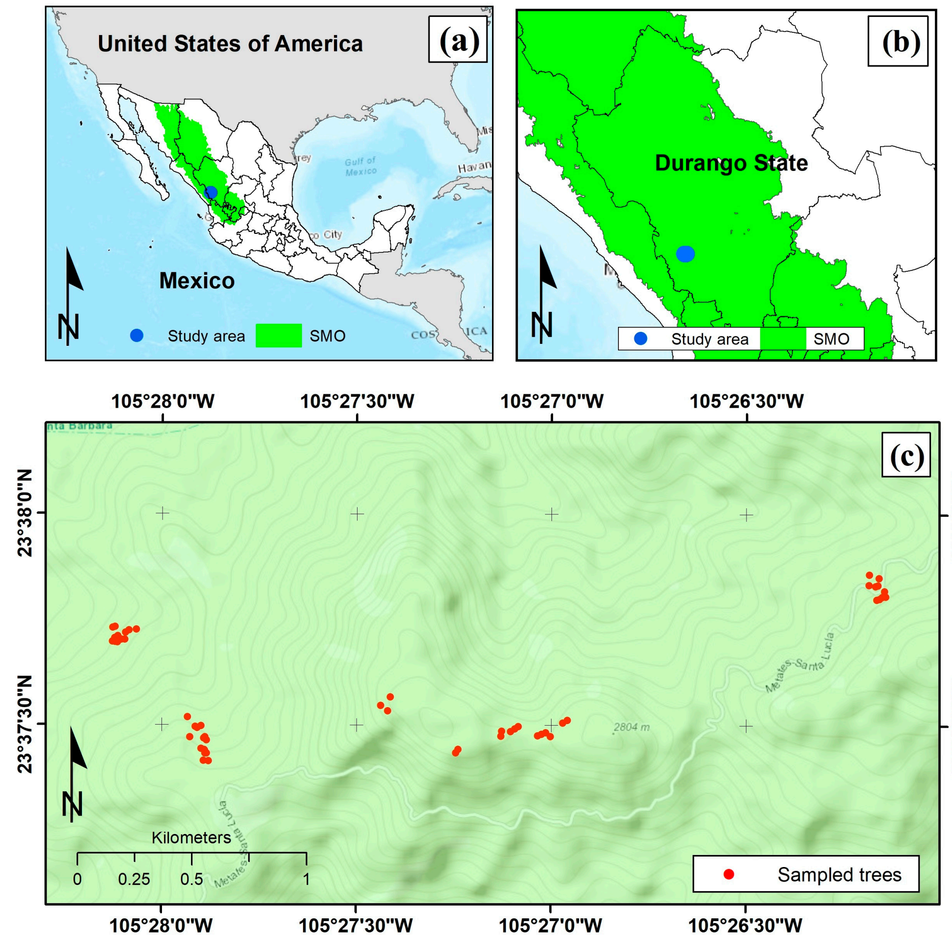

Figure 1. (**a**) location of the study area, (**b**) location of the study area in the context of the SMO, and (**c**) geographic distribution of collected tree cross-sections.

2.3. Fire Reconstruction

Samples with fire scars were analyzed using standard dendrochronology techniques to determine the exact calendar year of each fire scar [27]. In all samples, total ring-width was measured with a precision of 0.001 mm using the Velmex measurement system [28], and the dating quality was validated with the COFECHA program [29].

2.4. Seasonality of Fires

The season of fire occurrence was estimated based on the relative position of each fire scar within the annual ring (Figure 3a): Early Earlywood "EE" (Figure 3c), Middle Earlywood "ME" (Figure 3d), Late Earlywood "LE", Latewood "L", and Dormancy "D" (Figure 3b) [30,31]. The location of fire scars within the annual ring was grouped into two categories for further analysis: (1) spring (EE + D); and (2) summer (ME + LE + L) [9,17].

2.5. Determination of Tree Age

Increment cores were also dated using standard dendrochronology techniques [27]. The approximate age of each tree was estimated by counting the number of rings and adjusting for missing years when the growth core did not reach the pith [32]. The quality of dating was validated with the COFECHA program [29].

2.6. Fire Interval Analysis

Fire history data were explored using the FHAES software [33]. Two periods of fire history were analyzed: (1) full fire history (from the oldest to the most recent scar); and (2) from the establishment of the oldest tree to the establishment of the youngest tree.

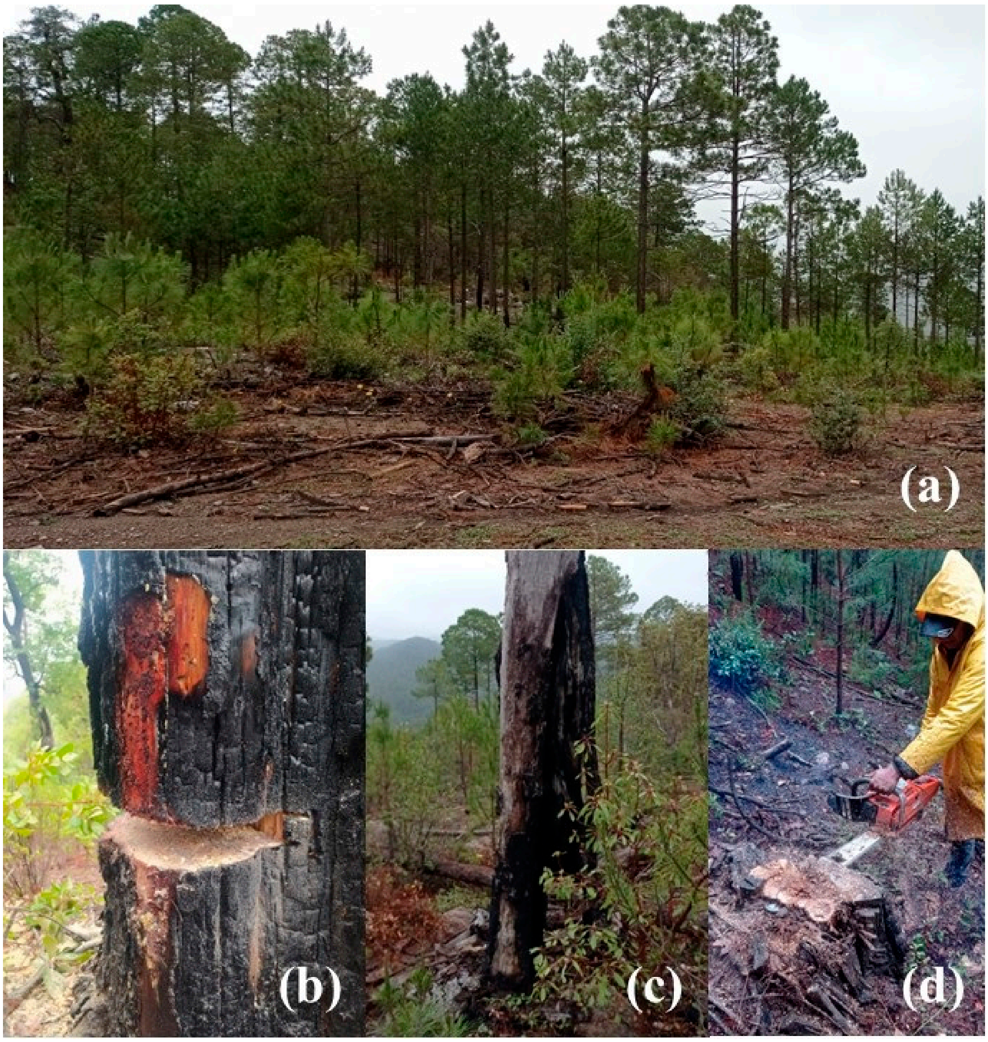

Figure 2. (**a**) Example of dominant ecological conditions in the study area. Fire-scarred samples were collected from a combination of (**b**) standing live trees, (**c**) standing logs, and (**d**) stumps.

For each period, fire history descriptive statistics were obtained, including mean fire interval (MFI), maximum and minimum fire intervals, and the Weibull median probability interval (WMPI) [9]. For each metric, three fire scar filters were considered: (1) all years with fire scars; (2) years in which 10% or more samples recorded a fire scar; and (3) years in which 25% or more samples recorded a fire scar. The 25% filter represents the years when fires were most extensive [34].

2.7. Climate–Fire Relationship

The relationship between climate variability and fires in the period 1940–2015 was determined by a superposed epoch analysis (SEA) using the FHAES software [33]. Three climatic proxies were used:

(1) The number of rainy days in the December–February period [35];
(2) Instrumental values of Palmer's Drought Severity Index (PDSI) for May [36]; and
(3) El Niño 3 Sea Surface Temperature (SST) index values for June-August (NOAA, https://psl.noaa.gov/data/climateindices/list/; accessed on 2 December 2022).

All values were calculated during the year of the fire, as well as five years before and two years after the year of the fire. The statistical significance of the SEA was evaluated by calculating the 95% confidence interval derived from 1000 bootstrap simulations.

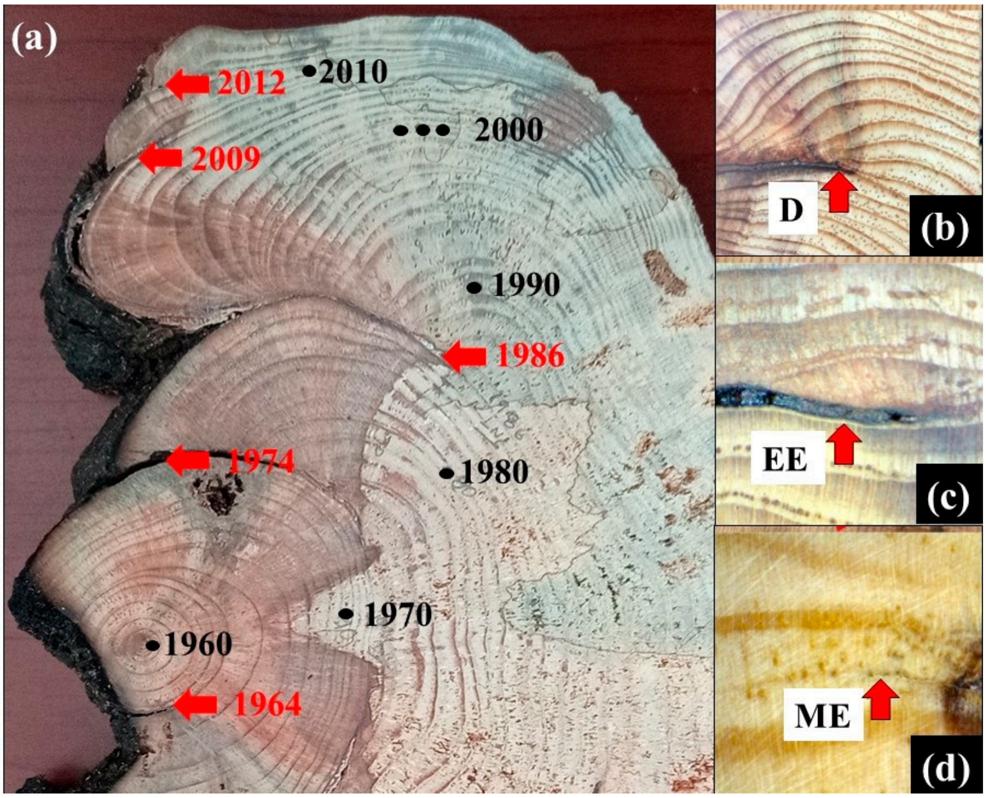

Figure 3. (**a**) An example of a fire-scarred sample that has been cross-dated using dendrochronological techniques. The specimen had five fire scars. Black numbers represent the calendar year of the sample. The numbers in red represent the calendar year when the wood was scarred. Examples of fire scars are: (**b**) the dormancy "D", (**c**) early-earlywood "EE", and (**d**) middle-earlywood "ME" within the annual tree-ring (This is adapted from [25]).

2.8. Relationship of Tree Age Structure with Forest Fires and Climate

The establishment of trees over time was graphically compared with the history of fires, particularly with extensive fires (fire scars are present in at least 25% of samples). Finally, to explore the influence of climate on post-fire recruitment, the number of trees established each year was correlated with rainfall data and PDSI values [36].

3. Results

3.1. Fire History

The 58 samples analyzed yielded a total of 137 fire scars. The oldest and newest rings corresponded to the years 1838 and 2020. The oldest scar was recorded in 1855 and the most recent in 2019, representing a reconstruction of the frequency of fires over the past 165 years. The period when scars were recorded in at least 25% of the samples ranged from 1855 to 2012 (Figure 4).

3.2. Fire Intervals

In the analysis of fire intervals for the period 1855–2019, and based on all years marked by fires, we found an MFI of 4.02 years and a WMPI of 2.4 years (Table 2). Based on the 10% filter, the MFI was 7.86 years, with a WMPI of 5.27 years. More extensive fires that produced scars in 25% of the samples occurred at intervals of less than 20 years (MFI and WMPI of 15 and 12.43 years, respectively). For the period 1940–2015, and based on all years marked by fires, fires occurred more frequently, with an MFI of 2.28 years, and a WMPI of 2.09 years. Considering fires that left scars in 10% of the samples, the MFI was 4.56 years, and the WMPI was 3.87 years. For fires that produced scars in 25% of the samples, we found an MFI of 12.17 years, and a WMPI of 11.21 years (Table 2).

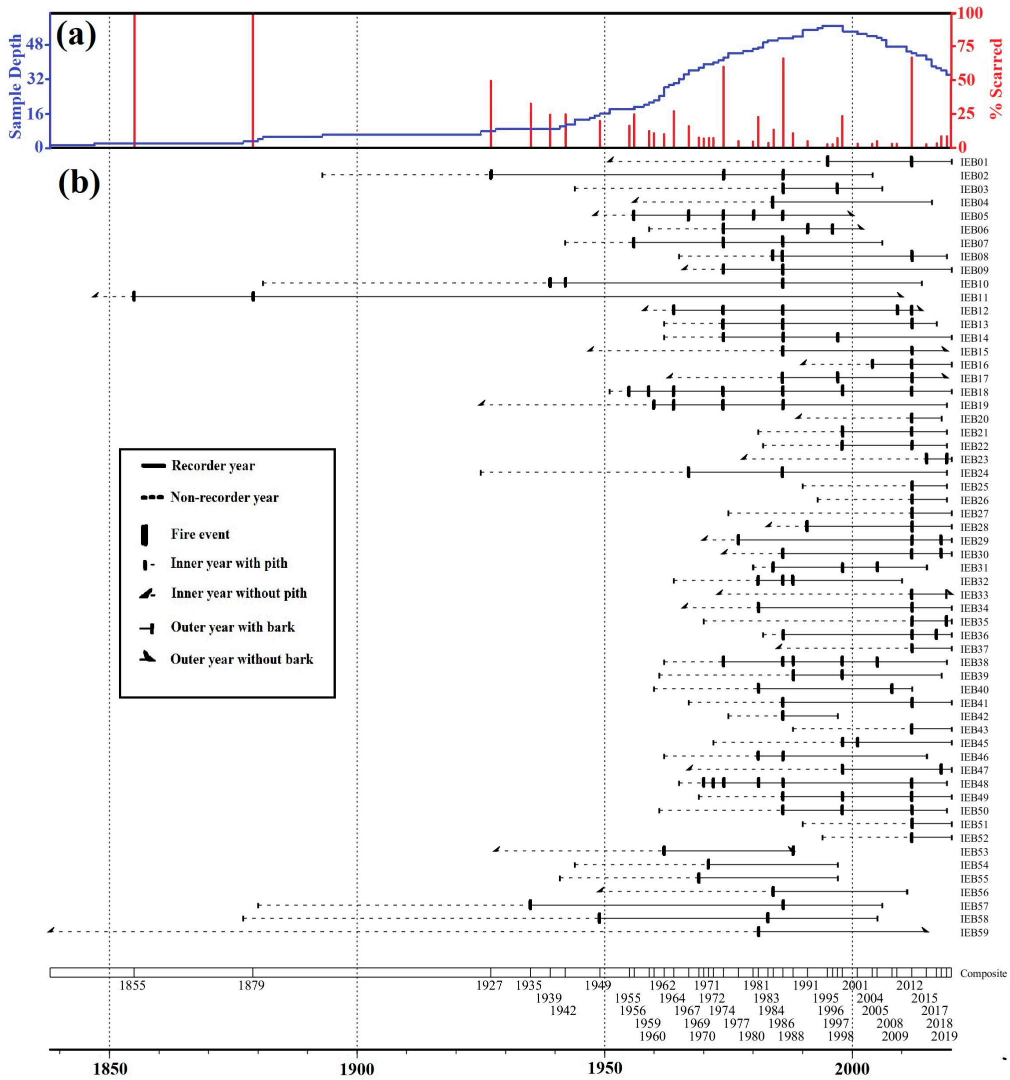

Figure 4. Timeline of fire history in the study area, (**a**) number of trees with recorded fire scars (blue line) and percentage of trees that recorded a fire per year (red vertical lines), (**b**) Individual timeline of a tree with fire scars represented by horizontal lines. Black vertical dashes represent fire scars recorded by that tree.

Table 2. Descriptive statistics of fire intervals.

Period of Analysis	Fire Interval Filter	Number of Intervals	MFI	Min	Max	WMPI
1855–2019	All scars	41	4.02	1	48	2.4
	≥10%	21	7.86	1	48	5.27
	≥25%	11	15	3	48	12.43
1940–2015	All scars	32	2.28	1	7	2.09
	≥10%	16	4.56	1	14	3.87
	≥25%	6	12.17	3	26	11.21

MFI: Mean fire interval; Min: Minimum frequency interval; Max: Maximum frequency interval; WMPI: Weibull median probability interval.

3.3. Seasonality of Fires

Seasonality was determined for 100% of fire scars, of which 38.0% were recorded at early earlywood (EE), and 39.4% were recorded at mid-earlywood (ME). As regards the timing of fire scars, 2.2% corresponded to late earlywood (LE), 4.4% to latewood (L), and 16.1% to dormancy (D). Based on the above, 54.01% of fires were classified as spring events and 45.99% as summer events (Table 3).

Table 3. Seasonality of fire scars.

Scars	Determined Seasonality	Undetermined Seasonality	D	EE	ME	LE	L	Spring Fires	Summer Fires
Number	137	0	22	52	54	3	6	74	63
Percentage (%)	100	0	16.1	38	39.4	2.2	4.4	54.01	45.99

EE: Early Earlywood; ME: Middle Earlywood; LE: Late Earlywood; L: Latewood; D: Dormancy.

3.4. Climate–Fire Relationship

The Superposed Epoch Analysis indicated that the frequency of fires in the period 1940–2015 was influenced by the climatic conditions recorded during the year of fire and those of years prior to each fire. Particularly, fires were influenced by the number of rainy days from December to February two years before the fire occurrence (Figure 5a). Regarding drought, fire occurrence was influenced by the drought conditions in May of the year of occurrence and the conditions within two years prior to the occurrence of fires (Figure 5b). As regards large-scale atmospheric circulation phenomena, we found that the climatic conditions indicated by the El NIÑO 3 index SST in June, July, and August, within 3, 4, and 5 years prior to fires, influenced their occurrence (Figure 5c).

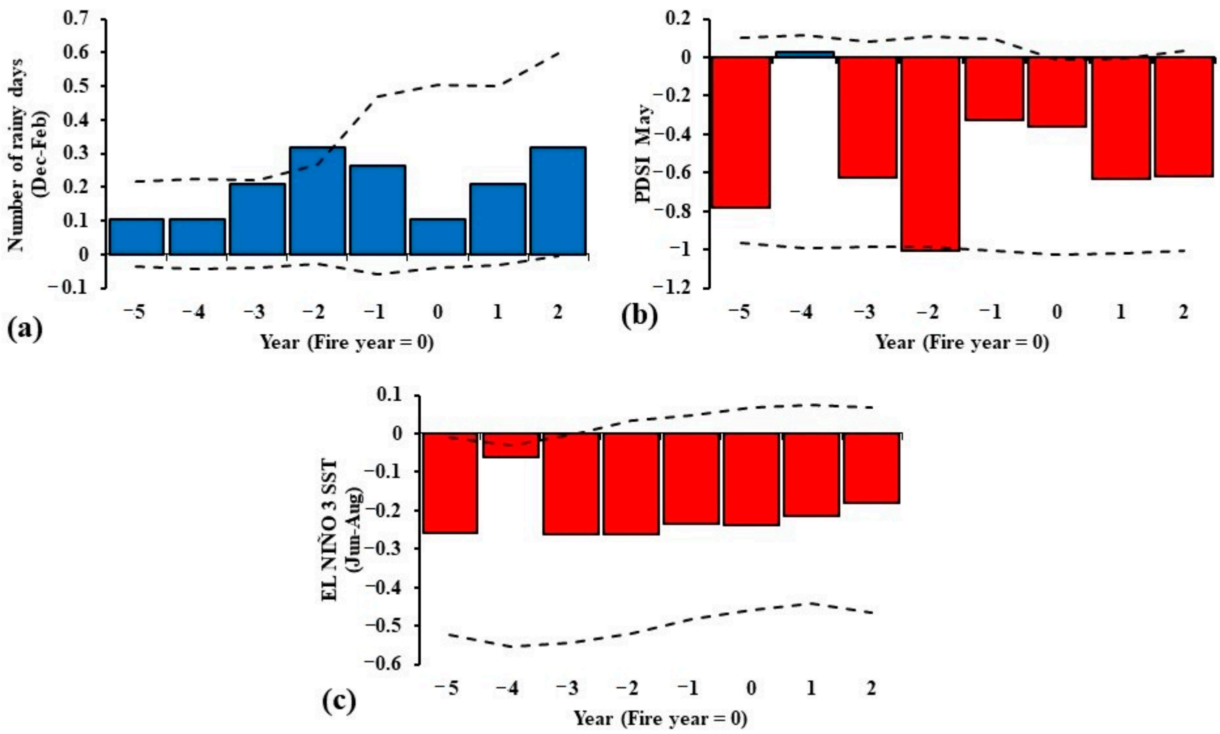

Figure 5. Superposed Epoch Analysis (SEA). Relationship between fire occurrence and (**a**) the number of rainy days in the months of December, January, and February, (**b**) PDSI (for the month of May) and (**c**) the NIÑO 3 SST index averaged over the months of June, July, and August. On the *X*-axis, the year in which the fire occurred is year zero, with climatic conditions on the *Y*-axis, which include conditions five years prior to the fire (negative values on the *X*-axis) and two years after the fire (positive values on the *X*-axis). The dashed lines represent a 95% confidence interval derived from 1000 Bootstrap simulations. The blue and red vertical bars represent wet and dry conditions respectively.

The most extensive fires (recorded in at least 25% of the samples) occurred in years with negative and near-zero positive PDSI values in the study area. In addition, drought conditions also prevailed over much of northern Mexico in most of the years of these fires (Figure 6).

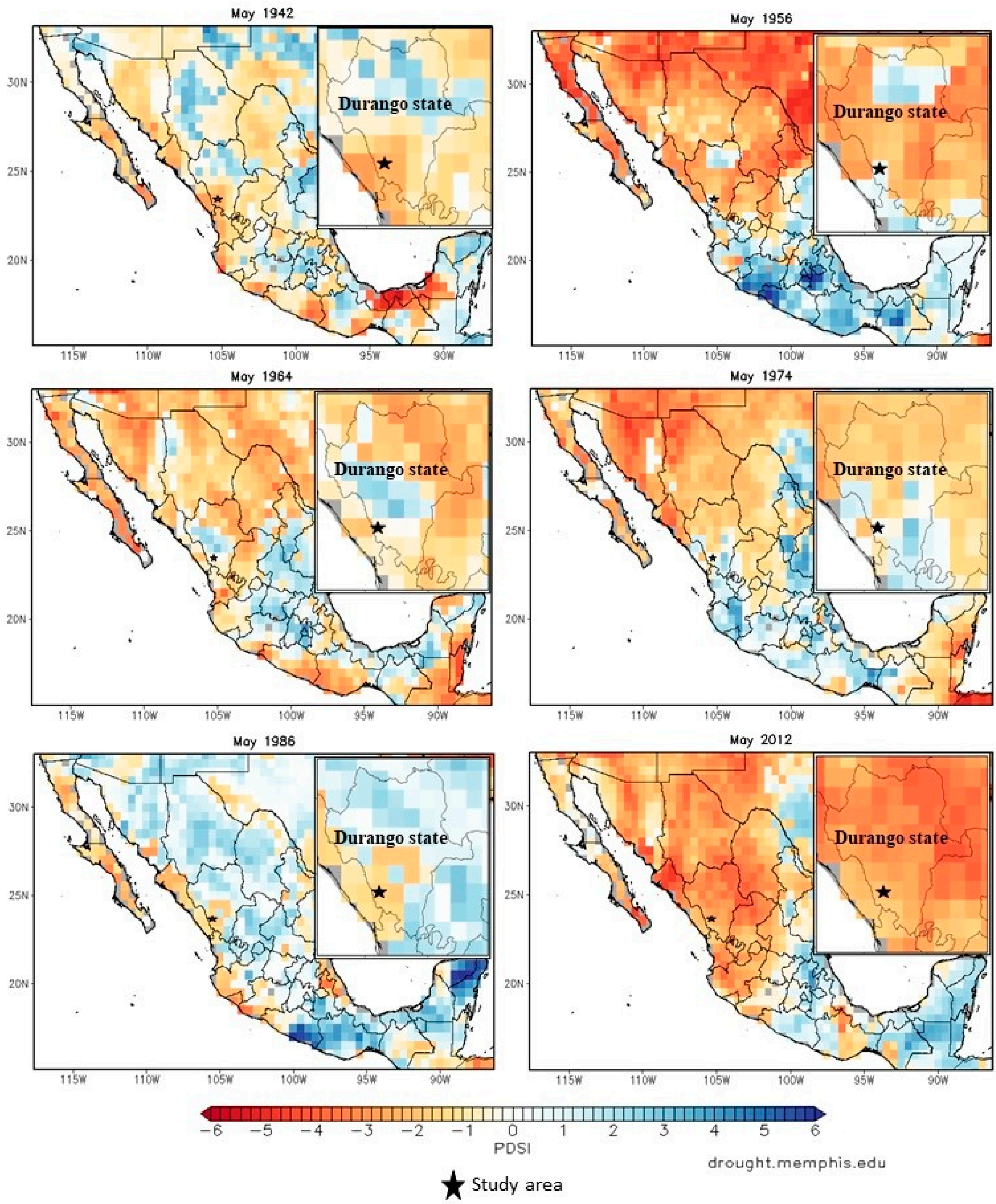

Figure 6. Drought conditions in Mexico during years of extensive fire occurrence in the study area [36].

3.5. Relationship of Tree Age Structure with Forest Fires and Climate

The tree species analyzed were *Pinus durangensis* Martínez, *Pinus leiophylla* Schiede ex. Schlechtedal & Chamissosubsp, *Pinus teocote* Schiede ex Schltdl, and *Pinus lumholtzii* Robins & Ferns. The first year of tree establishment, according to the analyzed samples, was 1940, while the last recorded year was 2015. The tree ages indicated that there were regeneration pulses after the occurrence of extensive fires (Figure 7). For the 1942, 1956, 1964, 1974, 1986, and 2012 fires, peak regeneration pulses occurred 5, 1, 5, 9, 2, and 1 years after the fire, respectively. To note, in all cases, tree regeneration occurred over at least 5 continuous years after the fire, showing a continuous regeneration pattern.

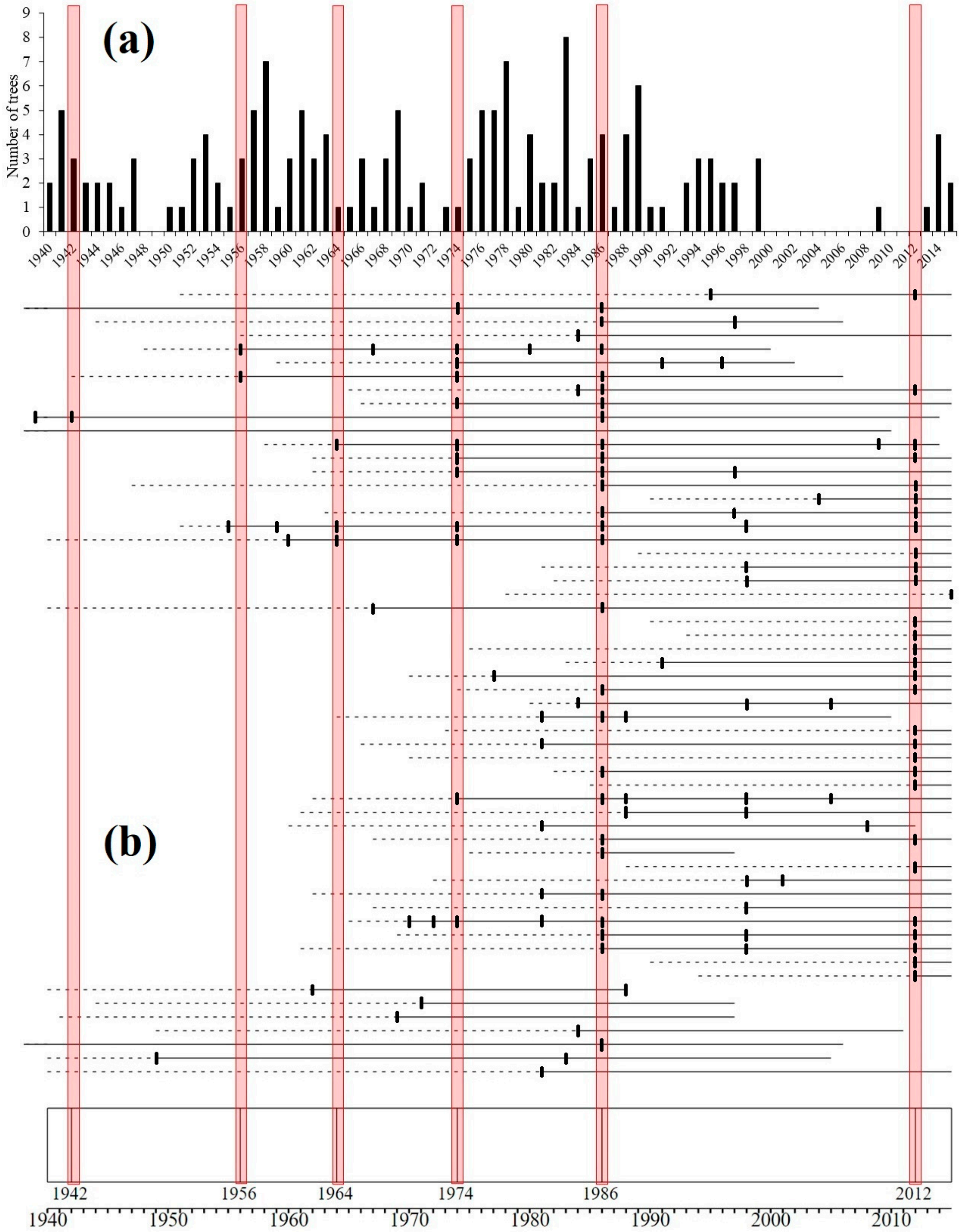

Figure 7. Graphical relationship between (**a**) tree establishment and (**b**) frequency of forest fires. Individual timeline of a tree with fire scars is represented by horizontal lines. Black vertical dashes represent fire scars recorded by that tree. The red lines represent the year of occurrence of extensive fires (scars marked in at least 25% of the samples).

Regarding the relationship between tree establishment and the dominant climatic conditions, a statistically significant ($p \leq 0.05$) positive relationship was found between the number of trees established per year and precipitation in December of the previous year. A negative relationship was also found between the number of trees established per year and PDSI values in September and October of the previous year (Figure 8).

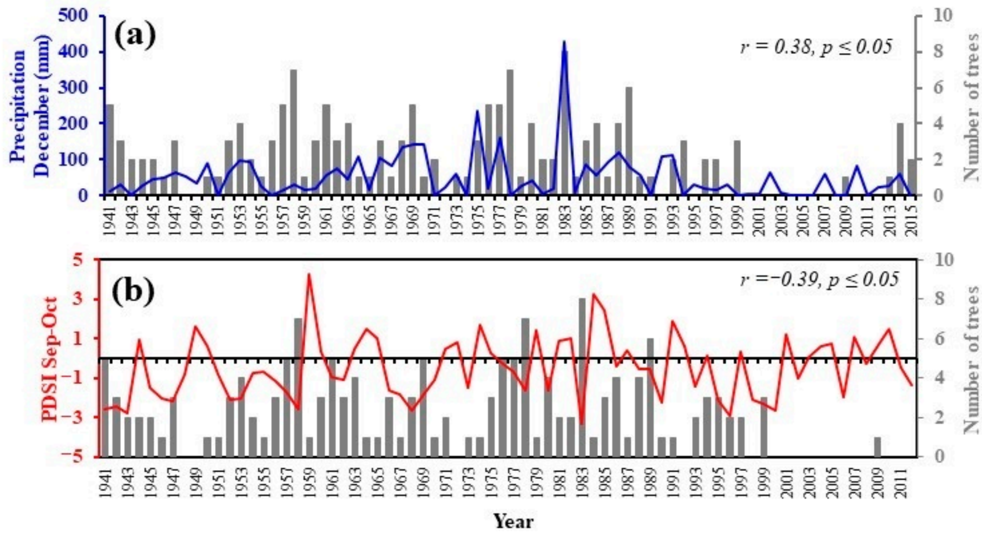

Figure 8. Graphical relationship between tree establishment and climate: (**a**) precipitation in December of the previous year and (**b**) PDSI values from September–October of the previous year.

4. Discussion

In this study, we reconstructed the fire history of a temperate forest located in the SMO and analyzed the influence of fire and environmental conditions on the recruitment rates of dominant forest species. Knowing the fire regime and its changes and effects on vegetation allows forest managers to develop plans to ensure the stability of these forests [7]. However, the management plans for many forests still lack quantitative information on the intensity, frequency, and seasonality of fires [21]. The findings reported herein will help to understand the fire regime and the historical influence of fire on vegetation, particularly in the study area. Given that the diversity of environmental conditions characterizing the SMO have favored a mixture of fire regimes, our results may not be representative of the entire ecological conditions of this mountain range. However, our results contribute to improve the network of site-specific fire history reconstructions for the North American tree-ring fire scar network [37], and to improve our knowledge of the influence of fires and climatic conditions in forest succession after the fire event.

4.1. Fire History

We reconstructed 165 years of fire history; however, the sample size was limited in the first 60 years, since almost 80% of the samples were no more than 70 years old. According to Sáenz-Ceja et al. [38], this is due to rapid re-population and intensive logging; therefore, the number of fire-scarred trees is limited, which also limits the reconstruction of extensive fire chronologies. Another aspect to highlight is that the area has a history of intensive logging, which seems to impact fire dynamics and tree regeneration [39].

4.2. Frequency of Fires

From the fire history analyzed, at least the past 70 years have been characterized by a regime of frequent and low-intensity fires; however, this does not preclude a similar frequency of fires in previous years. For example, a more extensive history of frequent forest fires has been found in areas near our study site [6], a pattern that may resemble the one in our study area, since climatic and vegetation conditions are similar over a large section of this region of the Sierra Madre Occidental.

Regarding the MFI, similarities were found with other studies conducted in the SMO. For instance, when considering all fires over the period 1855–2019, the MFI was four years, similar to the one reported by Fulé and Covington [16]. The MFI for the period 1940–2015 was 2.28 years, and is consistent with the MFI reported by Cerano-Paredes et al. [40] for the headwater of the Nazas River basin in the SMO. This is evidence that a higher frequency of fires has occurred in the study area in recent decades, in contrast with other SMO areas where a reduction in the frequency of fires after 1950 has been detected [6,7,17].

With regard to extensive fires (scars in at least 25% of the samples) and considering the periods 1855–2019 and 1940–2015, MFI values were 15 and 12 years, respectively. These results are similar to those of Rosales-Mata [41], who reports an MFI for extensive fires of almost 12 years in a zone adjacent to our study site. Similarly, Cerano-Paredes et al. [42] reported an MFI of nearly 14 years for a site in the Cerro El Mohinora Reserve, Chihuahua, within the SMO, and Sáens-Ceja and Pérez-Salicrup [43] found a similar MFI for the Monarch Butterfly Biosphere Reserve, located along the Trans-Mexican Volcanic Axes in the state of Michoacan, Mexico. This fire behavior can be attributed to the scarcity of combustible materials in the forest floor, as a result of frequent fires, relatively short periods with no fires, and a mosaic of forest patches that burned at different times [16].

4.3. Fire Seasonality

The evaluation of fire seasonality using the position of the fire scar within the ring has proven to be an accurate method for reconstructing the timing of historical fires [44]. Based on this method, most of the scars analyzed (54.01%) suggest that fires occurred mostly in the spring. In Mexico, the peak of the fire season in most regions of the country occurs during April, May, and June (spring) [45], before the summer rains and vegetation greening [46]. For the SMO, this information has been extensively documented by several studies, which support our results [7,40,42].

4.4. Climate-Fire Relationship

It is well known that climate and weather play a key role in forest fire dynamics [47]. In northern Mexico, a close relationship has been found between the occurrence of fires and climate [48]. Our results indicate that the occurrence of fires in the period 1940–2015 was influenced by both the climatic conditions in the year of occurrence and the climatic conditions in previous years. Specifically, the occurrence of fires was related to the number of rainy days in the December—February seasons of the two years prior to the event. In this sense, it has been mentioned that the presence of one to two wet years leads to the formation of a fine vegetation cover, which subsequently serves as combustible for fires in the following dry year [17].

A relationship was also found between the occurrence of fires and drought indicated by the PDSI, both in the year of occurrence and within two years before the fire. Unlike other regions of the country, the SMO requires more time (at least two years) for combustible materials to build up in amounts sufficient to sustain a fire. This can occur under conditions of low water availability in the soil and with the presence of combustible materials contributing to trigger the fire [49].

With regard to large-scale circulation phenomena, it is known that, in Mexico, the El Niño/Southern Oscillation (ENSO) modifies precipitation patterns in both winter and summer [50], which in turn has been related to the occurrence of forest fires. For example, in the southern United States and northern Mexico, warm events (El Niño) are associated with a lower incidence of fires, while cold events (La Niña) tend to favor a higher number of fires [51]. Likewise, our findings indicate that the occurrence of forest fires was influenced by dry conditions fostered by the El Niño phenomenon (negative El Nino SST Index values) in June—August of 3, 4, and 5 years prior to the fire.

Another aspect to consider is the occurrence of extensive fires, since they are commonly linked to dry years, caused by global and regional climate forcing mechanisms such as ENSO [40,42,51]. In the present study, the most extensive fires (i.e., fire scars in at least 25% of the samples) occurred under the dry conditions that dominated in northern Mexico

(Figure 4) [36]. In addition, the years of fire occurrence coincided with dry conditions present in the previous year and associated with ENSO.

4.5. Relationship of Tree Age Structure with Forest Fires and Climate

Fire may act as a disturbance that replaces the stand, or as a frequent disturbance of lower intensity that promotes continuous regeneration [52]. The unequal tree age structure found in the present study reflected a continuous regeneration pattern associated with a frequent, low-severity, low-intensity fire regime [14,20]. However, recruitment peaks were also observed after extensive fires. Although these fires are usually of high-intensity but infrequent, they cause considerable tree mortality, leading to the replacement of the stand and, subsequently, when weather conditions are adequate, they favor a synchronous or pulsed establishment of trees with a uniform or synchronous age structure [11,53].

The post-fire succession trajectories of vegetation depend on multiple factors [54,55]. Although seed availability is a major driver of tree regeneration after a fire [56], inter-annual climate variability in post-fire years may be a key factor to tree regeneration [57–59]. Our results showed that the dry conditions in September and October of the previous year, together with the December rains of the previous year, promote tree regeneration. This is because, although forest fires can occasionally create adequate conditions for seed germination and tree survival [60], adequate post-fire climate conditions are required [57], such as energy and humidity [61].

4.6. Management Considerations

The fire history characterized in the present study revealed a frequent low-intensity fire regime, which has contributed to the current forest structure. However, continuous recruitment is frequently impossible without major disturbance events [21]. This reflects the importance of both frequent low-intensity fires and infrequent high-intensity fires in the study area.

Since 1980, the roles of fire in several forest ecosystems and the role of humans in modifying fire regimes have been demonstrated in Mexico [62]. In this sense, it has been mentioned that for SMO forests with a fire regime such as the one observed in the present study, the exclusion of fires over long periods of time should be avoided to prevent the build-up of combustible materials that promote larger and more severe forest fires [40].

Climate change projections indicate a trend toward higher severity and frequency of fires [63]. In this sense, the application of novel fire management practices, such as prescribed fire, represents a suitable option in the face of such projections [7,11,62], since proper use of fire at appropriate intervals can serve to restore and maintain healthy forests [15].

On the other hand, a decline in tree regeneration and changes in the ecosystem after fires, especially high-severity fires, have also been foreseen [64]. In this regard, it has been suggested that the establishment or planting of trees in areas recovering from recent disturbances may help to delay the projected impacts of climate change [65].

In Mexico, the General Law on Sustainable Forest Development states that: *"...in the event of a fire, the legitimate owners of forest land are obliged to carry out the restoration of the affected area within two years maximum"* [66]. However, the roles of natural and managed regeneration in promoting forest recovery are little known, highlighting the need to strategically target economic, personnel, and time resources to effective reforestation [67]. It is our view that, after a fire, trees should be planted in an optimal time, considering the key factors for the regeneration and survival of the species, for example, those related to the nature of the fire, the post-fire environmental conditions, and the life-history characteristics of the dominant tree species before and after the fire [54,68], which could take a longer time for implementation.

5. Conclusions

This study reconstructed the fire history over the past 165 years, during which 41 fire events occurred. This fire history is associated with a regime of frequent low-severity fires and infrequent extensive fires, which together have shaped the structure of the current stand. The frequency of fires was driven by local and regional climatic conditions. The establishment of tree species was influenced by the frequency of fires and climate conditions in the years after each fire.

These findings contribute to the knowledge of the forest fire regime and its historical influence on vegetation, which will set the basis for better planning of fire management in the study area and the conduct of further studies addressing this topic in the region.

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