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Original Article

Effects of climate on historical fire regimes (1451–2013) in *Pinus hartwegii* forests of Cofre de Perote National Park, Veracruz, Mexico

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ABSTRACT

Cofre de Perote National Park (CPNP) in Veracruz, Mexico is part of the Transmexican Volcanic Belt, and its *Pinus hartwegii* forests reflect a balance between the various natural factors that represent the region's climatology and hydrology. Like many other areas in this region, the historical fire regimes of these forests and their relationship with climate are unknown, but are needed for sustainable management plans. The main objectives of this study were to reconstruct the historical fire regime in a *Pinus hartwegii* forest and decipher the influenced of climate. Our investigation focused in two study areas, Valle la Teta (VT) and Barranca Honda (BH). The VT study area was divided into three sites based on humidity and elevation: 1) Humid (VTH), 2) Dry Low (VTDL) and 3) Dry High (VTDH). The approximated area for each site was 30, 30, 35 and 50 ha, for VTH, VTDL, VTDH and BH, respectively. We collected 162 fire scarred samples to reconstruct the fire history for the last 550 years (1461−2013). The fire scarred samples contained 1240 fire scars, with most fires occurring in spring (95 %) or summer (5%). Prior to 1973, these sites were characterized by a frequent surface fire regime. In all four sites, the mean fire intervals ranged from 5 to 6 years (for fires that scarred ≥ 10 % of the samples) and 13–23 years (for fires that scarred ≥ 25 % of the samples). Extensive fires (≥ 10 %) coincided with significantly dry conditions based on the Standardized Precipitation Index (SPI), influenced by El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation Index (PDO). We also found a significant relationship between fire occurrence and ENSO, both in its warm phase, El Niño (21 fires ≥ 10 %) and in its cold phase, La Niña (32 fires ≥ 10 %). Synchronization of the cold phase of ENSO (La Niña) with the cold phase of the PDO (negative), facilitated severe drought conditions, resulting in fires with the greatest spatial extent. Since 1973, extensive fires have been absent from the study area most likely due to anthropogenic activities including active fire suppression. These results show a strong climate-fire relationship in these high elevation forests. The lack of fire in the last four decades is concerning and could potentially lead to unnatural stand-replacing fires, unless the historical fire regime is restored to maintain natural processes and increase forest resilience.

1. Introduction

Mexico's high-elevation *Pinus hartwegii* Lindl. forests are very important because they include endemic species and occupy only 1% of land area. As temperatures rise, these species are particularly susceptible to climate change given their adaptation to low temperatures (Hernández et al., 2005). In recent decades, increases in fire activity have also been attributed to global climate change (Westerling et al., 2006). Given the strong link between fire and climate, it is imperative to understand both the historical fire regime as well as the relationship

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between climate and fire within these forests. Understanding the disturbance patterns these forests evolved with is critical to making science based management decisions and maintaining healthy functioning ecosystems (Heyerdahl and Alvarado, 2003; Fulé et al., 2005; Allen et al., 2002).

1.1. Climate-fire relationship

Although fire has been recognized as an important disturbance in high-elevation tropical forests, research on this topic has been limited (Smith and Young, 1987; Rodríguez, 2001). Fire history information in *P. hartwegii* forests in central Mexico is relatively unknown, mainly due to the lack of a dendrochronology network that could be used to reconstruct historical fire regimes (Rodríguez, 2001). Fire history studies in high-elevation tropical forests and tropical forests in general are scarce (Martin and Fahey, 2006). In recent years two studies were conducted in *P. hartwegii* forests of central Mexico, one in Pico de Orizaba, Veracruz (Yocom and Fulé, 2012) and another in the northern sierra of Puebla (Cerano et al., 2016). These two dendrochronology based studies have enhanced our understanding regarding the relationship between fire and climate, though it remain unclear how this relationship changes across different regions in Mexico. That is, the influence of climate on historical fire patterns changes spatially across continents (Heyerdahl and Alvarado, 2003; Brown, 2006; Brown et al., 2008; Yocom et al., 2010; Falk et al., 2011; Cerano-Paredes et al., 2019), and therefore it is important to develop a network of sites to better understand and predict this spatial variability.

Rainfall patterns in Mexico are highly influenced by El Niño Southern Oscillation (ENSO) and its counterpart La Niña, which are a function of winter sea surface temperature in the equatorial region of the Pacific Ocean. In general, during El Niño winters, precipitation increases in northwestern Mexico and decreases in the central and southern region of the country. On the other hand, during La Niña winters, precipitation decreases in northwestern Mexico and increases in the central and southern Mexico (Magaña et al., 2003). The influence of ENSO on fire occurrence has been well documented in northern Mexico (Heyerdahl and Alvarado, 2003; Fulé et al., 2005; Yocom et al., 2010; Cerano et al., 2010; Cerano-Paredes et al., 2019). In central Mexico, Yocom and Fulé (2012) documented no relationship between ENSO and fire, while other studies suggest El Niño does have a significant influence on fire activity (Cerano et al., 2016).

Climate and therefore fire patterns in Mexico are also related to the Pacific Decadal Oscillation (PDO), a climatic pattern that associated with sea surface temperatures in the North Pacific (Mantua and Hare, 2002). Although the physical mechanisms relate the PDO are unclear (Evans et al., 2001), according to Newman et al. (2016) the PDO represents a combination of at least three main processes including; winds related to the Aleutian low, reemergence or ocean memory and westward moving Rossby waves, all operating at different time scales that result in SST anomalies. The PDO is a longer climatic oscillation than ENSO and in Mexico Pavia et al. (2006) suggest that the PDO teleconnectivity plays an important role in modulating precipitation and temperature anomalies. Other studies also support these findings, particularly in northern and central Mexico (Méndez et al., 2010). The PDO also appears to interact with ENSO to strengthen or weaken regional drought condition, which in turn influence historical fire occurrence patterns (Schoennagel et al., 2005; Sibold and Veblen, 2006). Gershunov and Barnett (1998) define two combination phases, constructive (of the same sign) and destructive phase (opposite sign). Although it has been suggested that linking the PDO to historical fires is problematic because different reconstructions yield different results (Kipfmueller et al., 2012), the PDO has been identified as a potentially important driver of regional fires in a variety of forested ecosystems in the Southwestern United States (Schoennagel et al., 2005; Kitzberger et al., 2007; Margolis and Swetnam, 2013) and northeast Mexico (Yocom Kent et al., 2017) particularly when both phenomena (PDO and ENSO) coincide in their cold phase (constructive phase). Although both climate patterns influence drought conditions in Mexico, the role of the PDO in relation to historical fire regimes in central Mexico remains unclear.

1.2. Changes in fire regimes

In the last several decades, it has become increasing clear that frequent fires play a critical role in maintaining certain forest structure patterns (Agee, 1993; Allen et al., 2002). Therefore understanding if and how historical fire regimes have changed, particularly with an ever increasing human footprint (Villarreal et al., 2019), is important in order to assess forest health, the potential impact of future fires and restoration needs. In the western United States, for example, the exclusion of historically frequent fires has resulted in increased tree densities and fuel accumulation, leading to larger and more severe recent fires (Swetnam et al., 1999; Singleton et al., 2019). In these forests, frequent fires historically sustained healthy forests by maintaining low tree densities and relatively open conditions (Iniguez et al., 2019). The exclusion of frequent surface fires results in increased tree recruitment and the creation of ladder fuels that allow fire to reach into the tree canopies facilitating stand replacing crown fires to which these forests are not adapted (Rodríguez and Fulé, 2003; Brown and Wu, 2005; Skinner et al., 2008; Iniguez et al., 2016). Fire regime changes from frequent low severity fires to infrequent fires can result in a loss of soils, forest land, wildlife habitat and alter ecosystem services including water and recreation (Westerling et al., 2006; Singleton et al., 2019).

Although fire suppression was widespread in western U.S. forests after 1900, fire regime changes within Mexican forests vary greatly in space and time (Yocom Kent et al., 2017). Tree-ring based fire history studies conducted in Mexico have mainly focused in the northern part of the country (Fulé and Covington, 1999; Heyerdahl and Alvarado, 2003; Fulé et al., 2005; Yocom et al., 2010; Cerano et al., 2010; Fulé et al., 2011). These studies have documented un-interrupted frequent low severity fire regimes in half of the sampled sites within Mexico (Cerano et al., 2010; Fulé et al., 2011). At other locations historical fire regimes have been interrupted at different times by various factors including land-use changes, road construction, logging and fuel breaks following the formation of communal lands called "ejidos" (Fulé and Covington, 1999; Heyerdahl and Alvarado, 2003; Fulé et al., 2005; Yocom et al., 2010; Villarreal et al., 2019). Studies in *P. hartwegii* forests, at Pico de Orizaba (Yocom and Fulé, 2012) and in the northern highlands of Puebla (Cerano et al., 2016), found an un-interrupted fire regime in the 20th century. Given the large variability in fire regime changes and relationships between fire and climate, there is a need for a greater network of studies to decipher the fire-climate relationship and understand fire history changes to inform local management decisions, particularly in high priority areas.

Cofre de Perote National Park (CPNP) in Veracruz, Mexico is important for ecological, economic and social factors. The area has protected status because these forests represent a balance between the various natural factors that interact with the climate and hydrology of the region (Diario Oficial de la Federación (DOF), 1937). One of the main risks threatening these forests are fires due to a warming climate. Therefore, it is important to understand the historical fire regime and how fires were influenced by climate in the past in order to make informed management decision that will sustain these forests in the future. This study is based on two research hypotheses. Our first hypothesis was that historical fire regimes have not significantly changed in the last few decades in regards to fire frequency. Our second hypothesis was that historical fire occurrence in CPNP was significantly influenced by climate variability.

2. Materials and methods

2.1. Study area

The geographic coordinates of CPNP are 19°25′33″ to 19°33′52″ north latitude and 97°06′55″ to 97°12′52″ west longitude. The elevational range of the Cofre de Perote is between 3000 m and 4250 m above sea level (masl), making it the seventh highest mountain in Mexico. In pre-Hispanic times, this mountain was called "Nauhcampatépetl" which means "hill of the four sides". It is part of the Citlaltépetl-Cofre de Perote volcanic range, at the eastern end of the Trans-Mexican Volcanic Belt (Fig. 1). This mountain range is composed of strato-volcanoes, slag cones and domes aligned northeast to southwest, which divides the Mexican Altiplano (Serdán-Oriental basin) and the coastal plains of the Gulf of Mexico (Carrasco et al., 2006). Glaciation during the late Pleistocene and early Holocene created glacial cirques and valleys (Carrasco-Núñez et al., 2010) i.e. La Teta, Honda, Infiernillo and El Tigre valleys (Fig. 1). This area is of great ecological, economic and social importance to the central region of Veracruz and areas above 3000 m were declared a "National Park", to conserve its forests (Diario Oficial de la Federación (DOF), 1937).

The large elevational range of CPNP over a distance of approximately 40 km, results in numerous microclimates and growing conditions. For example, the mountain is a barrier to the warm and humid winds coming from the Gulf of Mexico, which upon reaching it, quickly rise and cool, creating fog or rain on the eastern slope. As a result, the western slope of the Perote valley are in a rain shadow with less precipitation (Ramírez, 1983; Narave, 1985). In general, the climate within the CPNP is classified into two dominant types according to the Köppen classification modified by García (1987). The first, the Cb' (m)(f), a wet semi-cold climate dominated by summer rains and covers 5338 ha of the study area from the central part of the park to the northeast and southeast with precipitation ranging from 1.5 to 1.8 m. The second climate regime, Cb' (w2), includes at least 10 % winter precipitation and semi-cold temperature but dominated by summer rainfall. This climate covers an area of 6113 ha and extends from the central part of the park to the northwest and southwest aspects, with precipitation ranging from 1.0 to 1.2 m.

Within the CPNP there are 165 plant species. Vegetation types include alpine shubland (*Juniperus monticola* Martínez), pine forests (*Pinus hartwegii*) and fir forests (*Abies religiosa* Kunth Schltdl. Et Cham.). The study area also includes 178 wildlife species of which 67 are officially listed as threated or endanger of extinction in Mexico (Norma Oficial Mexicana 059) including 32 endemic and 55 protected species. The least numerous groups are amphibians with 14 species, 8 of which are endemic, such as the tree frog *Plectrohyla arborescandens* and the salamander *Pseudoeurycea leprosa* (Morales and y Aguilar, 2000; Morales et al., 2007).

2.2. Field methods

To sample fire scars we focused on the northwest aspect of the mountain because other potential sites lacked fire scars due to either high severity fire in 1998 or previous clear-cut logging. The northwest aspect of the CPNP study area was divided into two large study areas

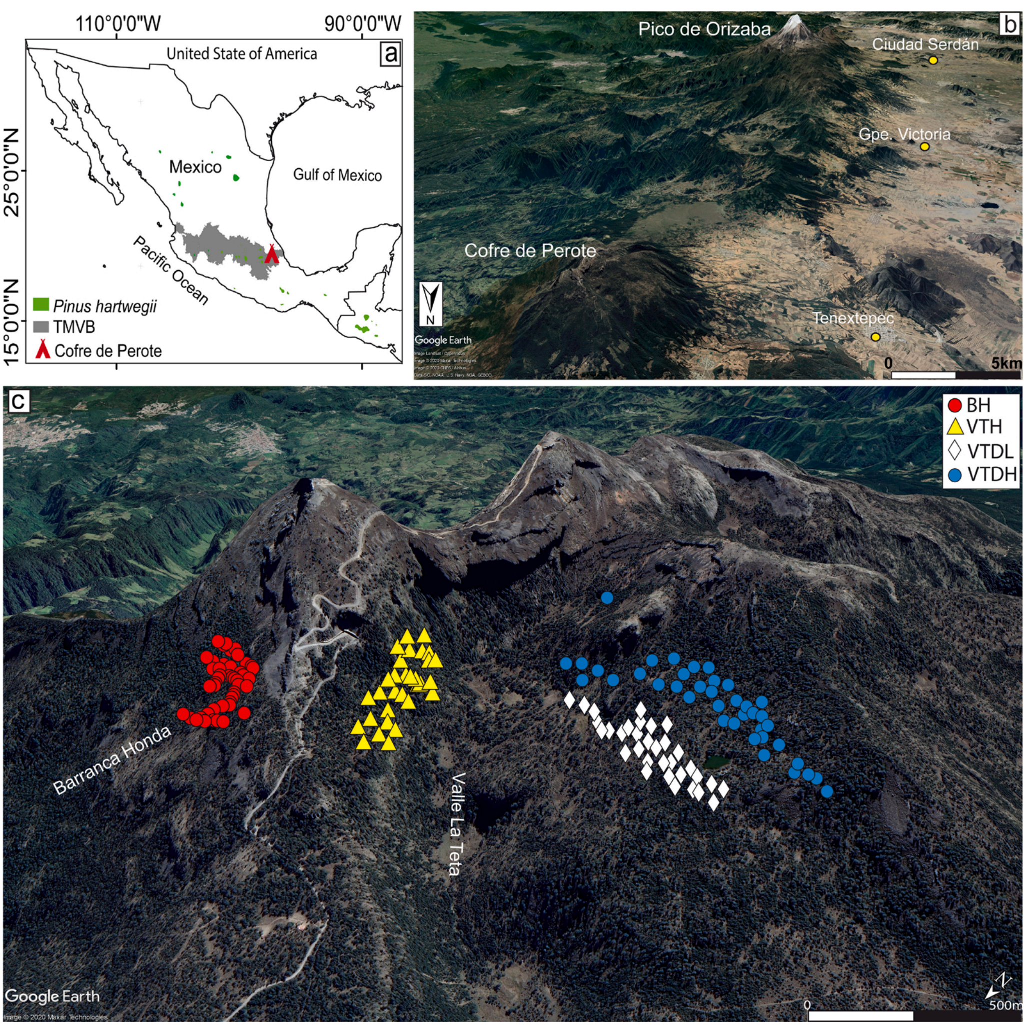

Fig. 1. Geographic location of Cofre de Perote National Park (CPNP) in the Transmexican Volcanic Belt (TMVB) and the spatial distribution of *Pinus hartwegii* (green color) a), map showing the sampling area CPNP and sub-regional topography b) and distribution of the study areas along the peak on the west face of CPNP, in different aspects and moisture conditions c). Tree sampling location for each of the four sites. Red circles correspond to Barranca Honda (BH) and in three different colors to Valle la Teta (VT), for the latter, triangles represent humid condition (VTH), diamond dry low condition (VTDL) and circles indicated dry high condition (VTDH). The National Park includes all areas above 3000 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Valle la Teta (VT, 3839–3960 masl) and Barranca Honda (BH, 3842−3938 masl). These two areas are separated by a formidable topographic fire barrier that is a steep rock outcrop lacking vegetation and fuels. Due to differences in aspects and humidity conditions, the VT study area was also divided into three study sites based on humidity and elevation: 1) Valle la Teta Humid (VTH, 3841−3949 masl), an area adjacent to a rock wall that creates a rain shadow and allows the area to retain moisture. The higher humidity favors a greater abundance of forbs and grasses. 2) Valle la Teta Dry Low (VTDL, 3839−3925 masl) and 3) Valle la Teta Dry High (VTDH, 3930−3960 masl). These areas lack streamflow and have greater sun exposure, while being dominated mostly by grasses and more open vegetation.

At each of these four sites we collected fire scar samples within areas of approximate 30, 30, 35 and 50 ha, for VTH, VTDL, VTDH and BH, respectively (Table 1; Fig. 2). The sampling strategy used was selective, that is within each study sites we selected trees based on specific characteristics including, evidence of fire scars, number of scars, and longest-lived trees.

We sampled individual trees with the most visible scars (Fig. 2c–e), best-preserved and longest possible fire records (Fig. 2a and b) (Arno and Sneck, 1977). This sampling approach if affective for reconstructing extensive fires in forested systems (Farris et al., 2010). Fire scarred samples were collected from stumps, logs, standing snags and live trees (Arno and Sneck, 1977). A chain saw was used to extract complete cross sections from stumps and logs, while partial sections were collected form standing dead and live trees. An emphasis was placed on taking sections from dead trees in order to minimize damage to live trees (Baisan and Swetnam, 1990).

2.3. Laboratory methods

In the laboratory, fragmented fire scarred samples were glued to each other while highly deteriorating samples were stabilized by gluing them to plywood prior to sanding and dating. All samples were polished with progressively fine sandpaper (40–1200), to achieve a uniform surface and to facilitate visibility of growth structures under a microscope. The exact calendar year of each annual ring was determined by comparing growth patterns (Stokes and Smiley, 1996). For live tree samples, growth charts were generated for each sample and used to create a master chart. Subsequently, dead trees were dated by developing a growth chart that was then matched with the master chart derived from live trees (cross dating). Using this technique, it was possible to determine the exact date of each growth ring. A master tree-ring chronology developed for Cofre de Perote based on *P. hartwegii*, was used as reference to date fire scar samples (J. Cerano-Paredes, unpublished data).

After comparing tree-ring patterns and pre-dating each sample, all rings within each sample were measured using a Velmex measuring system with an accuracy of 0.001 mm (Robinson and Evans, 1980). The quality of the dating was then statistically verified using COFECHA (Holmes, 1983). Fire scars were used as evidence of surface fires, given that tree survived the fire and recorded the event. Each fire scar was identified as a discontinuity in the cells along the boundary of the growth ring, where the cambium was damaged, followed by a suppression and deformation of growth (Dieterich and Swetnam, 1984).

The season of fire occurrence was determined relative to the position of each fire scar within the annual ring, based on the following categories: EE (early earlywood), ME (middle of earlywood), LE (late of earlywood), L (latewood) and D (dormancy or ring boundary) (Dieterich and Swetnam, 1984; Baisan and Swetnam, 1990). These categories were then grouped into seasonal periods: 1) spring (D + EE) and 2) summer (ME + LE + L) (Grissino-Mayer, 2001). The season of fire occurrence was determined for all scars dated in each of the sites.

2.4. Data analysis

The fire history database was analyzed using the FHX2 v3.2 (Grissino-Mayer, 2001). Fire scar trees were considered to be recording only after the initial fire scar. Trees were considered not recording if decay or subsequent fire made it impossible to date the fire-scar year. Formal statistical analysis included only the period with an adequate sample depth, starting with the first fire year when 10 % or more of fire scarred trees were recording at each site and ending the year samples were collected (Table 1) (Grissino-Mayer et al., 1994). Descriptive statistics included, Mean Fire Interval (MFI), Weibull Median Probability Interval (WMPI), minimum and maximum fire intervals. The WMPI is a measurement of central distribution, used to model the asymmetric distribution of fire intervals and to express interval recurrence in probabilistic terms (Grissino-Mayer et al., 1994; Swetnam and Baisan, 1996). These were analyzed using three different fire-scar filters: (1) All fires, which included every fire year that was recorded in at least one sample, (2) 10 % filter, which included only fire years recorded by at least 10 % of the recording samples, and (3) 25 % filter, which included only fire years recorded by ≥25 % of the recording samples. The 10 % filter is commonly used to estimate the frequency of extensive fires (Swetnam and Baisan, 1996; Fulé and Covington, 1999; Swetnam and Baisan, 2003; Farris et al., 2010) and was used here for all fire-climate analysis.

2.5. Fire-climate relationship

To determine the influence of local drought conditions and larger climate patterns on fire occurrence, we used Superposed Epoch Analysis (SEA) in the FHX2 program v3.2 (Grissino-Mayer, 2001). Four variables were used as climate proxies including:

1) A tree ring width chronology of P. hartwegii (Number of trees / samples 97/157, correlation between series $r = 0.42$, $P < 0.001$; chronology length 1436–2013) that explains 56 % of the variability of the winter precipitation in this area ($r = 0.75$, $P < 0.001$). For the calibration, we used the average climatic data from the 1966–2011 period (46 years) from the Tembladeras, Los Pescados and Perote meteorological stations, located nearly 3000 m asl (J. Cerano-Paredes, unpublished data).
2) The Standardized Precipitation Index (SPI) January-June, collected at the highest point of the Cofre de Perote (1901–2002), (IRI Analyzes SPI SPI-TS2p1_6-month 97.25 W-19.25 N) (Guttman, 1999).
3) Reconstructed El Niño Southern Oscillation (ENSO) Index. (1408–1978), (NIÑO 3 SST, December-February) (Cook, 2000).
4) Reconstructed Pacific Decadal Oscillation (PDO) index (1661–1991) (Biondi et al., 2001). We used the Biondi et al (2001) index because is based on wider geographic collection of tree-ring sites, including a site from northern Mexico. In addition, it is the longest series of PDO

Table 1
Physical description of the four study sites and fire-scarred tree characteristics in the Cofre de Perote National Park.

Site name	Site code	Elevation range (m)	Average slope (%)	Aspect	No. Trees collected/crossdated	No. scars	First scar (yr)	Analysis period (yrs)
Valle la Teta VT								
Humid	VTH	3841−3949	49	S	31/31	235	1461	1607−2013
Dry Low	VTDL	3839−3925	32	SE	33/33	301	1521	1544−2012
Dry High	VTDH	3930−3960	27	N	39/39	333	1607	1689−2012
Barranca Honda	BH	3842−3938	45	NE	59/51	371	1536	1607−2013

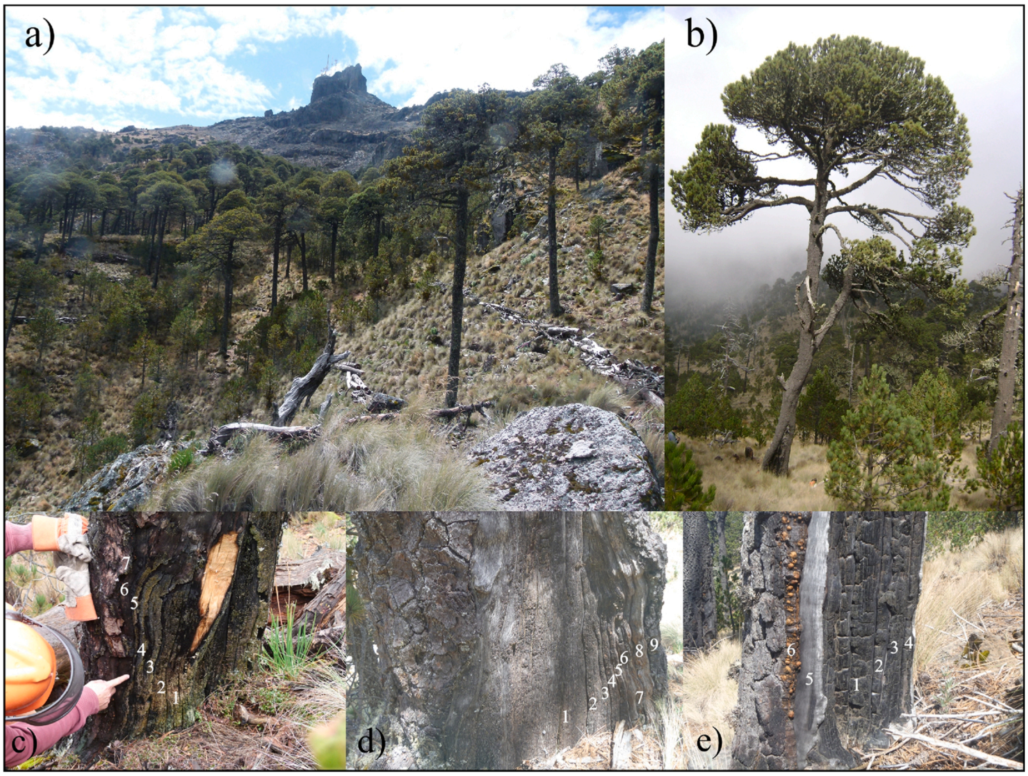

Fig. 2. Example of forest conditions in *Pinus hartwegii* forest in the Cofre de Perote (a), individual fire scarred tree (b), and close up view of fire-scars including trees with 7, 9 and 6, respectively (c, d and e). Photos credit: Julián Cerano-Paredes.

reconstructed using tree rings and hence it allows for a complete analysis of our fire scar record.

Each climatic variable was analyzed separately with the reconstructed fire history using the 10 % fire-scar filter to compare conditions during the fire year, as well as five years before and two years after the fire. To evaluate the statistical significance of the SEA analysis, confidence intervals (95, 99 and 99.9 %) were calculated using the bootstrapped distribution of the climate data based on 1000 permutations.

To further understand the relationship between different ENSO phases, we conducted an SEA using local climate conditions based on P. hartwegii annual tree-rings index (J. Cerano-Paredes unpublished data) to understand conditions during, prior to the fire year within fire that occurred during El Niño and La Niña years, separately. El Niño and La Niña years were identified from 1525 to 2002 using the Minimum Quality (MQ) adjusted magnitude score (Gergis and Fowler, 2009) associated with the three (four) proxy replication thresholds. This analysis was conducted using only extensive fire years (years when ≥10 % of the trees scarred) from 1607 to 2013.

In addition, we also conducted a separate analysis to understand the relationship between fire occurrence and the four possible ENSO/PDO phase combinations. To conduct this analysis we separated all 318 years between 1661 and 1978, first according to whether ENSO and PDO were positive or negative leading to four potential combinations. This frequency of each combination within the time period was then used as the expected proportion which was compared to the observed fire occurrence frequency using a Chi-square analysis to test for independence similar to Margolis and Swetnam (2013). Statistical test were conducted using actual counts but the results are shown as percentages to facilitated interpretation.

Finally, to determine the climatic condition within the reconstructed fire years (identified in ≥ 10 % of the samples), we used the June-August Palmer Drought Severity Index (PDSI) (1400–2012), in addition to NIÑO 3 and PDO. The PDSI index was generated for the upper part of the Cofre de Perote using the Mexican Drought Atlas (MXDA) (Stahle et al., 2016). Previous studies both in northern (Cerano-Paredes et al., 2019) and central Mexico (Yocom and Fulé, 2012; Cerano et al., 2016) have used the PDSI reconstructed by Cook (2000), based on the closest grid point to the study area. However, in this study we opted for the MXDA index in order to have a better representation of the local rather than regional climate condition.

3. Results

3.1. Fire regime

A total of 162 fire scared *P. hartwegii* samples were collected in CPNP, 103 were collected at VT (VTH = 31, VTDL = 33 and VTDH = 39) and 59 at BH. It was possible to date 100 % (103) of the samples from VT and 86 % (51) from BH. It was not possible to date eight samples (14 %), due to decay and suppressed/missing rings, which prohibited reliable dating. A total of 1240 fire scars were identified, 869 from VT (VTH = 235, VTDL = 301 and VTDH = 333) and 371 from BH (Table 1). Three of the four sites (BH, VTH and VTDL) had continuous tree-ring records from the early 1500s, with numerous samples from the 1600s. The VTDH site had a continuous record beginning in the early 1600s, with many samples after 1700 (Fig. 3). The earliest fire scar recorded for each of the study sites (BH, VTH, VTDH, and VTDL), was in 1536, 1461, 1607, and 1521, respectively; the most recent scar was dated in 2010, 2010, 2003, and 2003 for BH, VTH, VTDH, and VTDL, respectively (Fig. 3).

In general, fires were relatively frequent at all four sites, but smaller fires were more frequent than larger fires. For example, based on the all scars filter, all four sites had an MFI and WMPI of less than 10 years (Table 2). Extensive fires that were recorded on ≥10 % of samples at a site, were slightly less frequent but the MFI and WMPI were still less than 10 years, ranging from 5 to 8 years at the three VT sites. Fires that scarred ≥10 % of all samples were even less frequent at the BH site however, where MFI and WMPI were 13 and 11 years, respectively

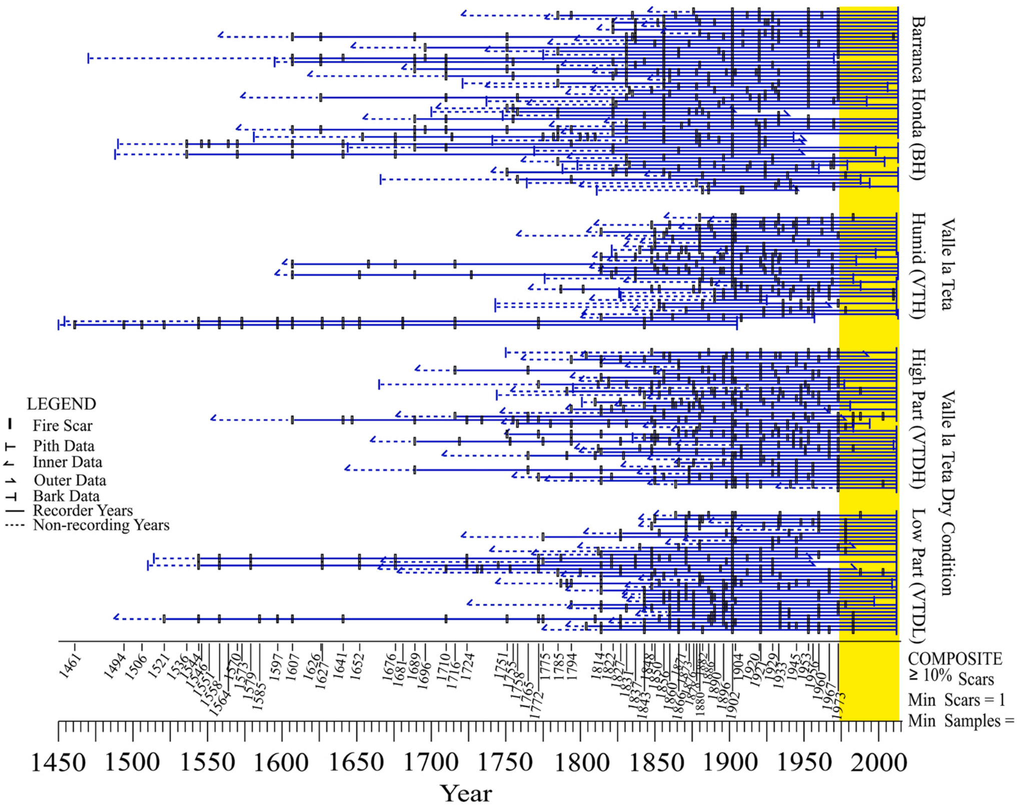

Fig. 3. Fire history chart from a *Pinus hartwegii* forest in the Cofre de Perote National Park, Veracruz, Mexico. Horizontal lines represent the time line of each individual tree. Dashed line before the first scar are periods when the tree was not recording and solid lines represent periods when the tree was able to record fires. Recorded fire scars are indicated as black vertical bars while the formation of a continuous vertical line indicates an extensive fire that was recorded by multiple trees. Extensive fires recorded by ≥10 % of the trees are shown with dates below the chart. The yellow bar indicates the reconstructed period (1973-2015) when the fire regime changes with fires becoming less frequent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Fire interval descriptive statistics for four sites, Valle de Teta Dry Low (VTDL), Valle la Teta Dry High (VTDH), Valle la Teta Humid (VTH) and Barranca Honda (BH). The VT composite includes the three sites of Valle la Teta (VTDL, VTDH, and VTH). This information is based on cross-dated fire scar samples from Cofre de Perote National Park, Veracruz, Mexico.

Site/Analysis period					
Category of analysis	VTDL (1544–2012)	VTDH (1689–2012)	VTH (1607–2013)	BH (1607–2013)	VT-Composite (1607–2013)
Number of intervals					
All scars	72	72	66	69	97
10 % scarred	58	49	49	29	59
25 % scarred	33	13	19	16	17
Mean fire interval (years)					
All scars	6.3	4.3	6.1	5.8	4.1
10 % scarred	7.5	5.8	7.4	12.6	6.3
25 % scarred	13.1	21.8	19.0	22.8	21.5
Weibull median interval (years)					
All scars	5.2	3.6	4.4	4.4	3.5
10 % scarred	6.4	4.9	5.6	11.0	5.5
25 % scarred	12.0	18.7	17.1	21.3	18.7
Minimum interval (years)					
All scars	1	1	1	1	1
10 % scarred	1	2	1	2	1
25 % scarred	2	2	2	4	5
Maximum interval (years)					
All scars	34	27	45	37	21
10 % scarred	34	27	45	41	21
25 % scarred	34	49	45	46	52
Average per-sample fire interval	20.5	21.3	22.9	30.9	21.6

Note: Statistical analysis were conducted for three fire-scar categories: (1) All scars: includes fire years recorded by one or more trees, (2) 10 % scarred: includes years when fires were recorded by 10 % or more of the recording sample trees, and (3) 25 % scarred: includes years when fires were recorded by 25 % or more of the recording sample trees.

(Table 2). The least frequent fires where those that scarred ≥25 % of the samples within each site. These fires generally occurred at interval greater than 15 years for all sites (MFI and WMPI of 21.5 and 19 years at VT and 22.8 and 21.3 years at BH, respectively). The MFI per sample was <25 years at VT and <32 years at BH. The minimum free intervals ranged between 1 and 5 years, for both VT and BH (Table 2). Conversely, maximum fire intervals at each site varied from 27 to 49 years depending on the site and filter.

3.2. Fire frequency changes

From the earliest recorded fire scars in the 1460s up to the early

1970s, fires were relatively frequent across CPNP. After 1973, however, there was an abrupt change in fire frequency (Fig. 3). In BH and VTH there has been an absence of fire since the early 1970s, resulting in 43 years without an extensive fire (10 % filter). Some fires occurred within VTDL and VTDH in the early decades of the 21 st century, but were less extensive compared to historical patterns. For example, since 1973 four fires were recorded at these two sites in 1978, 1983, 1988 and 2003, that scarred 12, 9, 5 and 4% of trees, respectively. The most recent fire interval detected at these sites is 13 years. When considering fires that scarred at least two samples per sites within the entire study area, however, fire intervals in recent years change abruptly to 43 years for BH and VTH, and 28 years for VTDL and VTDH. Furthermore, if we consider fires recorded by ≥10 % of the samples within the whole study area, then the current fire free interval is 43 years (Fig. 3).

3.3. Fire seasonality

Seasonality was determined for 71 % of the fire scars (Table 3), with most of the fires being recorded in the beginning of the early wood (95 %) or middle early wood (5%) of the tree ring. No scars were recorded at the end of the early wood, latewood and dormancy season. Therefore, 95 % of fires are considered spring fires and 5% in the summer fires (Table 3), suggesting that most fires occurred in the warm spring period between March and early June.

3.4. Climate-fire relationships

The SEA shows that in the last 400 years, the most extensive fires (10 % filter) coincided with significantly dry climate condition based on the tree-ring width indexes (Fig. 4a), SPI (Fig. 4b). A strong relationship was also found between fire occurrence and the negative phases of ENSO and PDO (Fig. 4c, d). No significant relationship was found on years immediately prior to the fires (Fig. 4). Within the last 550 years, extensive fires (10 % filter), in the Cofre de Perote occurred during El Niño (Fig. 5a) and La Niña (Fig. 5b) phases, both of which caused dry conditions leading to significantly low tree-ring indices during the year in which those fires occurred (Fig. 5).

Observed fire occurrence during each of the four PDO/ENSO phase combination was significantly ($P < 0.05$) different than expected based on the frequency of each of these phase combination (Fig. 6). In general, the most common phase combination was same sign combinations of ENSO and PDO (+P + N and -P-N, constructive phase), which occurred during 63 % of all years. Within our study area extensive fires (10 % filter) occurred during all four phases combinations, however almost 50 % of such fires occurred during years when both PDO and ENSO were in a negative phase. This phase combination was associated with the most severe drought during the reconstructed fire period (mean PDSI -1.70, -P-N). Alternatively fewer extensive fire (17 %) than expected (32 %) occurred on your when PDO and ENSO were both positive (Fig. 6), likely because this combination also produced the wettest conditions (mean PDSI = 0.50). In destructive (opposite) phases warm (cold) PDO and a cold (warm) ENSO occurred relatively similar to expected frequencies (Fig. 6).

4. Discussion

4.1. Fire seasonality

The majority of fires in the CPNP occurred in the spring (95 %), which is consistent with the seasonality found in *P. hartwegii* forests in the Sierra Norte de Puebla, where 92 % of fires were recorded early in the growing season (Cerano et al., 2016). Conversely, at Pico de Orizaba, Yocom and Fulé (2012) reported that 95 % of the scars were observed in the dormant period, prior to growth initiation and only 3% were recorded during the growing season. This difference in seasonality is likely because fires in Pico de Orizaba are predominantly human caused fires that occur in February and March, while human ignitions are less of a factor in the PNCP, where fires occur in April and May. Dormancy and early growth categories in this region are both considered spring fires (Grissino-Mayer, 2001). On the contrary, few fire scars (5%) were recorded within the earlywood, which according to Grissino-Mayer (2001) corresponds to the summer season (Swetnam et al., 2001). Very few summer fires were also recorded in the Pico de Orizaba (1.5 %) (Yocom and Fulé, 2012) or in the Sierra Norte de Puebla (8%) (Cerano et al., 2016).

In CPNP and across central Mexico the spring season coincides with the least precipitation, highest temperature (Servicio Meteorológico Nacional (SMN), 2017) and lowest photosynthetic rate (value of NDVI, Tucker et al., 2005) or greatest vegetation stress of the year (Fig. 7). Likewise, historically this dry period is synchronized with high incidents of lightning or electric discharges (Servicio Meteorológico Nacional (SMN), 2017, Fig. 7) a phenomenon that may have initiated natural fires in this area. Contemporary fires in *P. hartwegii* forests also occur between January and June (Rodríguez, 2001), which coincides with dry spring conditions. In general, the summer rains, which start in June, increase fuel moisture prohibiting fire spread and ending the fire season (Fig. 7). Similar seasonal patterns have been found in northern Mexico and the southwestern U.S., where most fire occurrences coincide with lightning during the dry spring-early summer period (Swetnam et al., 2001).

4.2. Fire regime

Over the last 550 years, the fire regime in CPNP was dominated by frequent surface fires. When considering all fires, the MFI was similar to fire frequencies reported at other *P. hartwegii* forests in central Mexico (Yocom and Fulé, 2012; Cerano et al., 2016) and other regions such as Sierra Madre Oriental (Yocom et al., 2010). Rodríguez (2001) predicted that *P. hartwegii* forests had an average fire frequency of approximately

Table 3
Seasonal distribution (number and percent) of the fire scars at the four study sites based on the positions of fire scars within annual rings.

Site/Analysis period	Season (determined)	Season (undetermined)	D	EE	ME	LE	L	Spring fires[A]	Summer fires[B]
VTDL 1521−2012									
Number	225	76	0	214	11	0	0	214	11.0
%	74.8	25.2	0	95.1	4.9	0	0	95.1	4.9
VTDH 1607−2012									
Number	231	102	0	217	14	0	0	217	14
%	69.4	30.6	0	93.9	6.1	0	0	93.9	6.1
VTH 1461−2013									
Number	165	70	0	157	8	0	0	157	8
%	70.2	29.8	0	95.2	4.8	0	0	95.2	4.8
BH 1536−2013									
Number	254	117	0	244	10	0	0	244	10
%	68.5	31.5	0	96.1	3.9	0	0	96.1	3.9

Note: The definition of the seasonality of fires was based on the methodology described by Grissino-Mayer (2001). D = Dormant, EE = Early earlywood, ME = Middle earlywood, LE = Late earlywood and L = Latewood. [A]D + EE = Spring fires. [B]ME + LE + L = Summer fires.

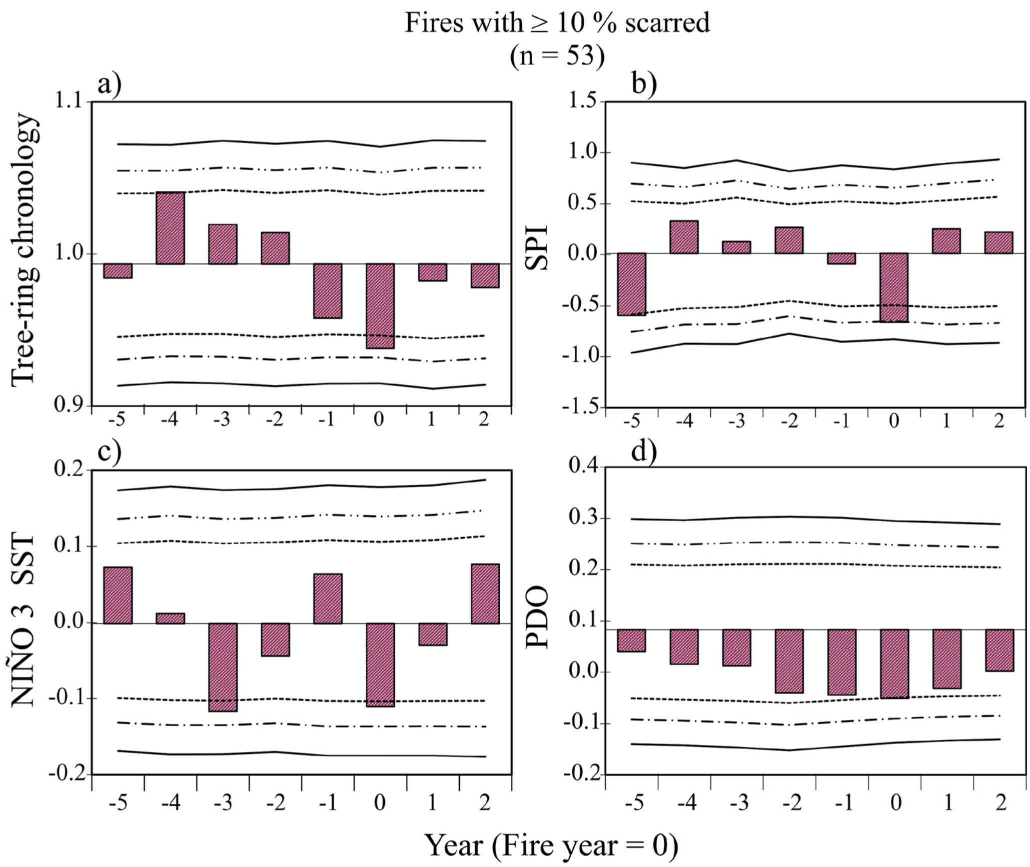

Fig. 4. Relationship between the occurrence of extensive fire (10 % filter) and local as well as regional climate for Cofre de Perote study area in central Mexico between 1607 and 2013 based on Superposed epoch analysis (SEA). Local climate conditions are represented by a) ring width index of trees, b) Standardized Precipitation Index (SPI) both of which were sampled within the study area. Regional climate patterns are represented by c) NIÑO 3 and d) PDO. Fire-climate relationship are lagged up to 5 years prior to and 2 years after the fire years represented as year 0. The three lines above and below in each plot represent the 95, 99, and 99.9 % confidence intervals based on Monte Carlo simulations of random distributions of annual conditions for each index.

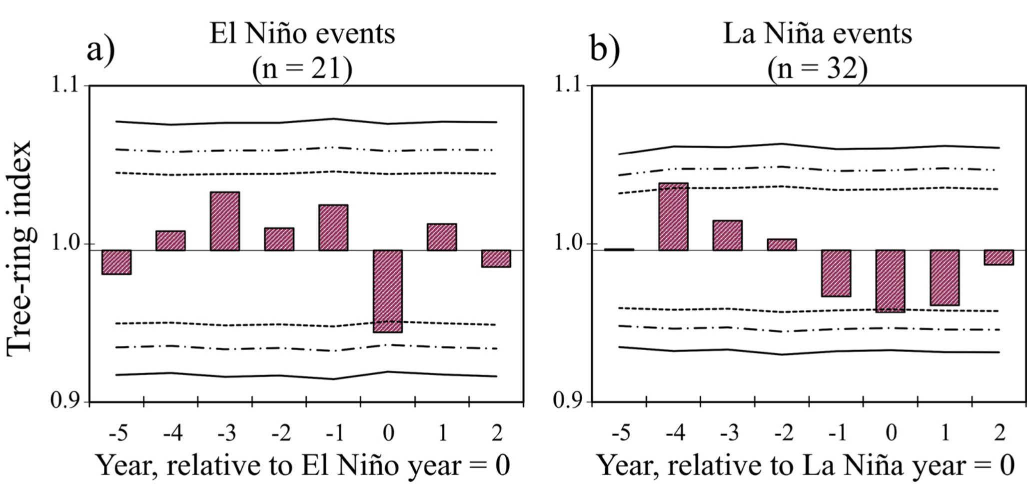

Fig. 5. Relationship between the occurrence of extensive fires (10 % filter) and tree-ring index, which represents local drought condition, during a) El Niño and b) La Niña events between 1607 and 2013. Fire-climate relationship are lagged up to 5 years prior to and 2 years after the fire years represented as year 0. Year zero is when the fire occurred while years -1 to -5 are 1 to 5 years prior to the fire year. The three lines above and below in each plot represent the 95, 99, and 99 % confidence intervals based on Monte Carlo simulations of random distributions of annual conditions.

five years and could not exceed 10 years. Our results reaffirm Rodriguez (2001), given that based on the all fires filter, all of our four sites had a fire frequency of approximately 5 years and none, exceeded the 10-year interval (Table 2). The frequency of large fires, however differs from other fire history studies in Mexico. That is, the MFI of large fires (recorded by >25 % of samples), was twice as long at CPNP (22.2 years) compared to both Pico de Orizaba (8.2 years) and Sierra Norte de Puebla (9.2 years). This was not expected given that the MFI of large fires reconstructed for the Sierra Madre Oriental are generally longer (14.5) than those reported for the central part of the Mexico. In fact, the intervals reconstructed for large fires in CPNP are the longest reported in high-elevation tropical forests (Table 2). This could be related to the more dissected topography at CPNP compared to other sites (Iniguez et al., 2009).

Our results suggest a high degree of synchrony between the two main study sites (VT and BH) despite formidable topographic barriers. For example, 51 % of the BH fire dates, were also recorded at the VT sites (Fig. 3), suggesting that half of the fire events in BH were extensive fires that likely spread throughout the entire Cofre de Perote study area. There is also relatively high fire synchrony between CPNP and other *P. hartwegii* forests in central Mexico. For example, of the 20 fire years reconstructed in the Sierra Norte de Puebla from 1876 to 2011 (Cerano et al., 2016), 12 (60 %) coincided with fire years recorded in the CPNP. Fire-scar synchrony was less apparent with sites in Pico de Orizaba, likely due to anthropogenic influences, however four fires recorded in the 20th century (1902, 1907, 1943 and 1960) (Yocom and Fulé, 2012)

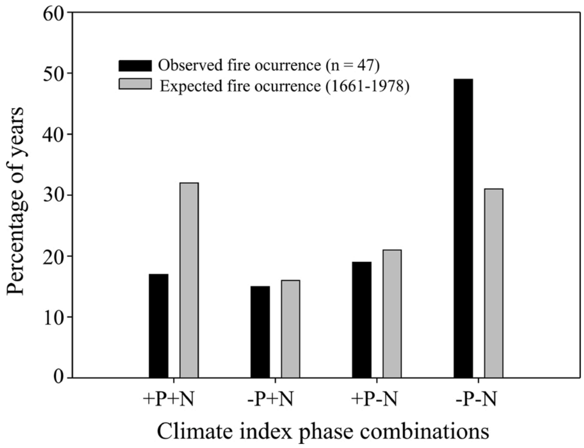

Fig. 6. Proportion of expected and observed extensive fire years (>10 % trees scarred) during each of four Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) combination in Cofre de Perote National Park in central Mexico. Expected frequencies were based PDO/ENSO phase frequency during the periods between 1661 and 1978.

were synchronized with fires recorded in the CPNP, three of which coincide with extensive fires. This pattern of intermountain synchrony between study areas is attributed to climate patterns shared by the forests in this region, which dictate the timing of extensive fires (Swetnam, 1993).

4.3. Climate-fire relationship

In Cofre de Perote, most extensive fires within the last 550 years occurred during significantly dry ($P < 0.05$, Fig. 4) years. This was an expected result given that extensive fires during dry years have been documented elsewhere in Mexico, North America and worldwide. The novel finding of this study, however is how these dry conditions at the study area are related to larger climate circulation patterns including ENSO and PDO (Fig. 4c, d). In general, El Niño events are associated with drought conditions in central Mexico, while the La Niña events are associated with drought conditions in northern Mexico (Magaña et al., 2003; Seager et al., 2009; Stahle et al., 2011). Based on this general understanding we would expect most fires in CPNP to coincide with El Niño events. Our results however, show that extensive fires occurred during both El Niño and La Niña events (Fig. 5a, b). In fact of the 53 widespread fires reconstructed in CPNP between 1607 and 2013, as expected, 21 fires were synchronized with El Niño condition (Fig. 5a and 8c). Unexpectedly, however, 32 extensive fire year also coincided with severe La Niña events (Fig. 5b and c). For example, La Niña events in 1676, 1880 and 1953, resulted in extreme drought that was centered in northern Mexico, but also extended into portions of central Mexico (Figs. 8a and 9).

This suggests drought conditions and extensive fires in our study area resulted from both severe and normal El Niño years as well as extreme La Niña years. In the latter, drought conditions were centered elsewhere but extended into our study area (Fig. 9). Likewise, extreme El Niño events can also facilitate severe drought conditions across multiple regions (Fig. 9). Examples of widespread El Niño events occurred in 1902, 1929 and 1998, which registered nationwide drought conditions (Figs. 8a and 9) and facilitated fires in central (Cerano et al., 2016) and northern Mexico (Fulé and Covington, 1999; Cerano et al., 2010).

Although ENSO and PDO differ in temporal and spatial scales, they interact to minimize and amplify their severity, thereby influencing fire conditions. That is, the severity of ENSO events, El Niño/La Niña, is generally dictated by larger atmospheric patterns such as PDO (Schoennagel et al., 2005; Kitzberger et al., 2007; Margolis and Swetnam, 2013). For example, droughts in the central and western United States are more intense when La Niña occurs during the negative PDO phase (McCabe and Dettinger, 1999; Westerling and Swetnam, 2003). Similarly in Mexico, a negative PDO (cold phase) can amplify the spatial extent of La Niña causing drought that would typically be centered in northern Mexico to extend south into central and southern Mexico, such as 1676, 1880 and 1953 (Fig. 9). This amplification of ENSO events by the PDO explains the majority of extensive fires (47 %) occur during the alignment of both the negative phase of the ENSO (La Niña drought condition) and the cold (negative) phase of PDO found at CPNP (Figs. 4c, d; b, c). Interactions between ENSO and PDO have been associated with the occurrence of extensive fire years in the western U.S. (Heyerdahl et al., 2002; Brown and Wu, 2005; O'Connor et al., 2014). Similar effects of PDO on climate have also been observed in the North Pacific (Mantua and Hare, 2002), southwestern North America (Higgins et al., 2000) and northern Mexico (Yocom Kent et al., 2017). The PDO cold phase can also have the opposite effect by weakening an El Niño event (Gershunov and Barnett, 1998). For example, some studies (Englearth and Douglas, 2002; Pavia et al., 2006) suggest that the PDO modulates precipitation anomalies and seasonal temperature in Mexico. Méndez et al. (2010) reaffirmed the influence of the PDO on the climate variability in the north and central parts of Mexico. Our results corroborate these studies indicating that the negative (positive) phase of the PDO favors winter droughts (rains) especially in the Mexican High Plains and northern Mexico, resulting in large fire years.

Just like PDO can influence the severity and extent of La Niña conditions, it can also have a similar influence during El Niño conditions. For example, the historic El Niño years of 1983 and 1998 (Trenberth, 1997), affected not only central and southern Mexico, as expected, but

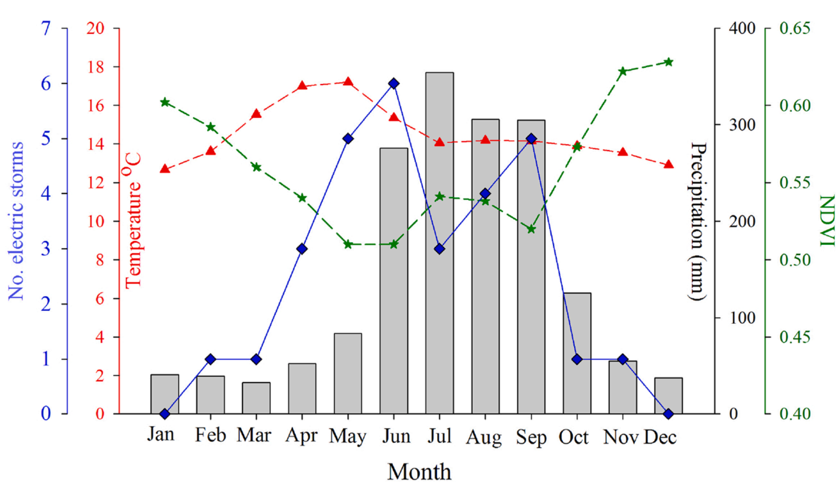

Fig. 7. (color) Monthly average precipitation (gray bars), temperature (red triangles dashed line), lightning activity (blue squares solid line) and normalized difference vegetation index (NDVI) (green stars dashed line) at the Cofre de Perote. Precipitation, temperature and electric storms are average values recorded from 1951-2010 at Tembladeras (3110 masl) and Los Pescados (3000 masl) weather stations (Servicio Meteorológico Nacional (SMN), 2017). Values of NDVI indicate the photosynthetic rate of the vegetation or the level of vegetation stress. The NDVI values are monthly averages for the period 1981-2006 for the vegetation of the Cofre de Perote (Tucker et al., 2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

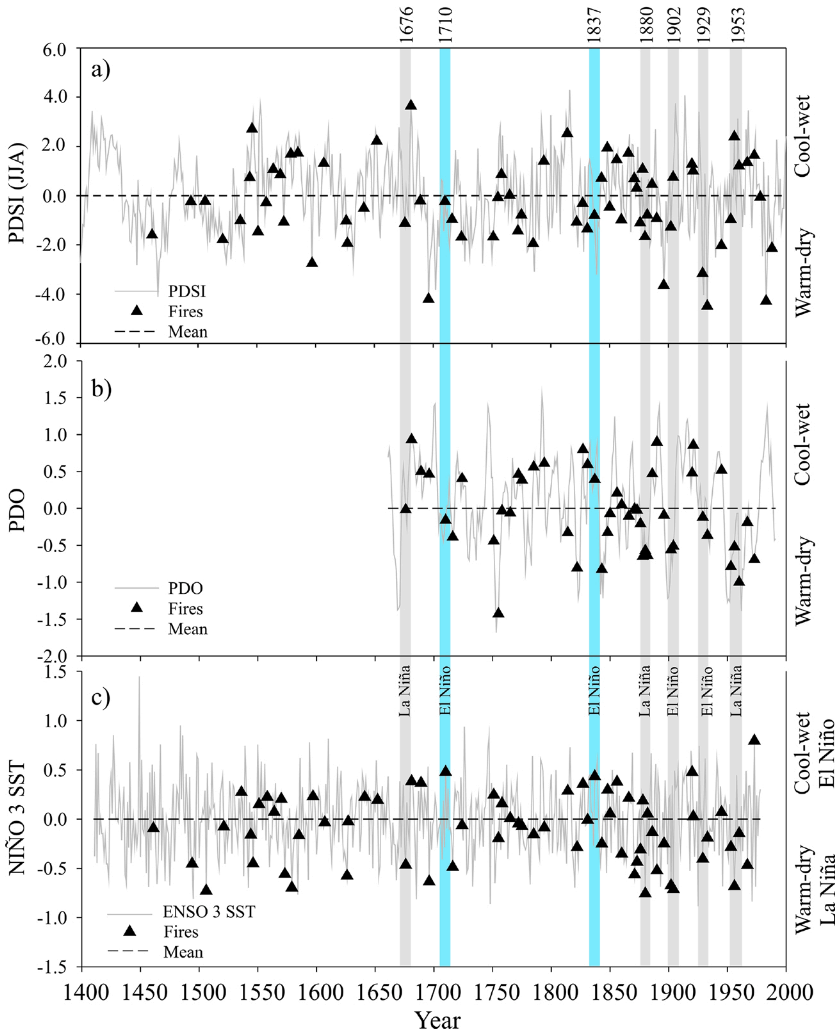

Fig. 8. Climate conditions during extensive fire years (triangles) in the Cofre de Perote National Park (67 fire years of 1400-2013). Local climate conditions are represented by (a) PDSI (JJA, Stahle et al., 2016), while broader climate conditions are represented by (b) PDO (Biondi et al., 2001) and (c) El Niño and La Niña (NIÑO 3 SST, Cook, 2000). The negative phase synchronization of ENSO and PDO is associated with severe drought conditions and the occurrence of fires nationwide, both in the El Niño and La Niña phases (gray lines). The light blue lines represent El Niño events with drought located in central and southern Mexico. Fire years are highlighted in both gray and blue and correspond to the years of fires indicated in the drought maps of Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

also northern Mexico, where high severity fires have been reconstructed (Cerano et al., 2010; Yocom et al., 2010). The 1998 El Niño is one of the most severe events in both central and southern Mexico (Fig. 9) (Rodríguez and Pyne, 1999). Although a 1998 fire was not recorded within our study area in the northwest side of the Cofre de Perote, the eastern part of the mountain was severely affected by a fire on that year (Lorenzo Vázquez-Selem, Geography Institute, UNAM, personal conversation). In fact, 19 % of the extensive fires occurred during El Niño (+N) and negative PDO (–P) phase combinations (Fig. 6) in our study area.

The positive relationship between fire occurrences and ENSO events in the cold La Niña phase and warm El Niño, have been noted both in *P. hartwegii* (Yocom and Fulé, 2012; Cerano et al., 2016) and *P. douglasiana* forests (Cerano et al., 2015) in the central region of Mexico. The results of our research in the CPNP confirm the significant influence of ENSO (El Niño and La Niña) on fire frequencies. Moreover, the synchrony of the negative phase (drought) of ENSO and PDO amplifies the spatial extent of La Niña events, facilitating droughts across a wider geographic area leading to favorable fire conditions throughout Mexico (Fig. 9). These results support our second research hypothesis, that historical fire frequencies in CPNP were significantly related to atmospheric phenomena of general circulation.

4.4. Fire regime changes

Previously reconstructed fire regimes elsewhere in high-elevation *P. hartwegii* forests (Yocom and Fulé, 2012; Cerano et al., 2016) in central Mexico, suggest these forest have had continuous fire frequency during the 20th century. Based on these prior studies we hypothesized an uninterrupted fire regimes and continued fire frequencies at CPNP. Our results, however, do not support this hypothesis, and instead suggest there have been drastic changes in fire frequencies, particularly after 1973 (Fig. 3). That is, our results show a clear change in the fire frequency after 1973 at all four sites in CPNP and a total cessation of fire within two sites (BH and VTH) (Fig. 3). In BH, fire frequencies started to change after 1933, with more extensive fires at longer fire (20-year) intervals (1933, 1953 and 1973). After 1973, the BH and VTH sites recorded only two (1978 and 2010) and three (1978, 1983 and 2010) fires, respectively. Each of these fires was recorded by only one tree, indicating these were localized fires that affected a very small area (Fig. 3). These results contrast with what has been reported for *P. hartwegii* forests in other areas of central Mexico, where uninterrupted fire frequencies have been reported during the 20th century (Yocom and Fulé, 2012; Cerano et al., 2016). Changes in fire frequencies after 1920, however have also been described in *P. hartwegii* forests in the Sierra Madre Oriental (Yocom et al., 2010).

According to historical archives locals exploited small portions of the high elevation forests in the CPNP, between 1870 and 1900 (Gerez, 1985). Agriculture and logging began after 1894 resulting in changes to the landscape. Clear cutting was mainly focused near sawmills; however, selective logging was practiced elsewhere (Zavala, 1977). By 1938, the negative effects of forest logging led the Mexican government to

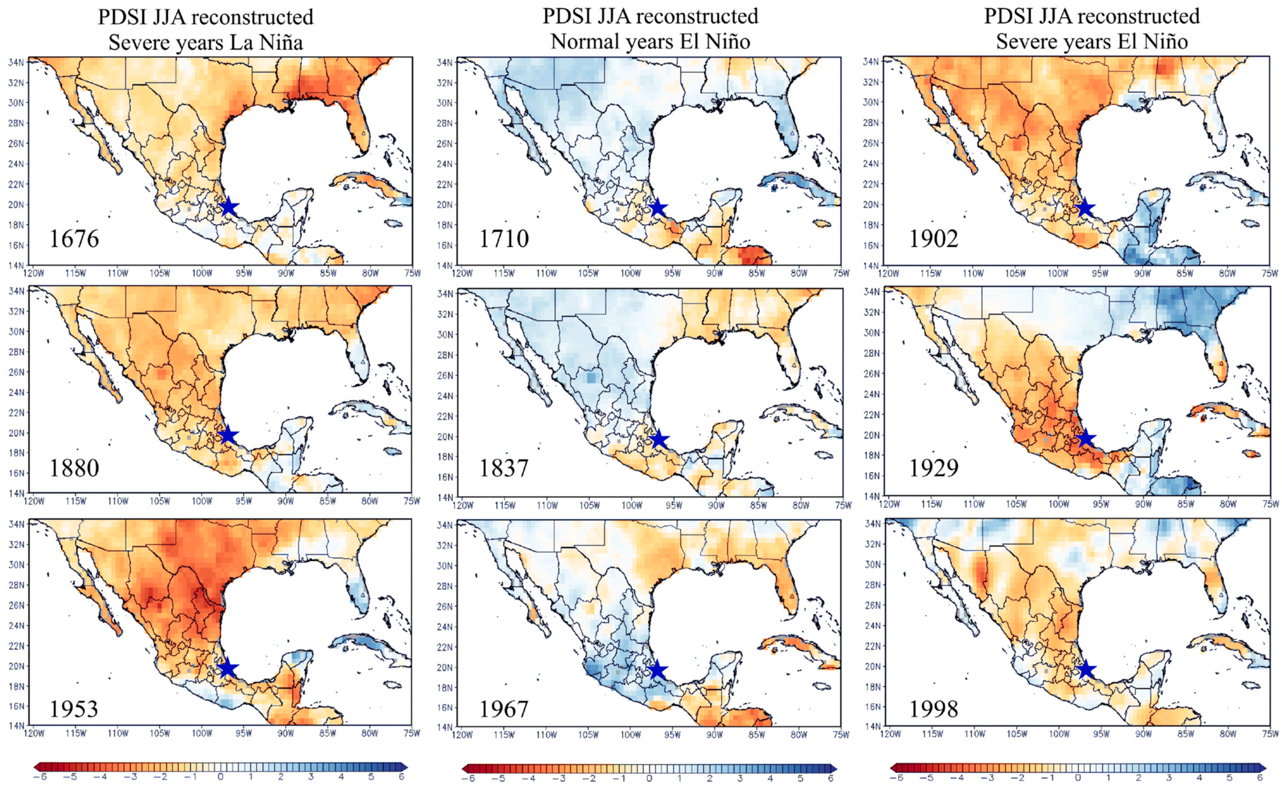

Fig. 9. Geographic extent and severity of drought conditions in Mexico (Stahle et al., 2016) during extensive fire years. The star symbol indicates the location of the study area. During severe La Niña events (left column) drought conditions are centered north of the study area but extend into central Mexico. While, during normal El Niño events (center column), drought conditions are generally focused in a smaller region of central Mexico. Severe El Niño events (right column), however are generally centered over our study area but have a larger spatial footprint and can extend into northern Mexico. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

declare the higher elevations (above 3000 m) areas of CPNP an Ecological Park, including lands endowed to the newly created ejidos. This declaration did not have the intended outcome and forest logging continued. In 1952, the Ministry of Agriculture and Development declared an indefinite logging ban throughout Mexico. In the CPNP officials were bribed by the loggers, who continued and even expanded timber-harvesting practices (Hoffman, 1989).

Following this failure, new forestry policies were initiated in the 1970s that regulated logging. These new policies, increased production with sustained yield and integrated forest owners in forest conservation, including technical assistance and government support (Jardel, 1986). These policies improved forest management and protection, including with the promotion of formal fire prevention and firefighting programs between 1964 and the 1970s in the Valley of Mexico. This ultimately led to the greater emphasis on fire suppression and is responsible for the lack of extensive fires in the last 40 years.

5. Management implications and conclusions

Fire regimes can be described as being controlled by either "bottom-up" (fuels) or "top-down" (climate) factors (Lertzman et al., 1998; Heyerdahl et al., 2001; Falk et al., 2007; Swetnam and Anderson, 2008; Conedera et al., 2009; Falk et al., 2010; Whitlock et al., 2010; Falk et al., 2011). In general, our study suggests that prior to 1973 the fire regime in CPNP were controlled by top-down processes given the significant relationship between climate (ENSO and PDO) and the occurrence of fires. Since 1973, the fire regime in CPNP is now controlled by bottom-up factors related to local human management. That is, despite the continuing climate related droughts, fires are no longer occurring because land managers are suppressing them. In general, more research is still needed regarding fire ecology in Mexican coniferous forests (Rodríguez and Fulé, 2003; Rodríguez, 2014). The absence of frequent fires, however could cause an increase in tree densities (Brown and Wu, 2005; Iniguez et al., 2016) and greater accumulation of fuels (leaves, grasses, shrubs and branches) (Fulé et al., 2005; Skinner et al., 2008), that could result in more severe stand-replacing fires. Such shifts have occurred in dry forests within the western U.S. and elsewhere. High severity fires, in turn, can also lead to loss of timber value, soil erosion, post-fire flooding and loss of ecosystem services including effects of water, recreation and deforestation. Given that these forests have not evolved with stand replacing fires, such events could threaten the sustainability of these forests and the ecosystems services they provide. This finding highlights the enormous impact forest management actions are having on biological processes and how these actions need to be better informed by scientific studies in order to avoid unintended consequences.

The novel climate-fire relationships, we found in this study, should also be incorporated as part of national fire tools and strategies that are currently being developed in Mexico. Given the strong relationship between climate and fire, managers can use climate monitoring information to potentially use fire as restoration and/or prepare for upcoming fire seasons based on climate patterns. Based on the results of our research and existing literature, we also encourage managers to whenever possible, restore the natural frequent surface fires regime in order to obtain ecological benefits and reduce the probability of stand-replacing fires (Pollet and Omi, 2002; Fulé et al., 2005). We encourage managers to consider the information on the historical fire regimes provided in this study and incorporate this information in the current objectives for the area and similar forests elsewhere. To ensure the long-term sustainability of these forests we encourage re-introducing fires gradually starting with small fires in each stand every 5–10 years in order to develop skills in fire management and create greater landscape fuel heterogeneity, thus reducing the risk or large high severity fires.

The results of this investigation will be relevant for park managers, who can use this information to justify the restoration and maintenance of historical fire regimes in the future. Such actions will ensure the conservation of the park's vast biological resources and hydrological services it provides to human settlements in this region. Future studies on forest structure are recommended to determine current fuel loads and to identify areas with greater fire danger, in order to achieve long-term conservation goals.

Declaration of Competing Interest

The authors report no declarations of interest.

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