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# Fire history and management of *Pinuscanariensis* forests on the western Canary Islands Archipelago, Spain

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ABSTRACT

Many studies report the history of fire in pine dominated forests but almost none have occurred on islands. The endemic Canary Islands pine (*Pinuscanariensis* C.Sm.), the main forest species of the island chain, possesses several fire resistant traits, but its historical fire patterns have not been studied. To understand the historical fire regimes we examined partial cross sections collected from fire-scarred *Pinuscanariensis* stands on three western islands. Using dendrochronological methods, the fire return interval (ca. 1850–2007) and fire seasonality were summarized. Fire-climate relationships, comparing years with high fire occurrence with tree-ring reconstructed indices of regional climate were also explored. Fire was once very frequent early in the tree-ring record, ranging from 2.5 to 4 years between fires, and because of the low incidence of lightning, this pattern was associated with human land use. After ca. 1960, the fire regime changed to a more widespread pattern at a lower frequency. Climate variability was not associated with widespread fires early in the fire record. After 1960, widespread fire years were significantly drier than normal while antecedent conditions were wetter. Over the last several decades fire suppression has essentially eliminated all but the largest, higher intensity wildfires, establishing a new fire regime. We suggest strategies that promote fire as a forest management tool to restore a fire regime consistent with historical patterns. Canary Island pine could be useful in management programs in fire prone environments of the world because of its fire trails (fire tolerance and sprouting ability).



## 1. Introduction

The importance of fire in influencing the structure and dynamics of most Mediterranean ecosystems is well known (Keeley et al., 2012). Fire influences essential ecosystem processes such as nutrient cycling, hydrological cycles, preparation of seed beds, and carbon sequestration. Understanding how fire regimes vary spatially and temporally is essential for understanding the long-term dynamics of forests (Swetnam, 1993), especially in an era of changing climates (Batllori et al., 2013). Fire can also disrupt forest plantations since most species planted world-wide (e.g. Monterey pine (*Pinus radiata*)) cannot survive severe fires. Better information on the range of fire regime parameters is important to help managers evaluate the ecological implications of proposed forest management strategies including those aimed at reducing the risk of high severity fire and conserving ecosystems.

Canary Island pine (*Pinus canariensis*) has been widely planted as an ornamental world-wide but is native to only five islands in the Canary Archipelago off northwest Africa: Tenerife, La Palma, El Hierro, La Gomera, and Gran Canaria. All islands of the Archipelago are of volcanic origin and volcanic activity spans 20 million years (Carracedo et al., 1999a, 1999b). Canary Island pine has one of the most restricted distributions of any of the >100 species of the genus *Pinus* (Parsons, 1981).

Canary Island pine has numerous traits related to fire effects and we separate them into three different groups (1) those life-history traits that are not only related to fire tolerance, such as longevity, (2) those related to the adults survival: thick bark, sprouting, etc., and (3) those that are related to post-fire recruitment, namely serotiny. Literature related to the adults survival after fire (thick bark, long needles, large buds, tall growth habit, deep rooting, sprouting capability) are discussed in Arévalo et al. (2001) and Fernandes et al. (2008). Sprouting capability of adult trees is one of the most striking characteristics of Canary Islands pine (Ceballos and Ortuño, 1976) (Fig. 1). The large accumulation of reserve carbohydrates in the sapwood parenchyma cells

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**Fig. 1.** Canary Island pine forests illustrating post-fire conditions: (A) plot D (see Table 1) where the last fire in 2005 consumed the lower crowns of live trees and resulted in scattered mortality of pine regeneration (note fire scarred tree in foreground); (B) and (C) are from plot G1, where crown fire resulted in prolific resprouting of adult trees and regeneration in the canopy gaps; and (D) plot G2 with large tree mortality and crown resprouting from crown fire in 2003.

explains its sprouting behavior (Climent et al., 1998). Otto et al. (2010) examined the mortality of mature Canary Island pines that experienced moderate to high severity fire and found zero tree mortality one-year post fire, even for the most severely burned area where crown fire had burned >70% of tree canopies. It also has serotinous cones that provide post-fire seed recruitment (Climent et al., 2004). This allows for post-fire recovery in the event of low survival or adult trees. As a result, Canary Island pine is one of the most resistant *Pinus* species to fire-induced mortality.

The indigenous people of the Canary Islands are the Guanche but there is little agreement on when they arrived from North Africa (Parsons, 1981). Human intervention on the Canary Islands has been particularly intense since the European colonization (XV-XVI centuries AD) although the use of fire by aborigines (I-XV centuries AD) is yet to be thoroughly investigated (Climent et al., 2004). From the Spanish establishment on the more mesic western islands beginning with Gran Canaria in 1477, the woodlands and forests were the object of intense exploitation (Parsons, 1981). Early after European settlement in the later XV century the cutting of trees near springs was prohibited and all forest fires were outlawed because of concerns of forest conservation.

There have been many uses of the Canary Islands forests over the centuries. Sugar manufacturing made the heaviest levies on the forests in the early years (Parsons, 1981). Tenerife and Gran Canaria each had twelve sugar mills in the 1560s, while La Palma had four and La Gomera had one. Pine needles (pinocha) sometimes mixed with heather, broom, and bracken fern (*Pteridium* sp.), provided the most important source of income from the forests of the Canary Islands over the centuries (Parsons, 1981). The peasant custom of collecting the fallen needles from the forest floor was recorded as early as the middle of the nineteenth century. The collection of pine needles was done for domestic animal bedding with increased intensity during and immediately after World War II and had all but exhausted existent supplies (Ceballos and Ortuño, 1976, cited in Parsons, 1981). With this actions, a significant portion of the surface fuels (the thick layer of long needles on the ground) were removed frequently for animal bedding use.

Little has been written about the fire regime of Canary Islands pine forests and if it has changed over the centuries. Climent et al. (2004) estimated that lightning ignited less than 0.5% of fires in the Canary Islands and Höllermann (2000) estimated 0.4% were lightning caused, with the great majority of current fires human caused. However, low frequency natural fires from lightning were probably still able to spread over large areas of steep mountainous country before European settlement because of continuous surface fuels in these forests (Höllermann, 2000). Despite the low frequency of natural fires in the Archipelago, fire is considered an important management tool (Arévalo et al., 2014a,b,c). Generally positive fire effects on understory species composition, soil nutrients, and regeneration have been reported from both prescribed fires and wildfires (e.g., Arévalo et al., 2001, 2014a, 2014b, 2014c; Otto et al., 2010; Irl et al., 2014).

The objectives of this study are to quantify fire regimes characteristics of the Canary Islands pine forests on three western islands

(Tenerife, La Palma, and El Hierro) using dendrochronological methods. Specific questions addressed are: (1) What are the fire return intervals and are they similar between islands? (2) What is the season of past fires? (3) Did fire frequency vary across time? (4) How might this study inform fire and forest management in these forests? As this is the first tree-ring based fire history study in the Canary Islands we believe its implications could have far-reaching effects in forest management on the islands and be of interest in other parts of the world.

## 2. Methods

### 2.1. Study area

The Canary Islands are a Spanish archipelago (Fig. 2) located just off the northwest coast of mainland Africa, 100 km west of the southern border of Morocco. The islands include (from largest to smallest): Tenerife, Fuerteventura, Gran Canaria, Lanzarote, La Palma, La Gomera, El Hierro, La Graciosa, Alegranza, Isla de Lobos, Montaña Clara and Roque del Oeste.

Canary Islands pine forests, in varying conditions and density, cover 70,000 ha in the archipelago (Parsons, 1981). On Tenerife, pines form a continuous belt around the island between 1200 and 1800 m, although scattered stands may occur down to sea level and upward to 2200 m. On the island of El Hierro, and especially on the more mesic La Palma, there are still impressive stands of old-growth pines, but on Gran Canaria such stands are sparse and scattered (Parsons, 1981). In La Gomera, two relevant natural remains of pine stands do exist (only 18 ha) and now this pine covers nearly 2300 ha. During the last decades (from 1980), new Canary pine plantations have been established and, more significant, agricultural abandonment has provided room for new pine stands at lower elevations in all islands with this pine species.

Precipitation in the Canary Islands is seasonal with a summer drought (Puyol et al., 2002). The natural distribution range of Canary Island pine includes sub-deserts with less than 250 mm of rain per year, dry pine forests on southern slopes (350–500 mm of rain), sub-tropical cloud forests with >600 mm of rain per year, and high mountain stands reaching timberline (1700–2100 m of altitude) where frosts and snow occur in winter (Climent et al., 2004). In wet areas pines form a high canopy over a dense understory of tree heather (*Erica arborea*) and laurel-like species (*Mirica faya* and *Laurus azorica*) (Climent et al., 2004). In contrast, more xeric areas dominated by pines contain sparse woody shrubs but include a thick layer of pine litter on the ground.

### 2.2. Fire scar sampling

Our goal was to collect multiple clusters of fire-scarred trees (3–9 trees) in relatively small areas to estimate fire regimes characteristics in Canary Island pine forests on Tenerife, La Palma, and El Hierro. We selected areas in intact, mature forests where a conservative sample of intact fire-scarred specimens were available for collection. Plots were small (i.e., 1–2 ha) located in uniform slope and stand structure. We located fire-scarred trees within plots by systematically searching throughout the forest stands (Swetnam and Baisan, 2003; Fulé et al., 2008). Trees may not record, or preserve, all fires that burned to the bole (Stephens et al., 2010); therefore, all fire-scar years within a plot were combined to form a composite fire record (Dieterich, 1980). The sampling strategy was intended to maximize the completeness of an inventory of fire dates, while also collecting samples that were spatially dispersed throughout the forests (Swetnam and Baisan, 2003; Fry and Stephens, 2006). These sampling methods have been shown to yield unbiased estimates of past fire frequency (Farris et al., 2010).

Wedges were extracted using a chainsaw from live trees, snags, logs, and stumps. Each wedge was sanded to distinguish tree rings and fire scars. Fire scars were identified by the disruption and healing pattern of tree ring growth associated with the injury (McBride, 1983). Calendar years were assigned to each fire scar by cross-dating rings using common dendrochronological techniques (Dieterich, 1980; Swetnam et al., 1985). Patterns of tree rings were compared to each other, to the recent fire database, and to published tree ring chronologies for Atlantic cedar (*Cedrus atlantica*) collected in Morocco, which was obtained from the International Tree-ring Data Bank (https://www.ncdc.noaa.gov/paleo/study/2931–2934, 4992–4993). The chronologies from Morocco were used because they are relatively close to the Canary Islands and they were one of the few chronologies available in this region.

The season of fire for each fire scar was determined by examining the intra-ring scar position (Caprio and Swetnam, 1995). Scar locations were identified as EE (early earlywood), ME (middle earlywood), LE (late earlywood), LW (latewood), D (dormant or ring boundary) or undetermined (Dieterich and Swetnam, 1984; Caprio and Swetnam, 1995) as an estimate of past fire seasonality.

### 2.3. Analysis

Fire-scar data was stored and analyzed using FHX2 software (Grissino-Mayer, 2001). Fire return intervals were determined for composites of tree groups (i.e., plots) and for each island (composite fire return interval (CFI)). The broad composite (C01) includes

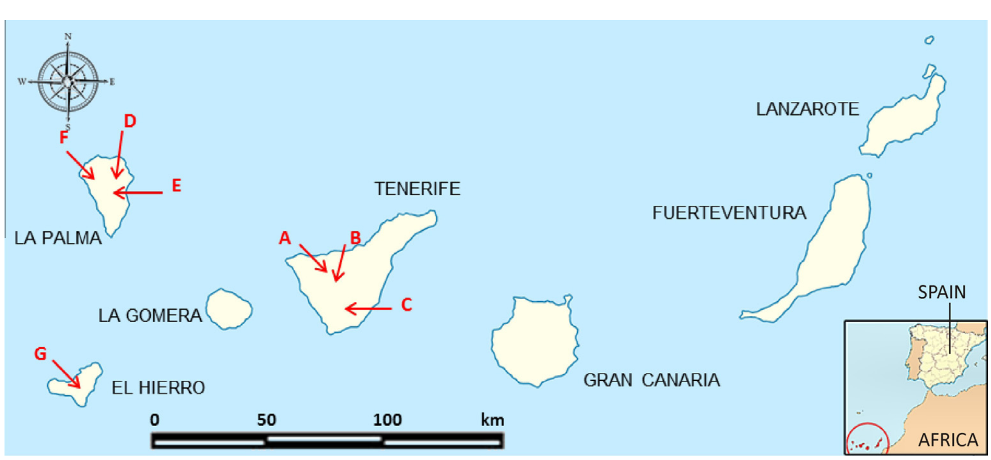


**Fig. 2.** Location of fire scar collections of *Pinuscanariensis* forest plots on three western islands of the Canary Island Archipelago.

all samples experiencing a fire scar. A more narrow composite (C25) includes fires that scarred a minimum of two trees and at least 25% of the recordable trees. Composites of multiple trees will often provide a more comprehensive record of fire events (Dieterich, 1980; Agee, 1993) since the composite filters (i.e., C25) removes relatively small fires (Swetnam and Baisan, 2003). A non-parametric Kruskal-Wallis test was used to determine if significant differences existed ($p < 0.05$) between plots, islands, or time periods (1850–1960 and 1960–2007) at each composite scale (C01 and C25). This time break period was chosen because of the change in pine needles (pinocha) collection intensity after World War II (Parsons, 1981), and effectiveness in fire suppression. If a significant difference was found, a Nemenyi test (non-parametric Tukey multiple comparisons test) was used to determine which plots or time periods differed ($p < 0.05$).

To identify the influence the interannual climate on fire, we used Superposed Epoch Analysis (SEA) to investigate whether climate conditions were significantly different ($p < 0.05$) between years preceding, during, and following (5-year span) high fire synchrony years (Grissino-Mayer, 2001; Swetnam and Baisan, 2003). Years with widespread fires (C25) were compared to three climate reconstruction indices: the summer North Atlantic Oscillation (NAO; Folland et al. (2009)), Palmer Drought Severity Index (PDSI; Wassenburg et al. (2013)), and El Niño/Southern Oscillation 3.4 (ENSO; Li et al. (2011)). NAO modulates the climate for much of Europe and North Africa (see discussion in García et al., 2001; Puyol et al., 2002); for the Canary Islands positive values are associated with drier than normal conditions and negative values are wetter than normal. Esper et al. (2007) used tree ring series from Morocco, northwest Africa, to reconstruct PDSI, which was updated by Wassenburg et al. (2013). We used the Li et al. (2011) tree-ring-width based reconstruction of the ENSO index derived from tree-ring chronologies from Asia, New Zealand, and North and South America. ENSO is the dominant mode of climate variability globally, and influences the pattern of precipitation on the Canary Islands (Puyol et al., 2002). In SEA, significant climate departures were those exceeding 95% confidence intervals determined by bootstrapping (1000 trials, Grissino-Mayer, 2001).

## 3. Results

A total of 68 fire scar samples were collected from 11 plots on the three western islands (Table 1, Fig. 2): 40 on Tenerife, 22 on La Palma, and 6 on El Hierro. Due to the paucity of dead wood in these forests the majority of scars were collected from live trees (76.5%), with the remainder from snags (2.9%), logs (16.2%), and stumps (4.4%). A total of 805 fire scars were assigned a calendar year, with the record spanning from 1709 to 2007. The average length of tree ring series was 169 years (SD 57.5 years, range 68–297 years). The average number of fire scars per sample was 11.8 (SD 5.2 scars, range 3–25 scars). Fire scar samples had a variable annual ring pattern; often with a few pinching rings successive to the fire year, but only proximal to the scar lesion.

**Table 1**
Characteristics of fire-scarred samples for all plots in Canary Islands pine forests (fire recorded from 1709 to 2007).

| Plot | No. samples | No. fire scars | Moisture type |
|---|---|---|---|
| *Tenerife* | | | |
| A1 | 7 | 49 | Mesic |
| A2 | 8 | 76 | Mesic |
| A3 | 6 | 83 | Mesic |
| B | 8 | 93 | Mesic |
| C1 | 2 | 14 | Xeric |
| C2 | 9 | 107 | Xeric |
| *La Palma* | | | |
| D | 11 | 169 | Mesic |
| E | 5 | 72 | Mesic |
| F | 6 | 70 | Xeric |
| *El Hierro* | | | |
| G1 | 2 | 21 | Xeric |
| G2 | 4 | 51 | Xeric |

### *3.1. Fire return intervals*

Fires were found to have been very frequent early in the fire-scar record (Fig. 3). Although the earliest recorded fire was in 1709, there were limited fire scars available in the 18th and early 19th centuries. The initial year for fire return interval analysis was chosen as 1850 based on visual inspection of the composite scar chronology and lack of a large number of samples prior to that date (Fig. 3). For plots, there was a significant difference between CFIs for C01 (K-W test statistic = 71.103, $p < 0.000$, df = 10) and C25 (K-W test statistic = 29.721, $p < 0.000$, df = 9) (Table 2). CFI for Tenerife C1 was higher than other plots on Tenerife, which was likely due to the small sample size and lack of recent fire evidence resulting in the relatively large fire intervals. Both plots on El Hierro had consistently higher CFI's compared to the other of the plots on the other islands (Table 3).

The average CFI for all fires (C01) for Tenerife, La Palma, and El Hierro was 1.4 years (median 1.0 years, range 1–9 years), 1.7 years (median 1.0 years, range 1–11 years) and 5.3 years (median 4.0 years, range 1–20 years), respectively. For larger scale fires (C25), the average CFI was 11.2 years (median 4.5 years, range 1–64 years), 15.2 years (median 13.0 years, range 2–42 years), and 10.2 years (median 7.0 years, range 1–45 years) for Tenerife, La Palma, and El Hierro, respectively. The number of small fires decreased dramatically after ca. 1960, the cutoff for the pre-suppression (1850–1960) and current (1960–2007) time periods. After 1960, the mean CFI increased for both composites (C01 and C25), except for El Hierro, where the mean decreased (Tables 1 and 3).

### *3.2. Season of fires*

The position of fire scars within annual growth rings, which infers fire season, was determined for 65% of the scars. Fires burned mainly late in the growing season (latewood = 36.5%) and after trees had stopped growth for the year (dormant = 27.7%) (Fig. 4). For early growing season fire scars, 2.1% were found in the first third of the early-wood, 7.4% in the middle third of the early-wood, and 26.2% in the last third of the early-wood. After 1960 there was a shift towards preponderance of late season fires, across all islands, although the sample size was smaller.

### *3.3. Fire-climate relationship*

SEA of the climate indices with widespread fire years (combined C25 from all three islands) were not significantly correlated ($p > 0.05$, graphs not shown) to climate indices early in the fire record (1850–1960). After 1960, widespread fire years were associated with negative PDSI, indicating drier than average conditions, and prior to widespread fire years, fires were associated with positive values of ENSO ($p < 0.05$, Fig. 5).

## 4. Discussion

Fire frequency was very high on Tenerife and La Palma before 1960, after this period fires burned at lower frequency and fire events were more synchronized (Fig. 3). Using all fire scar samples (C01), the fire return interval in our plots on Tenerife and La Palma

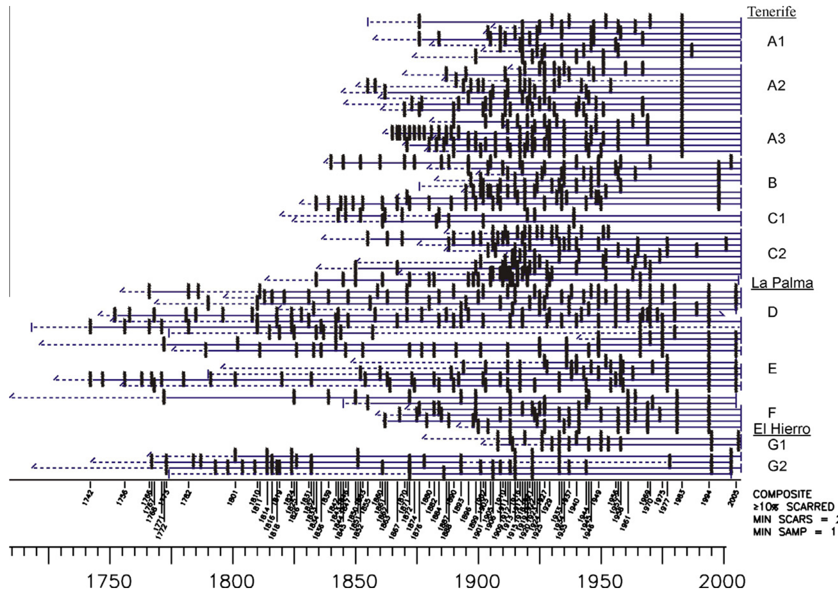


**Fig. 3.** Composite fire activity of Canary Islands pine forests on three of the western islands. Horizontal lines represent the age of each fire scar sample, with the vertical lines representing fire events. Dash lines indicate null (non-recorder) years. The list of years at the bottom represents the composite (scarring more than 10% of the samples and at least two trees) for all samples.

**Table 2**
Composite fire return interval data (years) for all plots in Canary Islands pine forests (1850–2007). C01 includes all fire scars and C25 includes fire scarring two or more trees and at least 25% of recording samples. Within each composite, means followed by different letters are significantly different ($p < 0.05$) between plots.

| Plot | Composite | No. intervals | Mean | Median | Range |
|---|---|---|---|---|---|
| *Tenerife* | | | | | |
| A1 | C01 | 33 | 4.0a | 3.0 | 1–20 |
| | C25 | 9 | 14.6b | 10.0 | 1–33 |
| A2 | C01 | 50 | 3.0a | 2.0 | 1–24 |
| | C25 | 15 | 7.0a | 4.0 | 1–24 |
| A3 | C01 | 47 | 3.0a | 2.0 | 1–24 |
| | C25 | 20 | 6.0a | 4.0 | 1–24 |
| B | C01 | 57 | 2.7a | 1.0 | 1–28 |
| | C25 | 20 | 5.6a | 3.0 | 1–40 |
| C1 | C01 | 11 | 14.1b | 9.0 | 1–68 |
| | C25 | – | – | – | – |
| C2 | C01 | 64 | 2.5a | 1.0 | 1–12 |
| | C25 | 15 | 10.5ab | 3.0 | 1–74 |
| *La Palma* | | | | | |
| D | C01 | 57 | 2.7a | 2.0 | 1–11 |
| | C25 | 24 | 5.7a | 5.0 | 1–14 |
| E | C01 | 39 | 4.0a | 3.0 | 1–17 |
| | C25 | 12 | 8.7ab | 7.0 | 1–18 |
| F | C01 | 40 | 3.9a | 3.5 | 1–13 |
| | C25 | 11 | 9.8ab | 12.0 | 3–16 |
| *El Hierro* | | | | | |
| G1 | C01 | 15 | 6.6c | 5.0 | 1–37 |
| | C25 | 6 | 16.5b | 14.0 | 1–45 |
| G2 | C01 | 18 | 8.7c | 7.0 | 2–34 |
| | C25 | 9 | 17.3bc | 11.0 | 4–62 |

was approximately 2.5–4 years (minimum 30 intervals; Table 1) which is one of the shortest reported in the literature. Fire return intervals on El Hierro were longer partially because of a smaller sample size and the more xeric conditions in its pine forests. More synchronous fires have burned recently and they are a challenge to managers since they can spread over large areas that include homes and other developed infrastructure.

A few fire history studies across the world have also found similar high fire frequencies including in longleaf pine (*Pinus palustris*) forests in the southeast USA (Stambaugh et al., 2011), ponderosa pine (*Pinus ponderosa*) forests in the southwest USA (Dieterich, 1980; Van Horne and Fulé, 2006), and in a mixed pine-oak forest in the Sierra Madre Occidental in north-central Mexico (Fulé et al., 2011). The mean fire return interval in longleaf pine forests for the period 1650–1905 was 2.2 years and there was evidence for years of biannual burning (Stambaugh et al., 2011). Mean fire return intervals in ponderosa pine forests in north-central Arizona were approximately 2 years (Dieterich, 1980; Van Horne and Fulé, 2006) and in Chihuahua, Mexico, Fulé et al. (2011) found very frequent fire (fire return intervals of approximately 2 year) in a mixed pine-oak forest that still included an indigenous (native peoples who continue to manage these lands) fire regime.

With a low incidence of lightning ignited fires in the Canary Islands (Höllermann, 2000; Climent et al., 2004), the vast majority

**Table 3**
Composite fire return interval data (years) by time period in Canary Islands pine forests. C01 includes all fire scars and C25 includes fire scarring two or more trees and at least 25% of recording samples.

| Site | Composite | Period | No. intervals | Mean | Median | Range |
|---|---|---|---|---|---|---|
| Tenerife | C01 | 1850–1960 | 98 | 1.1 (0.4) | 1.0 | 1–3 |
| | | 1960–2007 | 18 | 2.6 (2.2) | 2.0 | 1–9 |
| | C25 | 1850–1960 | 10 | 11.0 (16.4) | 3.5 | 1–43 |
| | | 1960–2007 | 1 | – | – | – |
| La Palma | C01 | 1850–1960 | 80 | 1.4 (0.8) | 1.0 | 1–5 |
| | | 1960–2007 | 17 | 2.7 (2.7) | 2.0 | 1–11 |
| | C25 | 1850–1960 | 2 | – | – | – |
| | | 1960–2007 | 5 | 9.2 (5.1) | 11.0 | 2–14 |
| El Hierro | C01 | 1850–1960 | 25 | 4.4 (2.7) | 4.0 | 1–11 |
| | | 1960–2007 | 4 | 7.3 (7.1) | 5.5 | 1–17 |
| | C25 | 1850–1960 | 16 | 6.8 (3.2) | 7.0 | 2–13 |
| | | 1960–2007 | 3 | 4.0 (3.6) | 3.0 | 1–8 |

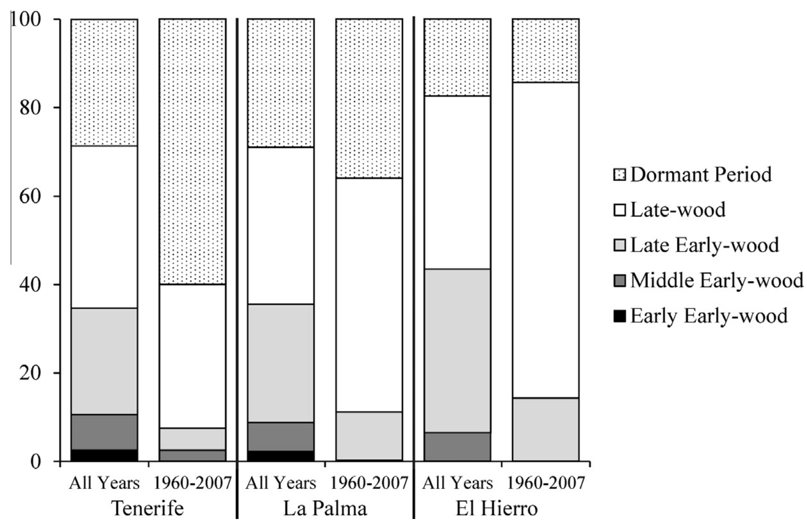


**Fig. 4.** Percent intra-annual tree ring position of *Pinuscanariensis* fire scars, by time period (all years = 1709–2007). A total of 76 samples were collected from three islands.

of the fires recorded in this study must be human-caused. Fires were once commonly used to manage adjacent agricultural lands and to increase forage for livestock. Many of these fires probably spread into forests and were recorded in our fire history plots. High fire frequency kept surface fuel loads low and this probably limited fire size, especially before 1960. Using short-interval prescribed fire could reduce the opportunity for large fires in the Islands.

The average fire return interval nearly doubled in the latter half of the 20th century. The increased harvest of pine needle litter after World War II (Parsons, 1981) probably produced the change in fire regimes seen in Fig. 3 in approximately 1960–1970. The long needles of Canary Island pine produce a highly flammable litter layer that is the main fuel for fire spread. Removing the litter increased the fire return interval. Fuel accumulation would then have increased because of decreased litter harvest, which combined with effective fire suppression shifted the fire distribution to larger or more intense fires. Other reasons for decreased fire frequency in the later part of the 20th century include increased use of kerosene for heating versus charcoal and firewood and fire-prevention programs that became more effective in the 1970s (Parsons, 1981).

Pausas and Fernández-Muñoz (2012) also found a change in fire regimes in the Mediterranean Basin after the 1970s. Before this decade (since 1850), there were many small fires that affected only small areas. However, after the 1970s, fires were larger, affecting more area and scarring many more trees. Abandonment of livestock and agriculture is the main cause of an increased fuel loads in this region (Millán et al., 1998). Fuel homogeneity and continuity are major facilitators of both a larger fires and higher fire line intensity (Vega-Garcia and Chuvieco, 2006). The impact of fire in the recruitment dynamics and in the entire ecosystem has been found (Rozas et al., 2013).

Canary Island pine is an excellent species to record fire scars because of its ability to survive almost all fires. Other commonly used species used in fire scar studies such as ponderosa pine and giant sequoia (*Sequoiadendron giganteumin*) can survive high levels of crown damage (Stephens and Finney, 2002) but cannot recover from severe fire similarly to Canary Island pine. Sprouting is a general trait in Canary Island pine and it occurs extensively after severe fire (Fig. 1). Epicormic shoots with juvenile leaves appear in abundance after crown scorching and allow the affected pine canopies to recover in just a few years (Climent et al., 2004). The fire stimulated resprouting begins about three months after high severity fire (Höllermann, 2000), which is also found in coast redwood (*Sequoia sempervirens*) after high intensity fire (Finney and Martin, 1993). After 2–3 years it is difficult to see evidence of past fire as the entire Canary Island pine tree crown has commonly regrown.

The intraring position of the fire scars lends insight to the seasonality of fires (Caprio and Swetnam, 1995). In this study, over half of the scars in which location was determined were in the late-wood portion of the annual ring and during the dormant period (i.e., ring boundary). The exact position of the intraring scar location relative to season has not been directly assessed for Canary Island pine; based on the recent fire database, fires occurring in

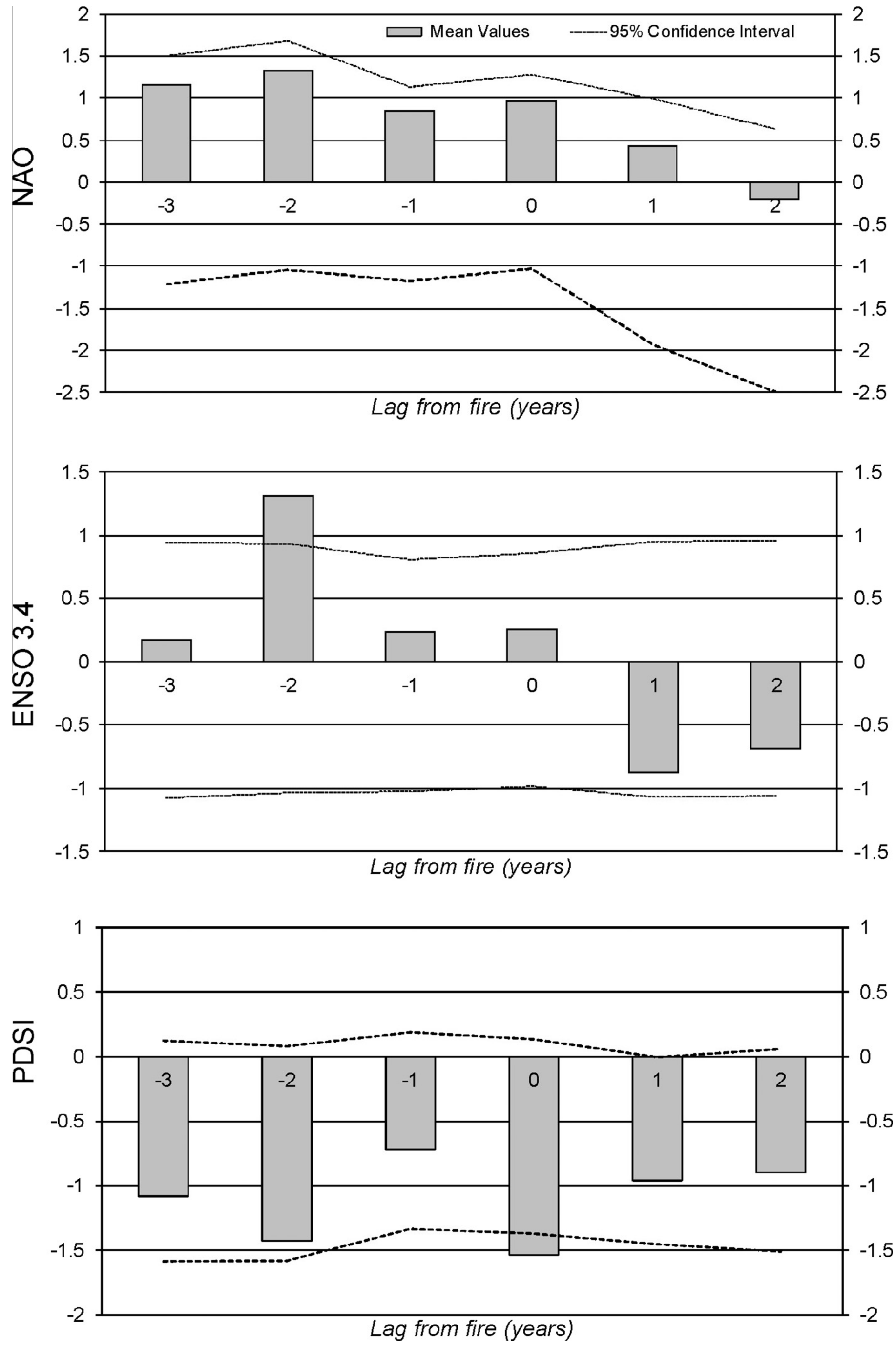


**Fig. 5.** Superposed epoch analysis (SEA) of climate variability with years preceding, following, and during (lag year = 0) widespread fire years in the post-suppression period (1960–2007). PDSI, Palmer Drought Severity Index; ENSO 3.4, El Niño/southern Oscillation index 3.4; NAO, North Atlantic Oscillation. Confidence intervals are based on 1000 Monte Carlo simulations.

July to September were predominately latewood scars. The proportion of late-season fires increased in the recent period (1960–2007) which may be due to the effectiveness of fire suppression agencies, especially in early season fires where fire behavior may be mitigated due to higher fuel moistures and favorable weather conditions. Fulé et al. (2008) found a preponderance of dormant period fire scars (76%) in old-growth *Pinus nigra* forest in eastern Spain. Farther south, fire scars in Atlantic cedar forests in northern Algeria were predominately in the latewood portion (70–76%) of the annual ring (Slimani et al., 2014). Latitudinal gradients in fire seasonality- the proportion of early season scars decreasing with an increase in latitude- has been identified in frequent-fire conifer forests in western North America (Brown and Shepperd, 2001; Skinner et al., 2008). While a similar pattern is apparent in this research, additional studies are needed to ascertain intraring scarring position relationships in this region. In contrast, Touchan et al. (2012) studied fire history in European black pine (*Pinus nigra Arn.*) forests in Greece and determined that all the fires occurred during the period of active tree growth.

The fire resistance of Canary Island pine varies within its native range. Thick bark (unpublished forestry inventories, D. Molina personal communication, 9-4-16) provenances of this species coincide with moderately to highly productive areas where fires have been frequent and intense over the last decades. Conversely, thin-barked individuals occur in dry areas where most pine stands are sparse, understory is scarce or null, and fires burn solely the litter layer (such as on El Hierro). The poor relationship between bark thickness and other dendrometrical variables (age or xylem radius) suggests an adaptive response related to fire regimes rather than a consequence of stand growth (Climent et al., 2004). A similar relationship was found in Monterey pine populations in California and Mexico subject to different levels of anthropogenic fire that influenced tree bark thickness (Stephens and Libby, 2006). The use of thick bark Canary Island pine populations in forest plantations could be an advantage, especially in areas where large, high severity fires are burning pine plantations in Australia, Chile, and South Africa. More work on the breeding of desirable plantation traits is needed for Canary Island pine but they would be able to resprout from severe fire whereas Monterey pine, maritime pine (*Pinus pinaster*) and other common plantation species cannot. Care would have to be taken to only plant Canary Island pine in areas already developed for plantations (to reduce the area dominated by non-native species) and in climates that are favorable to it.

Fire–climate relationships were analyzed by period because fire pattern changed ca. 1960 to a less frequent regime. The influence of land use and management on fire-climate dynamics has been depicted in frequent-fire conifer forests in western North America (e.g., Fry and Stephens, 2006; Skinner et al., 2009; Margolis and Swetnam, 2013). Early in the fire record, the years preceding, following, or during widespread fire years were not significantly correlated with seasonal to annual drought conditions as depicted with PDSI. This same result also applied to interannual climate variability patterns in NAO and ENSO. This is surprising since annual rainfall is highly correlated among the three islands (Puyol et al., 2002), and annual rainfall is moderately correlated with winter NAO (García et al., 2001; Puyol et al., 2002). Characteristic annual summer drought on the western Canary Islands may facilitate conditions for large fire years once fuels have accumulated regardless of immediate, regional climatic fluctuations. Local factors such as precipitation from fog (Marzol et al., 2011) and frequent ignitions from human, may override or confound the influence of regional-scale climate (see Keeley et al., 2012). Conversely, widespread fires considered at the spatial scale of our study area may be decoupled from landscape-fire incidence, and deciphering these signals may require additional sources of evidence (e.g., Colombaroli and Tinner, 2013).

After 1960, annual to seasonal drought conditions (low PDSI) were related to years when fires were widespread in the study areas as measured by the higher percentage of trees scarred. Our findings agree with Sarris et al. (2014) where recent large fire years in *Pinus nigra-Abies cephalonica* forests in southern Greece coincided with below normal precipitation. In the Canary Islands, this pattern of drier conditions coupled to recent larger fires would be expected if fire suppression policies were effective at suppressing most fires under low-moderate weather conditions. Additionally, two years preceding more recent widespread fire years were associated with above normal ENSO conditions. This suggests extended periods of drier than normal conditions are a precursor to the recent large wildfires on the Canary Islands. Both Fulé et al. (2008) and Slimani et al. (2014), from eastern Spain and northern Algeria, respectively, did not find a correlation between drought conditions and fires. Their explanation, similar to ours for the lack of correlation between fires and ENSO early in the scar record, was that frequent ignitions associated with human land use may have been the predominant influence. ENSO has a multiscale influence on fire regimes in conifer forests in the western North America (discussed in Yocom et al., 2010); generally widespread fire years have been associated with warmer and drier than normal conditions. However, the overriding influence of ENSO variability on fire regimes is complex, and this relationship may be modulated by interactions with other climate-forcing mechanisms (Margolis and Swetnam, 2013), and by the location of the forest relative to the ENSO dipole (see Fry and Stephens, 2006; Yocom et al., 2010).

In the last few decades there has been increased interest in the restoration of Canary Island pine forests. It has been recognized that the extensive degradation of native Canary Island forests and woodlands was not a matter of fire impact, but was due to detrimental land use practices and heavy wood exploitation in the past (Höllermann, 2000). Wildfire activity has increased in recent years on the islands, and in the last 50 years, a total of 20,000 ha of pine forest have been burned on Tenerife. Because the total pine forest in Tenerife is >40,000 ha (del Arco et al., 1992), the amount of fire could be considered lower than expected in an ecosystem with a high adaptation to fire (Arévalo et al., 2001). The low number of fires in some areas of the pine forest of Tenerife has slowed restoration (Arévalo et al., 2001). Human activities have increased the rate of fire but only locally and fires today affect a relatively small area of the pine forest (Höllermann, 2000).

It has been suggested that regular fires at intervals <20 years would favor and accelerate the restoration of the Canary Islands pine forests (Arévalo et al., 2001), with minimal impact to soil nutrient composition, understory species composition, and regeneration (e.g., Arévalo et al., 2001, 2014c; Méndez et al., 2015). Our fire history information complements this view but we recommend using a variable fire return interval when using prescribed fire in these forests. Fire was once a very common process in the Canary Island pine forests on Tenerife and La Palma, and probably in other areas of its native range except in the most xeric locations. While the vast majority of the fires are ignited by people a fire regime of predominantly low intensity fires every 5–15 years would be an improvement over the current fire regime. Furthermore, understanding long-term forest dynamics in relation to variation in fire regime attributes such as frequency, seasonality, and severity (see Otto et al., 2010) will provide guidance on the appropriate use of fire as a management tool.

Fire suppression resources on the islands could concentrate their resources on protecting properties and assets rather than on the more remote areas of Canary Island pine forests. In the recent decades, more productive sites (characterized by a high sapwood area per hectare) have suffered more frequent and intense fires (Climent et al., 2004). These areas could be prioritized for prescribed fire treatments to re-introduce the fundamental ecosystem process back into these forests and to help reduce high intensity fire and potential damage to adjacent human resources.

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