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Land use and climate influences on fire regimes within *Pinus greggii* Engelm. var. *greggii* forest stands in the Sierra de Zapalinamé, Coahuila, Mexico

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Abstract

Background: Understanding fire regimes is important for developing conservation strategies for drought-tolerant species with serotine cones; although, no fire-frequency studies have been undertaken in *Pinus greggii* a serotine species.

Hypotheses: Fire occurrence in *Pinus greggii* stands are related to climatic conditions prior to and during the fire year, but fire regimes have changed in the last two decades induced by anthropogenic disturbances changing the fire regime.

Studied species: *Pinus greggii* Engelm. Descriptive statistics of the fire regime. Superposed Epoch Analysis.

Study site and dates: El Penitente, Cañón de las Norias, Cañón del Negro, in the municipalities of Arteaga and Saltillo, Coahuila. Year 2019.

Methods: Samples from 99 fire-scarred trees at three sites in the Sierra de Zapalinamé Coahuila were collected and dated using dendrochronological techniques.

Results: The fire regime was analyzed from 1840 to 2014. Most fires occurred in spring, except in CNO, where fires occurred in summer. The average fire interval for the three sites was 4-7 years with small fires, more extensive fires were less frequent (8-15 years). The occurrence of fires in TVE was significantly associated with indices of the Southern Oscillation (SOI). Fire frequencies have changed in recent decades, due to land-use changes at CNO and CNE, but not at TVE, the most isolated site with least human disturbance.

Conclusions: The fire regime in populations of *Pinus greggii* was associated with natural climate variability and sites with greater human influence showed no significant association with climate.

Keywords: dendrochronology, El Niño 3.4, fire history, forest management, serotine cones.

Resumen

Antecedentes: La comprensión del régimen de incendios es esencial para desarrollar estrategias de conservación de bosques tolerantes a la sequía con conos serótinos; sin embargo, no existen estudios en este tema para *Pinus greggii*.

Hipótesis: La ocurrencia de incendios está relacionada con las condiciones climáticas antes y durante el año del incendio; el régimen de incendios ha cambiado en las últimas dos décadas relacionadas con causas humanas.

Especies de estudio: *Pinus greggii*. Estadística descriptiva. Análisis de Sobreposición de Época.

Sitio y años de estudio: El Penitente, Cañón de las Norias, y Cañón del Negro, Arteaga y Saltillo, Coahuila. 2019.

Métodos: Analizamos muestras de 99 árboles con cicatrices de fuego con **técnicas dendrocronológicas** de tres sitios en la Sierra de Zapalinamé, Coahuila.

Resultados: Se analizó el régimen de incendios de 1840-2014. Los incendios ocurrieron en primavera, excepto en CNO, en verano. El intervalo medio de incendios fue de 4-7 años con incendios pequeños, los incendios más extensos fueron de 8-15 años. Los incendios en TVE se asociaron significativamente con el índice de Oscilación del Sur (SOI). La frecuencia de los incendios ha cambiado en las últimas décadas, debido al cambio de uso del suelo en CNO y CNE, pero no en TVE, el sitio con menos perturbaciones humanas.

Conclusiones: El régimen de incendios en *Pinus greggii* se asoció con la variabilidad climática natural y los sitios con mayor influencia humana no mostraron una asociación significativa con el clima.

Palabras clave: dendrocronología, El Niño 3.4, historia de incendios, manejo de bosques, conos serótinos.

Increases in human populations in Mexico have resulted in greater demand of environmental services provided by forest ecosystems, particularly forage for livestock grazing, hydrological resources, and recreational services. In addition, increases in global temperatures and droughts, make forests more vulnerable to fires (IPCC 2018). Sustainable forest management requires an understanding of the fire regimes within different forest types, including changes in fire history patterns and the controlling factors. Forest managers also need to consider functional traits and ecological characteristics of the species including those with serotine cones, since these features help to characterize fire regimes, and are needed to develop management practices to preserve the ecological characteristics needed to maintain the ecological functionality of these community (Fulé *et al*. 2005, Lamont *et al*. 2020, Rodríguez-Trejo & Fulé 2003). This is particularly important for *Pinus greggii* var. *greggii* an endemic species in the Sierra Zapalinamé a protected mountain range that is the main source of water for the Saltillo, Coahuila city with a population near a million people (CNA 2024, Villanueva-Díaz *et al*. 2009). *P. greggii* occurs in small fragmented stands in the Sierra Zapalinamé (Donahue & Lopez-Upton 1999, Farjon 2013, Ramírez-Herrera *et al*. 2005); however, it is not protected by Mexican regulations, despite the decree on protected areas, law regulations and fire suppression policies (Sáez-Ceja & Mendoza 2024, Sáenz-Ceja *et al*. 2025); however, it is included on the IUCN (International Union for Conservation of Nature) red list, in the category of nearly threatened due to the fragmentation of its populations (Farjon 2013). *P. greggii* has serotinous cones indicating that has historically co-evolved with natural fires (Farjon *et al*. 1997, Rodríguez-Trejo & Fulé 2003); however, intensive grazing, landscape fragmentation by human settlements, road construction, logging activities, and suppression of natural fires have potentially changed the natural fire regime (Poulos *et al*. 2013, Yocom *et al*. 2010).

To understand fire regimes, it is also important to understand the role of climate and other factors that play a crucial role in fire occurrence. Wet years favor fuel accumulation, whereas dry years facilitate combustion of forest biomass and of the organic material accumulated in the forest floor (Baisan & Swetnam 1990, Swetnam & Betancourt 1998). Such scenarios have been associated with large-intensive fires occurring in northern Mexico in 2011, as the area was affected by an intensive hurricane in 2010 that allowed fine biomass accumulation followed by dry conditions in 2011 that triggered intensive fires (Marín *et al*. 2018). In general, in northern Mexico, the occurrence of fires is associated with drought conditions typically measured using the Palmer Drought Severity Index (PDSI) (Villanueva-Díaz & McPherson 2002). At regional scale, studies suggest that the amount of precipitation occurring in the winter-spring season determines the presence or lack of regional fires, although periods with prolonged drought spanning from winter to summer also tend to influence the frequency and extent of fires (Arizpe *et al*. 2020). Similarly, regional drought conditions are typically associated with large-scale atmospheric phenomena such as El Niño Southern Oscillation (ENSO) that modulate precipitation in northern Mexico, where dry years are associated with La Niña events (cold phase) and wet years with El Niño events (warm phase) (Stahle *et al*. 2016). Historically these climatic patterns explain fire synchrony across sites (Brown *et al*. 2008) as well as the fire season length (Heyerdahl *et al*. 2001). In recent years, the relationship between ENSO and the fire occurrences has been less consistent in the Sierra Madre Oriental, possibly due to bottom-up controls as human activities (Yocom *et al*. 2010, 2017).

Fire history studies in in the Sierra Madre Oriental (Poulos *et al.* 2013, Yocom *et al*. 2010, 2014, 2017) and Sierra Madre Occidental, suggest that conifer forests have evolved with frequent low-intensity surface fire regimes. That is, smaller fires typically occurring at intervals of less than 10 years with a relatively large-fires occurrence every 6-17 years. Larger fires were also most often associated with dry La Niña years, although at the end of the twentieth century this relationship appears to have changed in the Sierra Madre Oriental (Fulé & Covington 1997, Heyerdahl & Alvarado 2003, Fulé *et al*. 2005, Cerano-Paredes *et al*. 2010, 2019, Meunier *et al*. 2014). Additional studies on forest species in this region have found average fire intervals of 4.1 to 5.6 years, associated with small fires (Sáez-Ceja & Mendoza 2022). Changes in fire regimes in these mountain ranges has been associated with recent land-use changes including, logging activities, intensive livestock grazing, agrarian land re-distribution, and landscape fragmentation associated with human settlements. These factors facilitated fire suppression efforts beginning in the mid-twentieth century and have resulted in drastic changes in fire regime (Fulé & Covington 1997, Heyerdahl & Alvarado 2003, Fulé *et al.* 2005, Yocom *et al*. 2010, 2014, 2017, Poulos *et al*. 2013, Cerano-Paredes *et al*. 2019). In addition, in recent decades there have been greater efforts in firefighting programs including better coordination between federal, state, local and civil institutions. Hence, it is important to understand how fire patterns have changed and how those changes are related to climate change, given that similar fire regimes changes have had detrimental consequences in other forests communities of North America (Singleton *et al*. 2019).

The lack of fire history information in *Pinus greggii* var. *gregii* forests is currently limiting conservation efforts. Understanding the historical fire regime associated with these ecosystems would allow forest managers to evaluate the effect of recent fires to develop sustainable management strategies so that these areas can continue providing ecological benefits to human populations (Fulé *et al*. 2005, Cerano-Paredes *et al*. 2019). Similarly, understanding the interaction between climate and fires constitutes technical information that can help predict the occurrence of intense fires, which is useful to establish management plans to minimize risks (Heyerdahl *et al*. 2001).

The hypotheses for this study are that fire occurrence in these relict forests was historically related to dominant climatic conditions (*i.e.,* temperature, precipitation) prior to and during the fire year; and that fire regime changes in the last two decades are associated with human influences. The objectives of this study were to: 1) reconstruct and compare fire history patterns (frequency, extent and seasonality) in three sites of *Pinus greggii* var. *greggii* in the Sierra de Zapalinamé, Coahuila; 2) examine the relationship between fire occurrence and climate patterns including climate drivers such as ENSO and; 3) examine fire regime changes in recent decades.

Materials and methods

Study area. This study is focused on *Pinus greggii* populations located in the Sierra Zapalinamé preserve in the municipalities of Saltillo and Arteaga, in the southeastern part of the state of Coahuila, Mexico (POE 2017). This area is part of the physiographic province Sierra Madre Oriental and physiographic subprovince Basin and Range (González 2017, INEGI 2011). The climate of the study area is temperate sub-humid (Cx) with an average annual precipitation of 490 mm, occurring mostly in the summer season. Annual average temperature ranges between 12 to 18 ºC. The higher elevations of the sierra are characterized by a semi-cold sub-humid climate (C(E)x) with an average annual temperature of 5 to 12 ºC (INEGI 2000, García 2004, Mendoza & González 2017). The most representative soils are Leptosols, shallow in depth with less than 10 cm, rocky dominant with indurated material preventing trees to have and expanded root system (INEGI 2004, IUSSWG 2014).

Study sites. Three sites of *Pinus greggii* were selected: 1) Cañón del Negro (CNE), 2) Cañón de las Norias (CNO), and 3) El Penitente (TVE), (Figure 1). The average distance between sites was 9 km. The vegetation at these sites is represented by pure stands of *Pinus greggii,* with only minor components (less than 5 % canopy cover) of other species including *Pinus arizonica* Engelm. and shrubby species such as *Juniperus* and *Quercus* (Ramírez-Herrera *et al*. 2005). *Pinus greggii* forests are found at mid elevations (2,400-2,800 m altitude), within these mountains with the lower elevation's forests dominated by pure stands of *Pinus cembroides* and upper elevation communities composed of *Abies* sp. along with stands dominated by *Pinus hartwegii*. The three selected sites represented a general gradient of land use/human impacts. The CNE site was located close to a town with road access to the site. The CNO had sparser (rural) human impact but also had road access that facilitates goats and cattle grazing, as well as firewood extraction and recreation. TVE is more remote with minimal nearby human settlements and no nearby roads due the steep slopes.

Field sampling. Fire scar samples were collected at each site in 2019, by cutting partial cross-sections or wedges from live trees as well as snags, stumps and logs (Baisan & Swetnam 1990, Agee 1993, Cerano-Paredes *et al*. 2020). The samples were cut using either a chainsaw or hand saw, then georeferenced with a Garmin® 64sx GPS and assigned an identification code. Most samples were from *Pinus greggii*, but also included samples of *Pinus arizonica* Engelm. The area of fire scar collection sites was approximately 10 ha at TVE, 25 ha at CNO and 20 ha at CNE. Similarly, the number of trees collected at each site also varied (Table 1).

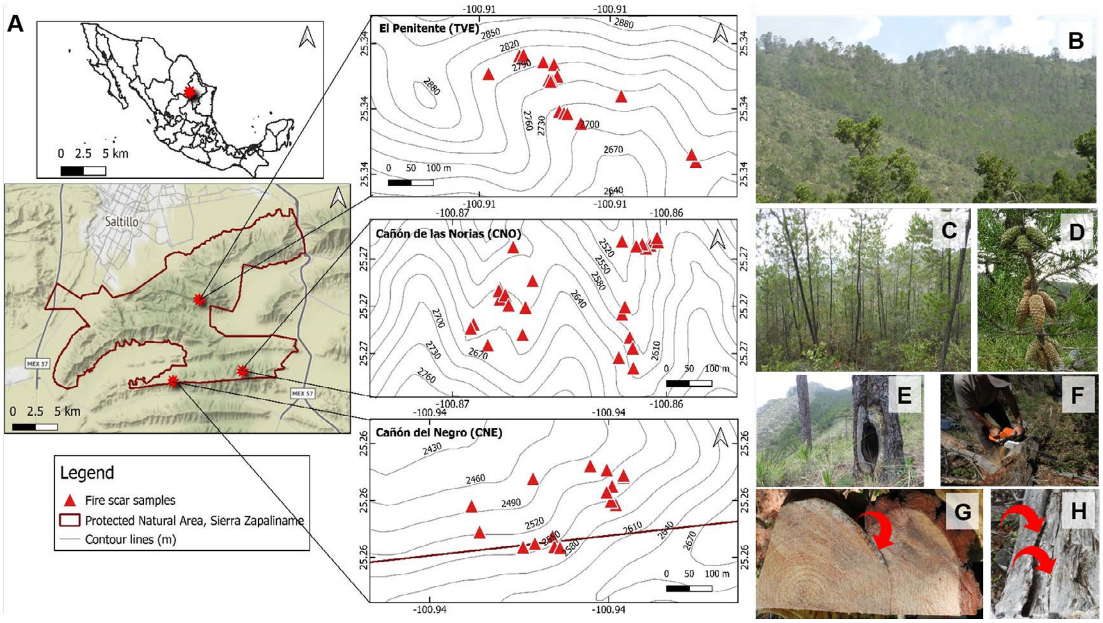

Figure 1. A) Location of the study sites of *Pinus greggii* var. *greggii* within the Sierra de Zapalinamé, Coahuila, Mexico; B) Forest with different canopy structure; C) Stands with potential occurrence of past high-severity fires; D) Serotine cones; E) Fire scar; F) Cutting of a fire scar on a dead tree; G) Fire scar in a living tree; H) Dead tree with two fire scars.

Laboratory methods. In the laboratory, fire scar samples were polished with a sequence of coarse to fine-grained sandpapers, ranging from 60 to 1,200 grid. The calendar year of each individual tree ring and the year of fire scar formation was determined using dendrochronological techniques. This included using the principle of tree-ring cross-dating, based on shared growth patterns among trees, and correcting dates based on the presence of missing or false rings, micro-rings or ring with growth problems derived following fire damage (Stokes & Smiley 1968, Baisan & Swetnam 1990). To date dead fire scar samples, tree-ring growth patterns were graphed (skeleton plot), to determine the year in which the fire-scars were recorded as well as the death date. Growth patterns were verified using a master chronology of *P. greggii* developed for the Sierra de Zapalinamé (Velázquez-Pérez *et al*. in preparation), which was dated (Holmes 1983) and standardized (Cook 1987) according to conventional methodology (Stokes & Smiley 1968).

The season of fire occurrence was determined for each fire scar by determining the location of the fire-scar within the tree-ring (Baisan & Swetnam 1990). A total of five seasonal classes were used including: early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L) and dormancy (D). The season of fire occurrence was defined by grouping these categories into the spring (D + EE) and summer (ME + LE + L) seasons (Grissino-Mayer 2001).

Data analysis. Fire-scar and seasonality analysis were conducted using the FHAES *(Fire History Analysis and Exploration System)* program version 2.0.2 (Brewer *et al.* 2016). Fire chronologies were analyzed by study site (Hein-

Table 1. Number of collected and dated trees in the three *Pinus greggii* var. *greggii* sites in the Sierra de Zapalinamé, Coahuila.

Site	Collected / dated trees	Living and dead trees dated (%)
El Penitente	29 / 25	72 / 28
Cañón de las Norias	50 / 44	25 / 75
Cañón del Negro	30 / 30	40 / 60

selman 1973) to calculate the following descriptive statistics: mean fire interval (MFI), minimum and maximum fire interval (MinFI and MaxFI) and Weibull median probability interval (WMPI) (Grissino-Mayer *et al*. 1994, 2001, Brewer *et al*. 2016). A separate analysis was conducted to compare long-term patterns to the period from 1998-2019, since 1998 was when fire protection program started in the study region (CONAFOR 2019). Fire frequency statistics were analyzed based on the following filters: 1) all fire scar years, and 2) years when two or more trees recorded a fire at the site. The period of analysis began after the first fire scar year within each site. In addition, we compared the synchrony of fire dates between sites.

Relationship between climate and fires. The relationship between climate and fire occurrences was analyzed using Superposed Epoch Analysis (SEA) in FHAES program version 2.0.2 (Brewer *et al*. 2016). This analysis utilizes two chronologies: 1) record of fire years based on fire-scar dates and, 2) a climatic series that overlaps the fire year's records. The SEA is a statistical method that compares climate conditions with fire occurrence, through an overlay of average climate data before, during and after the fire year (Grissino-Mayer 2001). We calculated confidence intervals at 95 % reliability to assess statistical significance, using simulation methods (bootstrapping) with 1,000 permutations of climate data, to ensure robust levels of confidence (Grissino-Mayer 2001, Meunier *et al.* 2014). We explored fire-climate relationships using four sets of climate data, including a regional drought index and two of global circulation phenomena. Regional conditions were represented using the Palmer Drought Severity Index (PDSI) of June-August (1400-2012) of the Mexican Drought Atlas (MXDA) (Stahle *et al.* 2016), and the Standardized Precipitation Evapotranspiration Index (SPEI) from January-April with a duration of four months (Vicente-Serrano *et al.* 2010). Global circulations patterns were represented using the Southern Oscillation Index (SOI) (1706-1977) where positive values are generally associated with dry conditions and negative values with wet conditions in northern Mexico (Stahle *et al*. 1998). The other climate proxy was El Niño region 3.4 for December-February (1950-2021) (NOAA 2021). Each index was analyzed separately with the reconstructed fires years for each study site, to determine local and regional climatic conditions before, during, and after the reconstructed fire years.

Results

Fire frequencies. A total of 109 fire scarred trees were sampled at the three sites, 99 (90.8 %) of those trees were dated, 95 *Pinus greggii* and four *Pinus arizonica*; while dating of ten remaining trees was not possible due to the wood decomposition and suppressed or irregular tree-rings. The TVE site had 25 dated samples that included 43 scars and 27 fire years over a period of 167 years (1840-2007) (Tables 1 and 3), with a fire-free period of 23 years *(i.e.,* 1919-1942) (Figure 2). The oldest living sample at this site was a *Pinus arizonica,* at an age of 218 years. The oldest fire scar was recorded in a *Pinus arizonica* tree. In contrast, *Pinus greggii* recorded fires beginning in 1918 with the oldest trees dating back to 1906 (Figure 2). Based on all fire scar years from 1840-1996, on average a fire was recorded at the TVE site every 7 years (MFI = 7.1 and WMPI = 6.1 years), with fire intervals ranging from 1 to 25 years. From 1998-2019, fire intervals decreased to less than 3 years (MFI = 2.3 and WMPI = 2.2 years) (Table 2). Larger fires that scarred two or more trees occurred at intervals between 6.0 and 15.4 years at each of the three sites (Table 2).

A total of 44 trees were dated from the CNO site including 54 fire-scars totaling 25 fire years (Table 3) between 1901-2012 (111 years). Fire frequencies did not change at CNO between 2001-2012, compared to the 1901-1996 period (Table 2). A total of 30 trees were dated from the CNE site including 44 fire-scars totaling 30 fire years (Table 3) between 1840-2014 (174 years), including a period of 25 years without fires (1851-1876) (Figure 2). Fire frequencies decreased in CNE between 1998-2014 compared to the period 1840-1996 (Table 2).

Each site had a distinct period of extensive fire years (years with 2 or more fire scars); however, the timing and length of those periods varied between sites. In TVE, the period with extensive fire years occurred between 1884 and 2007 with 33 % of all fires scarring two or more trees. The most extensive of these events occurred in 1943, 1948 and 2001 with six, four and three samples recording fire, respectively. At the CNO site, the period of extensive fires was shorter (1917-2007) compared to TVE. During that period, 11 of the 25 fire years (44 %) were recorded by two or more trees, the most extensive years occurred in 1951, 1953, 1957 and 1962 scarring four, nine, six and five samples, respectively. At CNE, the period of extensive fires ended earliest (1900-1972) compared to the other two sites, but only included two fire years that scarred more than 2 trees in 1939 and 1972 (Figure 2). During that period, 23 % of all fires scarred two or more trees.

Fire Seasonality. The season of fire occurrence was determined for 68 % of all fire scars (Table 4). Of these, 62.5 % were recorded in the early earlywood, 18.3 % in the mid earlywood and 19.1 % in latewood, with no fires recorded during the dormancy period. As a result, 62.5 % of the fires occurred in spring and 37.5 % in summer.

Table 2. Descriptive statistics of fire intervals for each of the three sites in *Pinus greggii* forests in the Sierra de Zapalinamé, Coahuila. WMPI: Weibull median probability interval.

Site	Period of analysis	Fire scar filter	Mean fire interval (MFI)	Minimum fire interval	Maximum fire interval	WMPI
El Penitente	1840-1996	All scars	7.1	1	25	6.1
	1884-2007	≥ 2 scars	15.4	1	49	10.4
	2000-2007	All scars	2.3	1	4	2.2
Cañón de las Norias	1901-1996	All scars	4.5	2	9	4.3
	1917-1996	≥ 2 scars	8.8	2	34	6.5
	2001-2012	All scars	3.7	1	5	3.4
Cañón del Negro	1840-1996	All scars	6.0	2	27	5.1
	1900-1972	≥ 2 scars	12.0	4	19	11.6
	1998-2014	All scars	--	--	--	--

Table 3. Number of fire scars, fire years and range for three *Pinus greggii* sites in the Sierra de Zapalinamé, Coahuila.

Site	Fire years	Fire scars	First fire year	Last fire year	Fire-free Periods
El Penitente	27	43	1840	2007	1919-1942
Cañón de las Norias	25	54	1901	2012	---
Cañón del Negro	30	44	1840	2014	1851-1876

Fire synchrony between sites. The three sites recorded fires on 60 different years, 16 of which were synchronized between two or more sites. Synchronized fire events were also recorded at all three sites in 1943, 1953 and 1996 (Figure 3).

Fire-climate relationship. The SEA results indicated that the reconstructed fire events in *Pinus greggii* forests occurred during dry years in TVE, CNO and CNE sites, based on the reconstructed PDSI index (June, July, and August) and the January-April SPEI index (Figure 4 A-F).

These conditions are related to positive winter SOI index values (December-February) (La Niña) and negative Niño 3.4 winter index values (December - February) (Figure 5A, B, E and F). However, climate indices were not significantly related ($P > 0.05$) with the year of fire, except the SOI index at the TVE site ($P < 0.05$) (Figure 5A). At the CNO site, fires generally occurred during a wet year, although they were not significantly related ($P > 0.05$) with negative values of the winter SOI index and the warm phase of the Niño 3.4 winter index (Figure 5C and D). The winter SOI index indicates that above-average moisture conditions dominated 1 to 3 years prior to the fire, although the relationship was not significant ($P > 0.05$) (Figure 5A, C and E). Conditions prior to and during the year of fire occurrence were also related to PDSI (Figure 5A- F) and SPEI indices, although this relationship was not significant ($P > 0.05$) (Figure 4A-F).

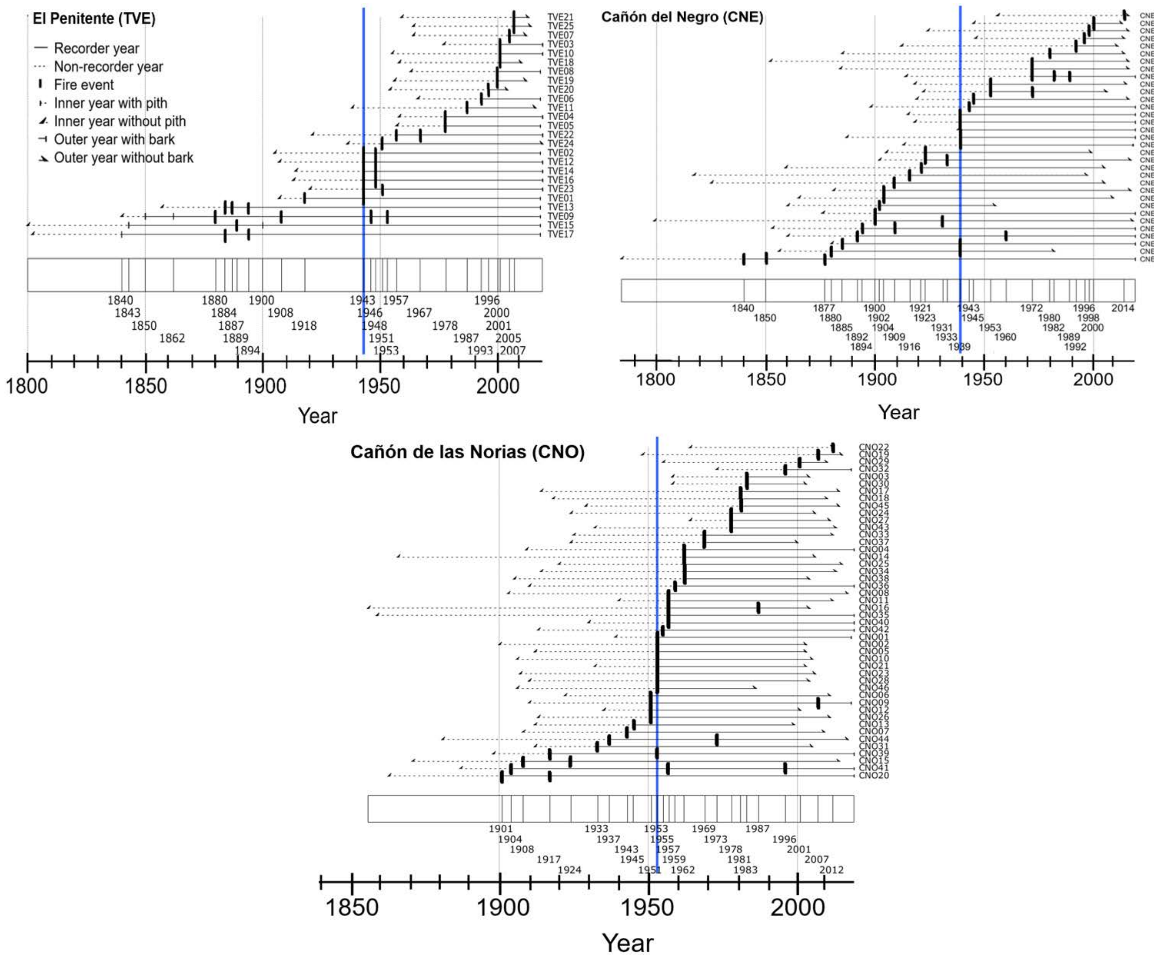

Figure 2. Fire history timeline for three *Pinus greggii* var. *greggii* forests sites in Sierra de Zapalinamé, Coahuila. Blue bars represent fire years recorded with the most recorded fire scars at each site. Fire years along the bottom are years in which a fire scar was recorded by one or more trees. The graphs for each site are based on all fire scars. The number of trees recording fires > = 1 and the minimum number of samples > = 1.

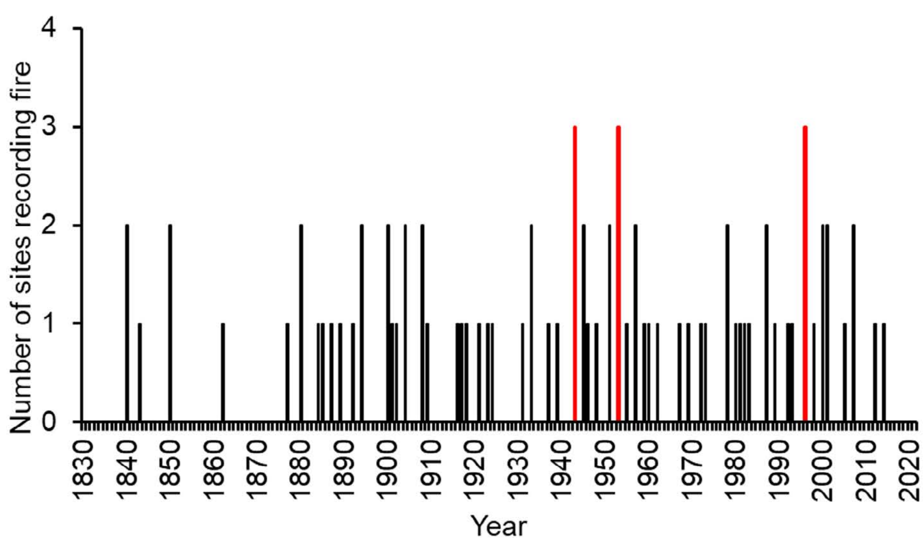

Figure 3. Fire synchrony between sites recorded in *Pinus greggii* forests of the Sierra de Zapalinamé, Coahuila. Red bars indicate fire year's recorded at all three sites.

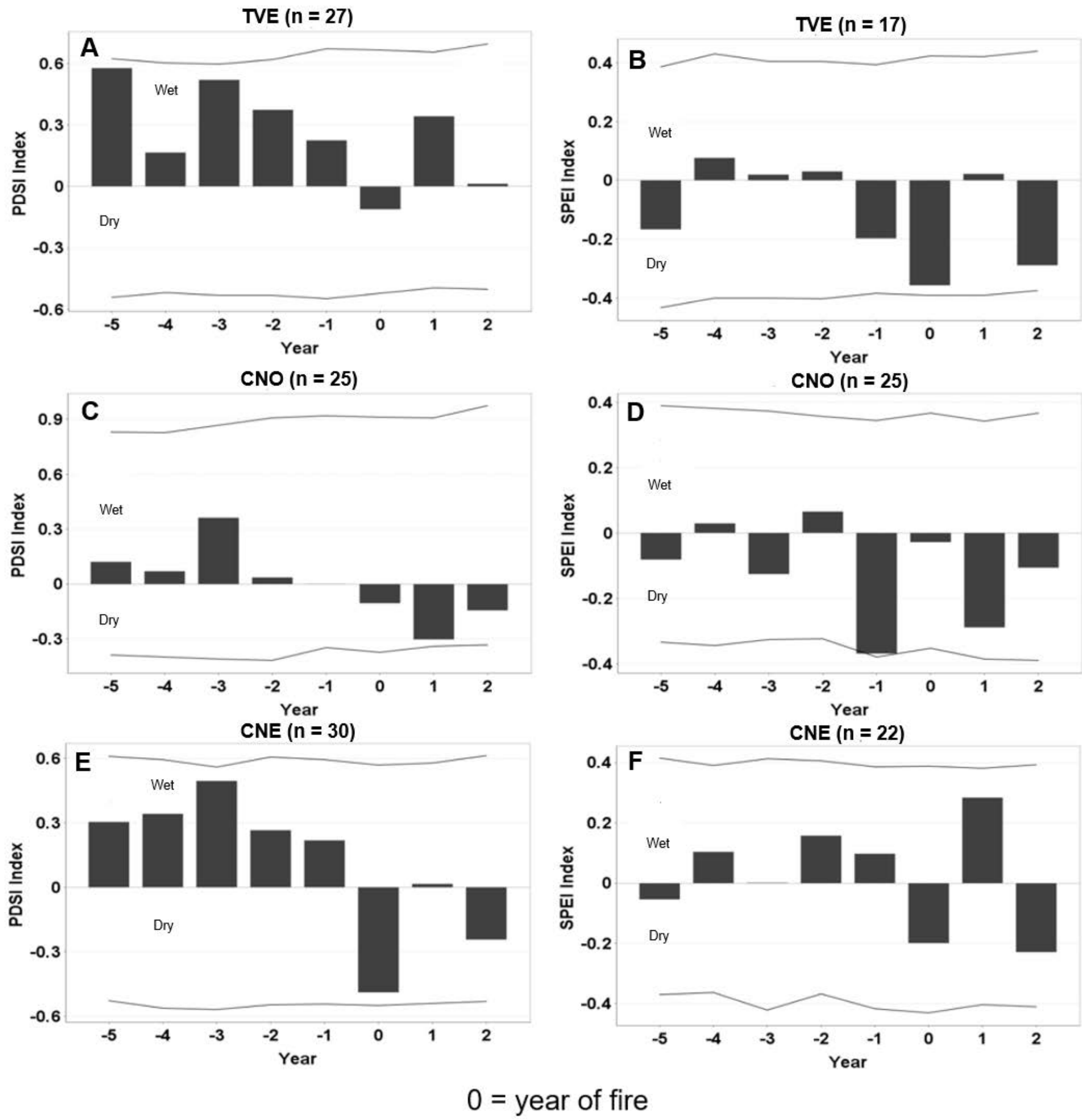

Figure 4. Results of the Superposed Epoch Analysis showing the influence of the reconstructed PDSI Index (June, July and August) and SPEI Index (January-April) on fires recorded in the three study sites of *Pinus greggii* forests in the Sierra of Zapalinamé, Coahuila. Negative numbers on the x-axis indicate the years before and positive numbers represent years after the fire. The bottom and top lines point the confidence interval to 95 %. The bars that intercept the lines are significant. The relationship between fire occurrence and PDSI and SPEI are shown for the A) and B) El Penitente (TVE) site, as well and C) and D) the Cañón de las Norias (CNO) site and E) and F) the Cañón del Negro (CNE) site.

Fires and their relationship to El Niño Southern Oscillation (ENSO) events. At the TVE and CNE sites, there was no significant relationship between extreme ENSO events in the winter and fire years ($P > 0.05$); however, these fires did tend to occur during the cold phase of La Niña (Figure 6A and C). At the CNO site, fires tended to occur in the warm phase (El Niño), which is associated with above-average moisture patterns in northern Mexico ($P > 0.05$) (Figure 6B). Dry conditions dominated at all three sites a year prior to the fire, although at the CNE site, wet conditions occurred two years before, this relationship was positive but not significant ($P > 0.05$) (Figure 6C).

Table 4. Fire seasonality based on the position of fire scars within the tree-rings, for the three *Pinus greggii* sites in the Sierra de Zapalinamé, Coahuila.

Site	Samples	D	EE	ME	L	Spring fires	Summer fires
El Penitente							
Number (n)	35	0	26	7	2	26	9
Percent (%)	82	0	74	20	5.7	74.3	26
Cañón de las Norias							
Number (n)	34	0	15	8	11	15	19
Percent (%)	63	0	44	24	32	44.1	56
Cañón del Negro							
Number (n)	26	0	18	3	5	18	8
Percent (%)	59	0	69	12	19	69.2	32

D = dormancy; EE = early earlywood; ME = middle earlywood; LE = late earlywood; L = latewood. D+EE = spring fires; ME + LE + L = summer fires.

Discussion

Fire Frequencies. Based on the results of all recorded fire years, we found that small fires were relatively frequent, with a mean fire interval of less than 7 years, while more extensive fires that scarred two or more trees were slightly less frequent, every 8-15 years within each site. These results are similar to those reported in Sierra Peña Nevada, Nuevo León, in forests of *Pinus hartwegii* (Yocom *et al*. 2010) and Maderas del Carmen, Coahuila (Poulos *et al.* 2013). For example, Poulos *et al*. (2013) also mentioned that most fires scarred less than 25 % of the sampled trees in Maderas del Carmen, Coahuila, suggesting that fire ignitions are frequent, but fire spread is usually limited resulting in a high frequency of small fires.

Despite a frequent fire regime in TVE, there were extended fire-free periods between 1918-1943. The absence of fires could be related to the logging of around 813,000 trees for railroad construction purposes between 1883-1905. At the same time, the railroad facilitated the introduction of sheep and goats into the region, as well as the extraction of firewood for commercial use (Valdés *et al*. 2017). In addition, the decree of federal fire suppression policies established in 1926 with the first forest law and state polices for fire suppression (POE 2006, Sáenz-Ceja *et al*. 2025) along with the protected decree of Sierra Zapalinamé in 1996 promoted the creation of firefighting brigades in 1998 (POE 1996), which contributed to disrupt the natural fire regime of the studied area. These changes in land use likely contributed to the decrease in available fuels resulting in limited fire spread within the entire region (Heyerdahl *et al.* 2001, 2003, Sakulich & Taylor 2007, Poulos *et al*. 2013). Similar patterns of interrupted fire patterns have been documented within the Sierra Madre Oriental, where the cessation of fire events was also attributed to land-use changes, including grazing, and the creation of communal lands (ejidos) (Yocom *et al.* 2010, 2014, 2017, Cortes-Montaño *et al*. 2012, Poulos *et al*. 2013).

Our results suggest that only one of the three sites (CNE) had a decrease in fire frequencies in the last two decades (after 1998). On the other hand, frequent fires have continued at CNO and increased at TVE. The factors responsible for these more recent changes are likely related, at least in part, to human activities including grazing (Poulos *et al*. 2013, Yocom *et al*. 2014) and organized fire suppression policies since 1998 (CONAFOR 2019) with the formation of community firefighting brigade which are stationed 2.5 km from CNE. Historical and current fire patterns at these sites confirms the spatial and temporal dynamics of fire regime in northern Mexico (Yocom *et al*. 2017). In general, fire frequencies have decreased the most within more accessible sites, while sites like TVE, with a lower human influence, continued to support frequent fires. Similar changes within more remote sites have also been documented elsewhere in northern Mexico (Meunier *et al.* 2014).

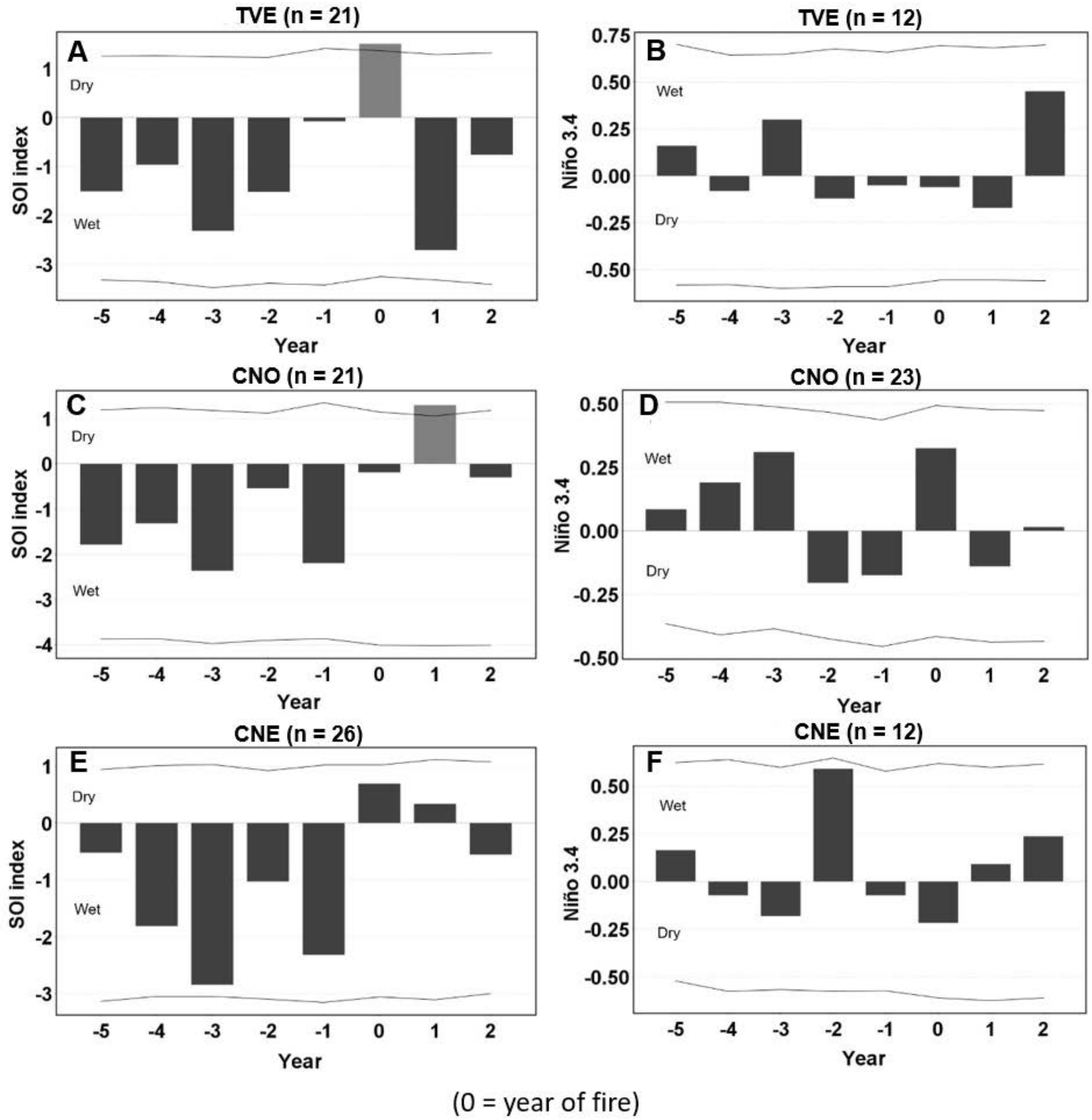

Figure 5. Fire climate relationship based on SEA analysis for the forest of *Pinus greggii*, in the three study sites of *Pinus greggii* forests in the Sierra de Zapalinamé, Coahuila. Negative numbers on the x-axis indicate the years before and positive numbers represent years after the fire. The bottom and top lines point the confidence interval to 95 %. The bars that intercept the lines are significant. A) and B) analysis with SOI and El Niño 3.4 Index for El Penitente (TVE) site. C) and D) correspond to analysis with SOI and El Niño 3.4 Index for Cañón de las Norias (CNO) site. E) and F) analysis with SOI and El Niño 3.4 Index for Cañón del Negro (CNE) site.

Fire Seasonality. Fires tended to occur in spring at two of the three sites analyzed, and in summer at the CNO site. Thus, most fires in TVE and CNE sites occurred between March and June. The dominance of fires in spring at the two sites was expected since this is the time of year with the highest temperatures and lowest humidity. In addition, similar spring season fires have been documented in conifer forests within northern Mexico in Durango (Cerano-Paredes *et al*. 2019) and southeastern Coahuila (Yocom *et al*. 2014). On the other hand, the dominance of summer fires in CNO was unexpected, but likely related to human activities (Yocom *et al*. 2014). Although this site is not close to a human settlement, it does have nearby road access.

Fire regime and its relationship to climate. Fire occurrences at two of the three sites were not significantly associated ($P > 0.05$) with global climate patterns, extreme ENSO, or drought indices (PDSI, SPEI). At the TVE site, however fires occurred during years with significantly positive SOI index values (Niña phase). In such year's, dry conditions prevail during the winter-spring period in northern Mexico. This pattern is similar to reports by Fulé & Covington (1997) in conifer forests within the northwestern region in Durango. The TVE site was also the only site where fire frequencies did not change overtime, which again suggests the remoteness of this site has allowed top-down factors such as climate to continue dominating. In contrast, the other two sites (CNO and CNE), show no significant relationship between climate and fire occurrence, suggesting a greater influence by local or bottom-up factors (Heyerdahl *et al.* 2001). That is, changes in fire frequencies, seasonality and the lack of climate controls on fire regime is probably due to fuel fragmentation related to land use changes. Over time, firewood extraction, timber harvesting, overgrazing, and road construction has resulted in greater fuel fragmentation and alterations of natural fire regimes (Meunier *et al.* 2014, Yocom *et al*. 2014, 2017).

In general, our results show a lack of fire synchrony both within and between sites, suggesting that most fires were relatively small. The lack of fire spread is explained by the fact that most fires occurred during non-drought conditions, suggesting that atmospheric moisture conditions were not ideal for fire spread (Farris *et al*. 2010, Yocom & Fulé 2012, Poulos *et al*. 2013, Forrestel *et al*. 2017). In addition, fire seasonality was also not synchronous between sites, although it is not clear if this is a new phenomenon. It is also unclear whether the lack of a climate-fire relation-

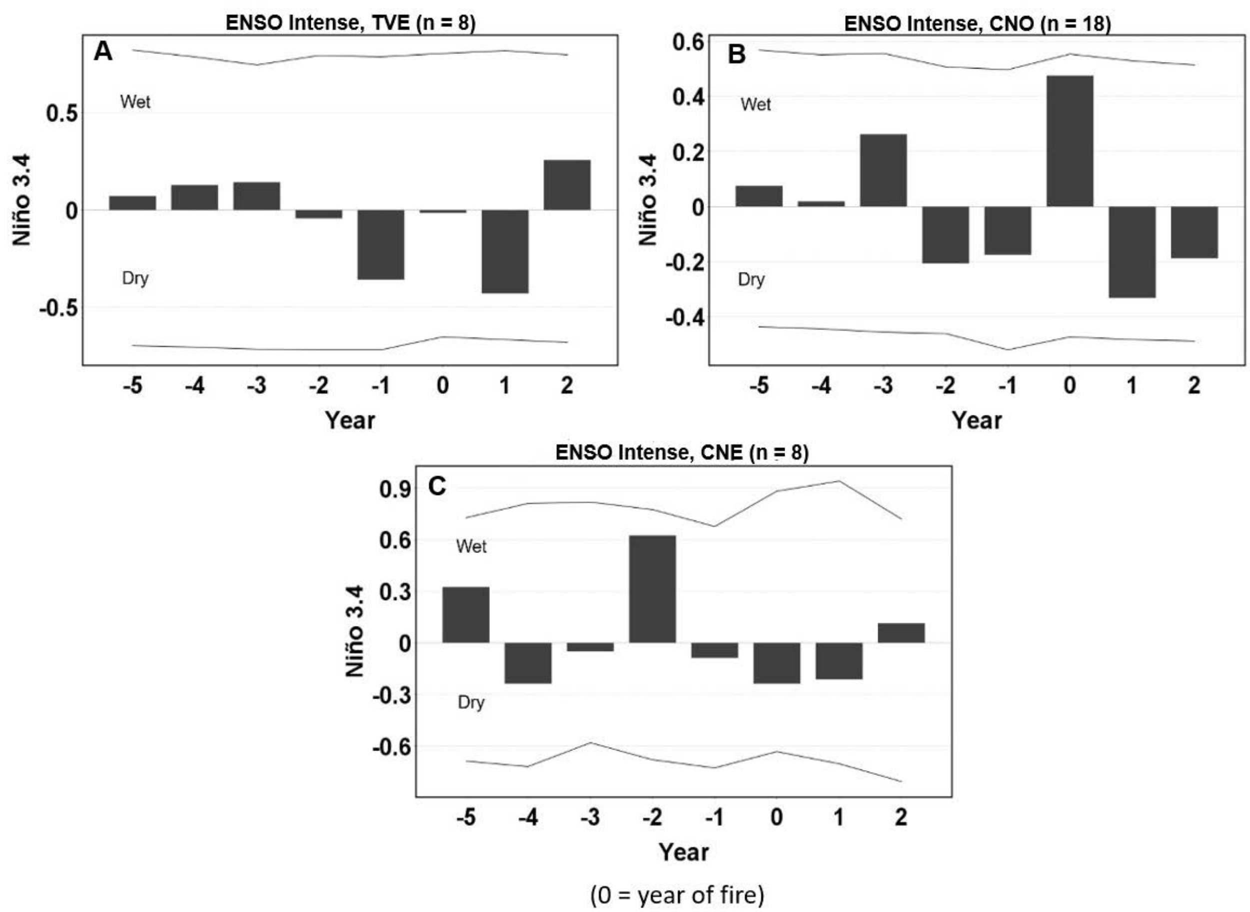

Figure 6. Influence of intense ENSO events (Niño 3.4 ± 0.5) on the fires that occurred in the three study sites: A) El Penitente (TVE), B) Cañón de las Norias (CNO) and C) Cañón del Negro (CNE) with dominance of *Pinus greggii* in the Sierra de Zapalinamé, Coahuila. Negative numbers on the x-axis indicate the years before and positive numbers represent years after the fire. The bottom and top lines point the confidence interval to 95 %. The bars that intercept the lines are significant.

ship we found in some of our sites has been in place prior to the twentieth century, because the reconstructed fires in the three study sites are mostly from the twentieth century. The lack of fire-scar evidence prior to 1900 could be related to several factors including the longevity of this species, stand-replacing fires (Forrestel *et al*. 2017) and/or wood harvesting associated with residents of nearby communities. In other fire history studies, fire occurrences were significantly influenced by large-scale circulatory modes primarily related to ENSO. For example, climate strongly influenced fire occurrence pattern in mixed forests but only prior to 1832 in southeastern Coahuila (Yocom *et al*. 2014), and prior to 1830 in Peña Nevada, Nuevo León (Yocom *et al*. 2010). Other dendroclimatic studies in the Sierra de Zapalinamé have also reported only a minor influence of ENSO patterns on interannual and multi-year climate variability, particularly after 1914 (Villanueva-Díaz *et al*. 2009).

Within all three sites we found, although not significant, wet conditions prevailed one to three years prior to the fire as indicated by winter El Niño 3.4 and winter SOI indices. Similarly, a study in the Sierra de San Luis, Sonora, reported that in the period 1887-2003, above-average moisture conditions before the fire years were more important than drought conditions during the fire year (Meunier *et al*. 2014). This is because higher moisture patterns favor the production of fine fuels, which when dried facilitate fire spread (Baisan & Swetnam 1990, Swetnam & Betancourt 1998). In the Sierra de Zapalinamé climate conditions before the fire also appear to be important to fire spread, although they were not statistically significant.

Management recommendations. In the future, fire frequencies and severity are likely to increase in the Sierra de Zapalinamé, due to climate change and increased landscape fuel homogeneity because of more active and effective fire suppression efforts (Covington & Moore 1994, Fulé & Covington 1997, Agee 1998). These changes could adversely affect *Pinus greggii* forests even though the species is well adapted to fire (*e.g.,* serotine cones) (Rodríguez-Trejo & Fulé 2003). To avoid the accumulation of fuels, forest resource managers in the Sierra de Zapalinamé, a State Natural Reserve must consider the extent and frequency associated with the historical fire regime presented here and consider allowing naturally ignited fire to spread naturally. Such fires could reduce fuel loads and the risk of future catastrophic high-severity fires, while maintaining natural processes and providing ecological benefits (Fulé *et al*. 2005, Cerano-Paredes *et al*. 2019).

In conclusion, the fire regimes within the forests of northern Mexico varied both spatially and temporally within the last century. The three sites in this study represent a gradient in fire regime changes related to land-use change and accessibility. Overall, we found a pattern of small but frequent fires occurring at all three sites; however, the CNE site, which was the closest to a town, has gone the longest without an extensive fire (since 1972), has fewer fires since 1998, and fire occurrences were not associated with climate patterns. Conversely, at the TVE site, which is topographically isolated and has less human disturbed, fire occurrences were significantly associated with climate patterns. In addition, this site has continued to experience frequent fires after 1998 including an extensive fire in 2007. The CNO site, which is not near a human settlement but has road access, has continued to experience frequent small fires but no extensive fires since 1983. At the CNO site fire occurrences were associated with the warm phase of Niño 3.4 and tended to occur in the summer, whereas the other two sites recorded mostly spring fires.

Although the dominant species at these sites are adapted to fires, increasing land use pressure suggests that fires, which are a natural process in these systems, may be more severe in the future. As a result, land managers will need to balance the need for ecosystem services and the natural role of wildfires to maintain healthy and sustainable *Pinus greggii* forest in northern Mexico. Even though future fire regimes are generally unknown due to climatic variability, additional research is needed to assess tree structure, recruitment, and fire management.

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