INFLUENCE OF CLIMATE AND LOCAL FACTORS ON FIRE IN HIGH-ELEVATION FORESTS OF MEXICO

By Larissa L. Yocom

A Dissertation

Submitted in Partial Fulfillment

of the Requirements for the Degree of

Doctor of Philosophy

in Forest Science

Northern Arizona University

May 2011

Approved:

Peter Z. Fulé, Ph.D., Chair

Peter M. Brown, Ph.D.

Thomas E. Kolb, Ph.D.

R. Scott Anderson, Ph.D.

UMI Number: 3467055

ABSTRACT

INFLUENCE OF CLIMATE AND LOCAL FACTORS ON FIRE
IN HIGH-ELEVATION FORESTS OF MEXICO

LARISSA YOCOM

Factors that affect fire occurrence operate on a continuum of scale, from fine-scale microsite variation in topography, fuels, ignitions, and weather to broad-scale global climate oscillations. Fine-scale factors interrupt fire synchrony across landscapes, while broad-scale factors synchronize fire across landscapes and even continents. This dissertation assesses the influence of fine-scale and broad-scale factors on fire occurrence in eastern and northern Mexico.

At Peña Nevada in northeastern Mexico, a temporal change occurred in the association between the broad-scale climatic factor El Niño Southern Oscillation (ENSO) and fires; before the 1830s La Niña events were significantly associated with fire years, while after the 1830s this association was not significant. This result suggests that ENSO effects have changed over time in this location and that phases of ENSO are not consistent indicators of precipitation, fire occurrence, or fire behavior in this part of Mexico.

At the northern end of the Sierra Madre Oriental in northeastern Mexico, three parallel mountain ranges were chosen to distinguish the influence of broad-scale vs. fine-scale factors. The mountain ranges received nearly identical broad-scale climatic

influence, but spread of fire between the ranges was unlikely. Broad-scale control would be indicated by high fire synchrony among mountains while fine-scale control would be indicated by asynchrony in fire occurrence. Fires were asynchronous among mountains, indicating a strong influence of fine-scale factors on fire occurrence.

In southeastern Mexico, Pico de Orizaba is North America's third-tallest peak. In 1975, researchers reported that increased human-caused burning was degrading the forests in this location. We investigated the fire regime and forest structure in this area and found that in the twentieth century a fire was recorded in at least one of six sites in 90 of 100 years; this very frequent surface fire regime consisted of mostly small and asynchronous fires. Inter-annual climatic variability was not an influential driver of fire, and no evidence of forest degradation was found in the research plots. A trend in the 21st century toward decreased fire could be cause for concern, as this could lead to an increase in tree density and a loss of resilience in the face of climate change and other future disturbance.

Finally, the influence of climate on the occurrence of fire across northern Mexico was assessed using a network of 52 sites in 5 regions in the Sierra San Pedro Mártir, the Sierra Madre Occidental, and the Sierra Madre Oriental. Across-region synchronous fires in northern Mexico were significantly associated with negative (La Niña) phases of ENSO and cool phases of the Pacific Decadal Oscillation (PDO). Although climate was a strong driver of fires historically and through the twentieth century at some sites, dates of fire regime interruption across northern Mexico were highly variable within and among regions. This result suggests that human land use change is the strong driver of fire regime interruption, and climate played little or no role in the widespread cessation of fire across much of western North America in the nineteenth and twentieth centuries.

In summary, this dissertation showed that both broad-scale and fine-scale factors influenced the occurrence of fire in eastern and northern Mexico, and many factors that affect fire occurrence cannot be disentangled. Understanding the historical influence of climate variability on fire occurrence may help us understand how future climate change will affect fire activity in western North America.

ACKNOWLEDGMENTS

This dissertation would not have been possible without the assistance and support I have received from professors, colleagues, staff, fellow graduate students, friends and family.

I would like to first thank my major professor, Pete Fulé, for the opportunity to work on this project and the unwavering support along the way. Pete has been a mentor, a colleague, and a friend, and I am truly grateful for the support and encouragement he has given me.

I would also like to thank the other members of my committee: Scott Anderson, Peter Brown, and Tom Kolb. All of my committee members were thoughtful and helpful, and this dissertation has been improved by their guidance and constructive comments.

The co-PIs on the grant that funded this research were wonderful colleagues and I learned a great deal from each of them. Besides Pete Fulé, I had the opportunity to work with Don Falk, Peter Brown, José Villanueva-Díaz, and Eladio Cornejo-Oviedo. Each of them is an excellent scientist with good ideas and has been helpful through the past few years. Julián Cerano, Vicenta Constante García, and Citlali Cortés Montaño were also knowledgeable colleagues.

Many people helped in the field or gave permission to work in various parts of Mexico, and I am grateful to all of them. I thank Davíd Medellín and Ejido La Encantada for permission to work on Peña Nevada, local ejidos in the northern Sierra Madre Oriental for permission to work on their land, and Pico de Orizaba National Park for permission to work in the park. Armando Becvort, Erica Bigio, Julián Charles, Rafaél de

Jesús Amador, Cameron Fulé, Oscar Hernandez de la Torre, Gustavo Medellín Pérez, Osvaldo Turlán Medina, Conrado Vasquez García, and Iván Zamudio were excellent assistants in the field.

Several people at the Ecological Restoration Institute were enormously helpful to this project. Don Normandin helped me learn what I needed to learn in the woodshop and has been a kind friend over the years. Walker Chancellor joined the team on several trips to Mexico and was a consistently cheerful, helpful presence. Scott Curran was always available for database help. Joe Crouse assisted in providing maps for the project. Linsey Baker helped me with so many administrative tasks over the years; she saved me dozens of hours and I thank her for that.

Several NAU undergraduate students were invaluable to this project, especially Christen Irby and Isaac Bickford. Both of them had a great sense of humor, were easy to spend long hours with in our travels south of the border, and worked hard. I am also thankful for help from Ian Hyp, Charles Machula, Cat McGowan, and Megan Nasto, who measured thousands of tree rings. Many others helped with sanding and other woodshop jobs; I am grateful to every one of them for their assistance.

Rachel Sheridan has helped tremendously in the lab and I appreciate her interest in the project. I also thank Celia García-Domínguez, who joined us for a sampling trip and worked on samples in the lab.

I would like to thank Katie Ireland and Amanda Stan for helping me a great deal by reading chapter after chapter; they provided great comments and I owe them a lot. My lab group and office mates were a consistent source of encouragement, humor, and support- particularly Hondo Brisbin, Brian Brost, Valerie Kurth, Donna Peppin, Rachel Sheridan, and Kristen Shive.

My family has been encouraging and supportive my whole life and I thank them so much for everything. My parents, Laura and Larry Yocom, my sister Gretchen Callison, my brother Chris Yocom, and my niece Sofia: thank you!

Finally, I would like to thank Keith Kent for his tremendous support, interest, and understanding. He was also a natural with the increment borer.

This dissertation was supported financially by a National Science Foundation grant (DEB-0640351), a National Science Foundation Doctoral Dissertation Enhancement Project grant (OISE- 1003845), and the Ecological Restoration Institute at Northern Arizona University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

This dissertation has been prepared in journal format. Consequently, there is some redundancy among the chapters. Chapter 2 is entitled "El Niño-Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time" and was published in *Ecology* in 2010. Chapters 3 through 5 will be submitted to journals for publication in the coming months. Because each chapter has been or will be published with co-authors, the pronoun "we" is used throughout the dissertation.

CHAPTER 1: INTRODUCTION

Factors that affect fire occurrence operate on a continuum of scale, from fine-scale microsite variation in topography, fuels, ignitions, and weather to broad-scale global climate oscillations. Fine-scale factors interrupt fire synchrony across landscapes, while broad-scale factors synchronize fire across landscapes and even continents. This dissertation is focused on the fine-scale and broad-scale factors that influence fire occurrence in eastern and northern Mexico.

The occurrence of synchronous, large wildfires over large areas of the western United States has been linked with large-scale climatic oscillations such as the El Niño-Southern Oscillation (ENSO). However, local factors such as fuel availability, ignitions, and topography influence the occurrence of fire as well. For example, ignitions, both natural and human, vary over space and time with probability of lightning strikes, proximity to human settlements, and variation in human land and fire use. Understanding the relative influence of broad-scale and fine-scale factors and at what scale they operate is important not only for our understanding of major ecological processes, but also for management reasons. For example, prescribed burning and thinning, which are practices designed to reduce fuel and therefore the risk of catastrophic fire, may be of little value if regional climate is the main determinant of widespread fire. In addition, a better understanding of how climate influences the occurrence of wildfire will help us look toward the future in an era of global climate change.

In the United States, several studies have linked climate and fire at the regional level. However, the large influence that humans have had on fire in the twentieth century through fire suppression, timber extraction, and livestock grazing make the patterns linking climate and fire difficult to assess in the past several decades. In Mexico, less is known about how climate affects fire. Mexico offers a unique opportunity to study the relationship between climate and fire in recent years since sites exist where fire regimes have not been completely interrupted by human land use, timber cutting, or fire suppression.

The first theme addressed in the dissertation is change in a climate driver of fire occurrence over time. Before the 1830s at Peña Nevada in eastern Mexico, La Niña events were significantly associated with fire occurrence. After the 1830s, neither La Niña nor El Niño was associated with fire and in recent decades, both extreme La Niña and extreme El Niño events, such as the extreme El Niño of 1998, have been associated with fire occurrence.

The next chapter was designed to test broad-scale and fine-scale influences on fire in a region of eastern Mexico. This chapter is focused on synchrony among mountain ranges that receive the same meso-scale climatic inputs due to their close proximity to each other. However, fires would be unlikely to spread between these mountain ranges because of the unique topography in the area, consisting of high mountain peaks separated by deep valleys. Fire synchrony among the three mountains was very low, and suggests that fine-scale factors are important in driving fire occurrence at this scale. Fine-scale factors that are likely important in this region include topography, ignitions, dominant tree species, and human land use; these fine-scale factors are inter-related.

The fourth chapter focuses on a site in central Mexico with very frequent fire and little influence from inter-annual climatic variability. This chapter describes the fire regime of a timberline forest in central Mexico, and is the first fire history study in the region of Mexico where El Niño events are typically associated with below-average precipitation. Fire in the study area was very frequent over the past century, but fires were unassociated with ENSO events. This area has most likely been heavily influenced by human-caused fire, but little or no degradation of the forest has occurred over the past century and the forest is well adapted to very frequent, patchy surface fires.

The fifth chapter has the broadest focus and includes data from across northern Mexico. Data from over 50 sites across northern Mexico were used to analyze the effects of ENSO, PDO, and Atlantic Multidecadal Oscillation (AMO) on historical synchrony and asynchrony of fire. Synchronous fires tended to occur during negative phases of ENSO, PDO, and the combination of these two phases, but AMO was not significantly related to synchronous fire occurrence.

This research substantially expands the continental-scale network of fire/climate/forest structure sites, adds to our understanding of the regulatory factors of fire regimes, and has immediate utility for conservation strategies at the study areas and related ecosystems. This is a unique study in that it covers a very broad scale in areas where fire history studies are limited or nonexistent. By working in areas of great biological diversity and conservation potential, these studies will form a starting point for future multi-disciplinary research and will be of practical value to conservation organizations that are seeking to maintain or restore these ecosystems.

CHAPTER 2: EL NIÑO-SOUTHERN OSCILLATION EFFECT ON A FIRE REGIME IN NORTHEASTERN MEXICO HAS CHANGED OVER TIME

Abstract

The El Niño Southern-Oscillation (ENSO) is a climate-forcing mechanism that has been shown to affect precipitation and the occurrence of wildfires in many parts of the world. In the southern United States and northern Mexico, warm events (El Niño) are associated with moist winter conditions and fewer fires, while cool events (La Niña) tend to favor dry winters and more fires. We tested this relationship in a region of northeastern Mexico by characterizing the historical fire regime and climatic influences. Fire regimes were reconstructed from fire-scar samples collected from 100 trees in three high-elevation sites on Peña Nevada in southern Coahuila. The sites were approximately 25 ha each and the site centers were approximately 1 km apart. The earliest recorded fire occurred in 1521 and the time period we used for analysis was 1645-1929. The sites were characterized by frequent surface fires before the 1920s. In the three sites, mean fire intervals ranged from 8.6 to 9.6 years (all fires) and 11.9 to 18.6 years (fires that scarred ≥25% of recording trees). The per-tree mean fire return interval was 17 years, and all three sites burned in the same year seven times between 1774 and 1929. After 1929, fires were nearly eliminated in all sites, likely due to human causes. We found a temporal change in the association between ENSO events and fires; before the 1830s La Niña events were significantly associated with fire years, while after the 1830s this association was not significant. In 1998 – when the most severe El Niño event of the past century occurred– the three sites experienced severe, stand-replacing fires that killed many trees that had

survived multiple surface fires in the past. Prior to the 1830s, fires tended to occur during dry La Niña years, but since then both La Niña and El Niño have been associated with dry years in this region, especially during the last three decades. This result suggests that ENSO effects have changed over time in this location and that phases of ENSO are not consistent indicators of precipitation, fire occurrence, or fire behavior in this area of northeastern Mexico.

Introduction

In western North America, the El Niño-Southern Oscillation (ENSO) is a climate-forcing mechanism that has been shown to affect precipitation and the occurrence of fires. Linkages between ENSO and the occurrence of forest fires have been recognized at scales ranging from local and regional (Swetnam 1990, Heyerdahl and Alvarado 2003, Brown and Wu 2005, Fulé et al. 2005, Skinner et al. 2008) to subcontinental and intercontinental (Kitzberger et al. 2001, Kitzberger et al. 2007). La Niña winters (ENSO cool phase) in northwestern Mexico are typically hot and dry, as they are in the American Southwest, and fires are more likely to burn during these years (Swetnam and Betancourt 1990, Heyerdahl and Alvarado 2003, Fulé et al. 2005, Kitzberger et al. 2007, Skinner et al. 2008). In southern Mexico, however, El Niño winters (ENSO warm phase) are dry and fire-prone (Magaña et al. 2003, Román-Cuesta et al. 2004, Seager et al. 2009).

The extreme El Niño event of 1998 was associated with a widespread drought and severe forest fires in Mexico. It was an unprecedented year for Mexico in terms of number of fires, area and biomass burned, smoke released, cost of suppression, and firefighter lives lost (Rodríguez-Trejo and Pyne 1999, Duncan et al. 2003). Most of the fires were located in the southern part of the country (Rodríguez-Trejo and Pyne 1999), where El Niño typically induces drought. However, severe fires also burned farther north in Mexico, in the Sierra Madre Oriental.

The Sierra Madre Oriental, in eastern Mexico, is located on or near the dipole where ENSO events have reverse effects; it is situated between areas where La Niña is associated with dry conditions (northwestern Mexico), and areas where El Niño is associated with dry conditions (southern Mexico) (Caso et al. 2007, Seager et al. 2009). Because of its geographical location on or near the ENSO dipole, it is unknown whether warm or cool phases of the oscillation are more likely to be associated with fire occurrence in this area. Severe fires burned in the Sierra Madre Oriental during the 1998 El Niño event, but the 1998 El Niño was extremely strong and therefore may have had atypical effects on fires in this region.

The types of fire behavior that occur in high-elevation forests of the Sierra Madre Oriental are also unknown. Severe fires in 1998 devastated many stands of trees, but this level of severity may have been an anomaly compared to the historical fire regime. *Pinus hartwegii* (Lindl.), a dominant tree species at high elevation in the Sierra Madre Oriental and elsewhere in Mexico and Guatemala (Farjon and Styles 1997), has several adaptations to fire, including thick bark and the ability to resprout after fire (Rodríguez-Trejo and Fulé 2003). While thick bark is usually considered an adaptation to surface fire, sprouting sometimes occurs in trees adapted to intense crown fire (Keeley and Zedler 1998). Although there have been several studies of *P. hartwegii* fire ecology, this is the first fire history study in a *P. hartwegii* forest and the first long-term fire history study in the Sierra Madre Oriental. González et al. (2007) reconstructed fire history of a pine-oak forest (*P. teocote, P. pseudostrobus*) in the northern Sierra Madre Oriental but their tree-ring record reached back only to 1868. Fire history studies in northwestern Mexico, in the Sierra Madre Occidental (Fulé and Covington 1994, Heyerdahl and Alvarado 2003), and in the Sierra San Pedro Mártir (Stephens et al. 2003) indicate that fires occurred frequently in the past and that fire regimes continued uninterrupted well into the 20th century. The Sierra Madre Oriental contains high biodiversity, including 59 endemic plant species that inhabit less than 6 km^2 each (McDonald 1993). At least 35% of timberline plant species in the range are endemic to the Sierra Madre Oriental (McDonald 1990). Peña Nevada, the location of our study, has 10 plant species endemic to the peak alone (McDonald 1993). We selected Peña Nevada to quantify long-term fire regimes because of its critical location in a transition zone of ENSO effects as well as the high conservation value of this rare ecosystem.

The objectives of this study were 1) to characterize the historical fire regime in the *P. hartwegii* forests of Peña Nevada, including fire frequency, type, size, season, and synchrony, and 2) to determine whether fire years were associated with ENSO. Specific questions included: What were the characteristics of the fire regime? Was the fire regime interrupted in the twentieth century? What are the effects of ENSO on fires in this region of Mexico? Were the fires in the 1998 El Niño an anomaly?

Study area

Peña Nevada, at 3540 m elevation, is located in the Sierra Madre Oriental in the state of Nuevo León, Mexico (Fig. 2.1). We focused on Peña Nevada (also called El Picacho San Onofre) primarily for biogeographical reasons: it is the southernmost peak in the high, consolidated part of the Sierra Madre Oriental that runs from just south of Monterrey to southern Nuevo León and southwestern Tamaulipas, and it is located between areas where ENSO events have opposite effects. We chose specific sites on the mountain because of their history of relatively light anthropogenic disturbance prior to the 1998 fire, the presence of *P. hartwegii* forests, which were least anthropogenically disturbed at the highest elevations, and the presence of old trees or old remnant wood. In addition, the sites were spaced along a broad ridgeline which would allow them to capture evidence of fires spreading up either side of the mountain.

The study area is located at approximately 3200 m above sea level. Climate data from lower-elevation weather stations to the southeast and southwest of Peña Nevada (Uvalles, 1565 m, and San Antonio Peña Nevada, 1680 m) averaged annual precipitation of 335 mm, with peaks in late spring and late summer (IMTA 2007). The precipitation at sites over 2800 m in the Sierra Madre Oriental is estimated to be 450-500 mm annually (Villanueva-Diaz et al. 2007), but the percentage of precipitation that falls as snow is unknown. Average yearly temperature at the two lower-elevation stations is 10.8° C (IMTA 2007), but the average yearly temperature at our study sites is certainly lower. The majority of lightning storms in the area occur in the spring (IMTA 2007). Exposed rock in the Sierra Madre Oriental is limestone (Ferrusquía-Villafranca 1993).

The sites we sampled are dominated almost exclusively by *P. hartwegii*. After the severe fire in 1998, some parts of Peña Nevada experienced high tree mortality and were later salvage logged. Because of this, much of the area we sampled was essentially clear-cut, with some pockets of intact forest.

In 1984, Andrew McDonald witnessed and took a photo of a recently burned area in a remote area on Peña Nevada, not near our sampling sites (personal communication 2009). The photo shows that some of the forest burned severely; only charred snags are left in the burned area. It is likely that the severe fire happened in 1983; the needles on the trees at the edge of the burn were orange but had not yet fallen by 1984. The year 1983 was dry at Peña Nevada, which also lends credence to the 1983 date.

Methods

We collected fire-scarred tree samples at Peña Nevada in 2007. We established three sites of approximately 25 ha each at San Onofre (SO), El Diferencial (DI), and Mesa Acuña (MA) (Fig. 2.1). The sites were spaced approximately 1 km apart and had comparable elevation and vegetation. All had moderate slopes, situated on top of a broad ridgeline. We systematically searched each site and took fire-scarred samples that would provide good spatial distribution throughout the site. We chose to sample trees of any species with the largest numbers of well-preserved fire scars (Van Horne and Fulé 2006), but we also sampled live trees, which often had only one or two scars, to ensure that the fire history extended up to the present. We used chain saws to remove partial cross-sections of fire-scarred trees. Data recorded for each sample were tree species and diameter, status (live, stump, snag, or log), slope, aspect, and fire scar height and aspect. We georeferenced each sample to map the spatial distribution of the samples.

In the laboratory, samples were sanded with increasingly finer grits of sandpaper until individual cells were clearly visible under a microscope. We crossdated each sample using a *Pseudotsuga menziesii* (Mirb.) Franco tree-ring chronology from nearby on Peña Nevada (Villanueva-Diaz et al. 2007). The crossdating of each sample was confirmed by a second dendrochronologist. We measured the ring widths of each sample and checked the crossdating with the COFECHA software program (Holmes 1983).

We identified fire scars to the year of origin by noting the crossdated ring in which the fire injury occurred (Baisan and Swetnam 1990). When possible, fire scars were determined to be located in the early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L), or on the boundary between rings (indicating a dormant (D) season fire). We assigned dormant season fires to the subsequent calendar year because most fires in monsoonal systems such as this one burn prior to the summer rains. We grouped fires into spring (D + EE) and summer (ME + LE + L) categories for seasonal evaluation.

Fire history statistics were calculated for periods in which there was an adequate tree-ring record. Each site was determined to have an adequate tree-ring record when at least 10% of total samples in that site were scarred. The same criterion was used when calculating statistics for the three sites combined. In the three sites combined, the period with an adequate tree-ring record was 1645-1929. Each site individually had an adequate tree-ring record from 1641 to 1920 (SO), 1645-1929 (DI), and 1774-1928 (MA).

Fire history statistics were calculated with FHX2 v. 3.2 software (Grissino-Mayer 2001). For each site and for all three sites combined, we calculated the composite mean fire interval between all fires and also between more widespread fires that scarred at least 25% of recording trees. Recording trees are trees that have been scarred by fire once; after an initial wound, trees of some species are more likely to scar in subsequent fires (Romme 1980) and therefore are "recording trees". We calculated Weibull median and modal fire intervals, and looked for temporal differences in mean fire interval, seasonality of fires, and fire relationship with precipitation and ENSO between the first portion of the period of analysis (1645-1831) and the second portion (1832-1929). We split the analysis at 1831/1832 not *a priori* but because one of our results, a graph of ENSO extremes and precipitation at Peña Nevada, showed an unexpected change in relationship around that time. We also examined the fire history at Peña Nevada for evidence of a hiatus in fire occurrence that would coincide with a late eighteenth-early nineteenth centuries gap in fire documented at many sites in the southwestern United States and northwestern Mexico (Swetnam 1990, Kitzberger et al. 2001, Stephens et al. 2003, Brown and Wu 2005, Skinner et al. 2008).

To evaluate climate conditions related to fire occurrence at our study sites, we used superposed epoch analysis (SEA) in FHX2 v. 3.2 (Baisan and Swetnam 1990, Swetnam 1993, Grissino-Mayer 2001) to compare independently-derived indices of ENSO and precipitation during fire years, for five years prior to fire years, and for two years after fire years. Reconstructions used include a reconstruction of winter ENSO (NINO3, Dec. to Feb., 1408–1978, Cook 2000), and a local precipitation reconstruction (Villanueva-Diaz et al. 2007). The time series of precipitation had no temporal autocorrelation, but the NINO3 index did. To address the temporal autocorrelation in the NINO3 index, we fitted autoregressive integrated moving average models based on lowest Akaike's information criterion and significant but uncorrelated parameter estimates (Brown et al. 2008). We used the white noise residuals in our analyses. To assess statistical significance in the SEA analyses, confidence intervals (95%) were calculated using bootstrapped distributions of climate data in 1000 trials. We compared ENSO and precipitation indices with the occurrence of all fires regardless of size, as well as widespread fires that scarred at least 25% of recording trees in all three sites. We completed these analyses for the entire period with an adequate tree-ring record (1645-

1929) and also for the first part of this period alone (1645-1831) and the second part alone (1832-1929).

We plotted extreme ENSO events on a local precipitation reconstruction based on *P. menziesii* annual rings (Villanueva-Diaz et al. 2007). Extreme winter SOI values were identified between 1699 and 1971 by Stahle and Cleaveland (1993), using tree-ring records from Mexico and the United States. Stahle and Cleaveland used two methods to reconstruct extreme SOI values, regression and classification, and considered the most accurate list of extremes to be a list of years when both methods obtained the same results for extreme winter SOI values. This is the list we used. After 1971, we determined extreme winter SOI values to be December-January-February (DJF) average values (SOI data from NCAR's Climate Analysis Section Data Catalog: http://www.cgd.ucar.edu/cas/catalog/climind/) that were more than 1.5 standard deviations from the average DJF values from 1935 to 2006. Using this method, extreme winter SOI values after 1971 were in 1974 and 1976 (La Niña events), and 1983, 1992, and 1998 (El Niño events).

Results

Fire history

We collected a total of 112 samples: 34 in SO, 48 in DI, and 30 in MA. The majority of samples were taken from stumps and all but one of the samples was from *P. hartwegii*; the exception came from a single *P. menziesii*. We were able to crossdate 100 of the samples (89%) and we identified 408 scars in total. We were unable to date 12 samples (11%) because of rotten wood, rings that were too tight, or an insufficient number of rings to permit reliable crossdating.

The earliest fire scar identified in our three sites occurred in 1521, and the last fire scars were from 1998, the year that much of the forest in our sites burned severely. Until the late 1920s, the fire regime at Peña Nevada showed relatively little variability across sites and through time (Fig. 2.2). The mean fire interval for all fires was within one year's difference between sites (SO: 9.3 years, DI: 8.6 years, MA: 9.6 years; Table 2.1). The mean fire interval for more widespread fires (those that burned ≥ 25% of the trees) was longer, and varied from 11.9 years in MA to 18.6 years in SO (Table 2.1). The Weibull distribution, which has been used in describing fire regimes because it is flexible, able to fit skewed data sets, and provides a standard way to compare fire regimes across ecological gradients (Grissino-Mayer 1999), fit our data well. Weibull median probability interval values were similar to mean fire interval values (Table 2.1). The mean fire interval for individual trees was 17 years. There were no statistically significant temporal differences in mean fire interval or percent of samples scarred between 1645-1831 and 1832-1929.

Two of the three sites (SO and DI) have a continuous record starting in the early 1500s and large numbers of samples starting in the 1600s. Site MA is the only site that does not have a continuous record that precedes the early 1700s. Two samples were found in MA that span the mid-1500s to the mid-1600s, but there is a gap in sample coverage between the mid-1600s and the early 1700s. MA did have one pulse of regeneration in the early 1700s; 7 out of 9 pith dates in that site were from between 1726 and 1742. Sites SO and DI had 18 samples that contained pith; pith dates were scattered from 1589 to 1892 with no pulse of regeneration evident at any time in either site.

Between 1774 and 1929, out of 38 years with fires, seven years (18%) had fires recorded at all three sites (SO, DI, and MA): 1786, 1819, 1831, 1838, 1899, 1909, and 1920. Twenty-two fire dates (58%) were unique to one site only and 9 fire dates (24%) were recorded at two sites. Although the sites did not share many of the same fire years, all three sites recorded similar numbers of fires during the period 1774-1929 (21 fires in SO, 23 fires in DI, and 17 fires in MA).

We were able to determine seasonality of 55% of the fire scars. Of those, 92% were found on the ring boundary, meaning that the majority of fires occurred in the dormant season (Table 2.1). Another 5% were found in early earlywood, and 3% were found in middle earlywood. No scars were found in the late earlywood or latewood.

A dramatic decline in fire frequency occurred after the 1920s (Fig. 2.2). Site SO experienced one fire between 1920 and 1998 (1955), DI had no fires between 1929 and 1998, and MA had one fire between 1929 and 1995 (1951). Site SO had a 43-year fire-free interval, DI had a 69-year fire-free interval, and MA had a 44-year fire-free interval. The fire-free periods in the twentieth century were unprecedented in the previous 300+ years: previously, the longest intervals without fire in each of the sites were 19, 32, and 16 years, respectively.

Peña Nevada showed no evidence of a hiatus in fire occurrence that would coincide with the gap in fire in the late eighteenth and early nineteenth centuries documented at many sites in the southwestern United States and northwestern Mexico. We did, however, observe a gap from the 1680s to 1717, and another period of few fires from the 1750s to 1774, as reflected in reduced fires per decade (Fig. 2.2).

Fire-Climate

ENSO events were related to fire occurrence in the early portion of our period of analysis, but the relationship changed over time. Results from the SEA analyses indicate that in the period 1645-1831 fires were likely to occur in La Niña years (years when NINO3 values were significantly below average; Fig. 2.3). This relationship was significant ($p<0.05$) for fires that scarred ≥25% of recording trees. Between 1832 and 1929, however, there is no significant relationship between ENSO and years when fires burned, regardless of the size of the fire. For fires that scarred ≥25% of recording trees before 1831, the 3-5 years before fire years had significantly above-average NINO3 values. After 1832, the year immediately prior to widespread fires (those that scarred ≥25% of recording trees) had significantly above-average NINO3 values.

The decoupling of La Niña and dry, fire-prone years in the early nineteenth century was further explored with additional analyses. First, SEA analyses associating extreme ENSO events and precipitation show that before 1830, extreme La Niña events (Stahle and Cleaveland 1993) were likely to be very dry ($p<0.01$), but approximately average after 1832 (Fig. 2.3). Second, by overlaying SOI extremes on a graph of reconstructed Peña Nevada winter precipitation (Fig. 2.4), it is evident that from 1700 to 1830, four of the five El Niño extremes corresponded with precipitation maxima and six of the seven La Niña extremes coincided with precipitation minima (Fig. 2.4). Between the 1830s and the 1970s, the extremes were less distinguishable in the Peña Nevada precipitation record; El Niño extremes still tended to be wet but La Niña extremes ranged from dry to wet conditions. In the late twentieth century, it appears the patterns of precipitation during extreme ENSO events have diverged even more dramatically. The El

Niño events of 1983 and 1998 were extremely dry years at Peña Nevada; 1998 was the second-driest year at Peña Nevada since 1508 in a precipitation reconstruction using Douglas-fir annual rings (Villanueva-Diaz et al. 2007). Since 1508, only 1805, which was an extreme La Niña year, was drier.

Regardless of ENSO phases, fires occurred more often in dry years at Peña Nevada throughout the period of analysis (Fig. 2.3). Only the "all fires" relationship between fire years and precipitation before 1831 did not reach 95% significance. The other categories of fire both before 1831 and after 1832 were significantly related to years of low precipitation. The seven years when fires occurred in all three sites were significantly dry, and there was also, on average, a significantly wet year two years prior to these seven fire years (not shown).

Discussion

What were the characteristics of the fire regime?

Before the 1920s, the fire regime at Peña Nevada was characterized by relatively frequent surface fires, as indicated by our reconstruction reaching back several hundred years. Individual trees were scarred by fire up to 10 times each; on average, individual trees were experiencing and surviving fires less than every two decades throughout their lives (individual tree mean fire interval 17 years). This is a conservative estimate, as not all fires leave scars on recording trees, and we excluded fires with uncertain dates from all statistical analyses. The historical fire regime at Peña Nevada is similar to the historical low-severity surface fire regime found in the more northerly dry coniferous forests of northwestern Mexico and the southwestern United States (Fulé and Covington 1999, Heyerdahl and Alvarado 2003, Stephens et al. 2003, Fulé et al. 2005). This is true even though the dominant species at Peña Nevada (*P. hartwegii*) is different from any species sampled in other fire history studies, and these sites are at a much higher elevation.

Unlike some high elevation sites in the western United States (Kipfmueller and Baker 2000, Margolis et al. 2007), we did not find evidence of stand-replacing fires from the 1500s through the early 1900s, although there is a possibility that site MA experienced a stand-replacing fire in the early 1700s based on the lack of sample coverage before 1725 and the pulse of regeneration between 1726 and 1742. In addition, although we found old, fire-scarred trees dating back centuries in our other sites, meaning that no stand-replacing fire at the 25-ha scale had occurred since at least ~1600, it is possible that smaller patches within our sites experienced high-severity fire that we did not detect. We conclude that the historical fire regime was dominated by low-severity surface fires, with the possibility of patchy stand-replacing disturbances in some sites.

A stand-replacing fire did occur in 1998 in all three sites after decades of fire exclusion, and there is evidence that a severe, stand-replacing fire occurred in 1983 on a different part of the mountain. There are two possible explanations for the seemingly anomalous severity of these fires in the late twentieth century. One is that decades of fire exclusion led to a buildup of fuels which facilitated the crown fires in the extremely dry years of 1983 and 1998. The other possible scenario is that our three ridgetop sites captured evidence of predominantly surface fires. We leave open the possibility that the larger Peña Nevada landscape historically experienced some severe fires as well as surface fires and that the late twentieth century severe fires were not as unusual as the evidence suggests.

More than half the fires during the period of analysis were small and burned in only one of the three sites sampled. Surprisingly, since the three sites are within a 3 km section of the ridgetop, fires were not generally synchronous between the three sites. Only seven fire dates between 1774 and 1929 were recorded at all three sites. These results suggest that fires in our sites were frequent but not usually very large. Frequent but small and asynchronous fires have also been found in western Mexico, in the Sierra Madre Occidental (Fulé and Covington 1999), although in other areas of the Sierra Madre Occidental fires were historically more large and synchronous (Fulé et al. 2005).

An unusual feature of the Peña Nevada fire history is the almost complete dominance of dormant-season fires (206 of 224; 92%); almost all of the fires recorded occurred before cambial growth began. Although little is known about growth phenology in this region, the dominance of scars on the ring boundary or in the early earlywood suggests that the majority of scars were formed in the spring or early summer. These seasonality results, including the lack of scars in the latewood, support the assumption that dormant-season fires occur in the spring rather than in the fall. We hypothesize that the high percentage of dormant-season scars at Peña Nevada is due to the high elevation. Cambial growth of trees likely begins relatively late in the year, while most lightning strikes in this area occur during the spring before the first precipitation peak in May (IMTA 2007). In sites studied in western Mexico, percentage of dormant-season fires ranged from 0.3% (Skinner et al. 2008) to 47% (Fulé et al. 2005) to 56% (Fulé and Covington 1999) to 63% (Heyerdahl and Alvarado 2003).

This is the first study to quantify fire history from fire scars in a *P. hartwegii* forest. This species is capable of basal resprouting, which has been interpreted in other tree species as an adaptation to stand-replacing disturbance, including crown fire (Rodríguez-Trejo and Fulé 2003). However, we did not see any *P. hartwegii* sprouts at Peña Nevada, and our data indicate that in our sites, the *P. hartwegii* forest sustained a surface fire regime for the past several hundred years.

Was the fire regime interrupted in the twentieth century?

The near cessation of fires after the 1920s is likely related to the formation of Ejido La Encantada on Peña Nevada in 1937. Ejidos are communities that live on rural lands that are held in common and managed with some level of governmental control (Thoms and Betters 1998). In the Sierra Madre Occidental, a decrease in the percentage of sites with fire around 1930 coincided with the granting of lands to ejidos (Heyerdahl and Alvarado 2003). Heyerdahl and Alvarado speculated that granting land to ejidos may have changed the fire regime through the introduction or intensification of cattle grazing, road building, logging, and changing the traditional role of fire. These same factors likely changed the fire regime at Peña Nevada when Ejido La Encantada was formed. Other hypotheses are less likely; there is no evidence of a climatic change in this area in the early 1900s (Villanueva-Diaz et al. 2007), and throughout Mexico fire regimes were disrupted during different decades (i.e. the 1930s and 40s [Fulé and Covington 1999] and the 1950s [Fulé et al. 2005]) or not at all. This suggests that climate is not responsible for the cessation of fires after the 1920s at Peña Nevada. Fire suppression policy is probably not the reason for the cessation of fires either: control efforts in this area have been limited in scope (local crews and landowners rather than engines and helicopters).

We have no data on human population history or the history of fire use at Peña Nevada, and we cannot distinguish human ignitions from lightning ignitions throughout the period of record. The many small fires on the peak indicate many local ignitions, meaning that fires did not always start in the centers of population in the valleys below. Given the elevation of the mountain, lightning strikes probably occur often. Lightning in this area peaks before the early summer rains begin, which is consistent with the fact that almost all fires with determinable season occurred in spring or early summer before cambial growth began. However, humans may also have ignited fires in these high-elevation forests. It is most likely that both lightning and humans caused fires historically.

What are the effects of ENSO and other climate patterns on fires in this region of Mexico?

As expected, fires tended to burn at Peña Nevada during dry years. This pattern did not change throughout the period of record. For most categories of fire, we saw no evidence that fires were related to high precipitation in years preceding fires, as has been found in many sites in the southwestern United States (e.g., Grissino-Mayer et al. 2004). However, the seven years in which fires burned all three sites show evidence of occurring two years after a wet year, which could indicate that the most widespread fires were influenced by the buildup of fine fuels during wet years.

The most striking characteristic of the relationship between ENSO, dry years, and fire at Peña Nevada is the shifting relationship between El Niño/La Niña, precipitation, and fire over time, with one shift occurring around 1830 and another occurring in the last few decades (around 1970). Before the 1830s, La Niña had a significant effect on the occurrence of fire at Peña Nevada: negative NINO3 values were strongly associated with fire years (Fig. 2.3). This is consistent with studies in northwestern Mexico and the southwestern United States, where La Niña years tend to be dry and associated with fires (Swetnam and Betancourt 1998, Heyerdahl and Alvarado 2003, Kitzberger et al. 2007, Drury and Veblen 2008). After 1830, the relationship between fire and La Niña at Peña Nevada was not significant. Fires continued to burn in dry years, but they were no longer associated with La Niña (Fig. 2.3). Since the 1970s, extreme ENSO events have been more erratic; the extreme El Niño events of 1983 and 1998 were very dry at Peña Nevada but the 1992 extreme El Niño was very wet (Fig. 2.4).

While numerous studies have associated ENSO patterns with fire occurrence in the Americas, to our knowledge this is the first study to document a change in the effects of ENSO on the occurrence of fire over time. The reason for the change is not clear. We hypothesize that the changing nature of the ENSO-fire relationship could be due to 1) the location of this study site, 2) climatic shifts associated with the late eighteenth-early nineteenth century gap in fire or 3) possible effects from climate change. Peña Nevada is located in the transition zone, or dipole, of ENSO effects: northwestern Mexico tends to be dry during La Niña events while southern Mexico tends to be dry during El Niño events (Magaña et al. 2003). Because this is the first fire-climate study in this part of North America, we do not know if this result is anomalous or typical. Tree ring chronologies and precipitation reconstructions from elsewhere in the Sierra Madre Oriental show that 1998 was anomalously dry in other places in northeastern Mexico. This is also evident in maps of extreme El Niño events created by Magaña et al. (2003).

The dryness in an El Niño winter normally extends up partway through Mexico, but in 1998 the drying extended much further north, including our study area. We will explore further whether geographic location in relation to spatial teleconnections is responsible for the shifting effects of ENSO on precipitation and fire as we analyze data from other fire-climate studies in this region, currently underway.

Although we saw no evidence of a hiatus in fire at Peña Nevada coincident with the late eighteenth-early nineteenth century gap in fire, as has been recorded at many other sites in North and South America, the first shift in ENSO effects at this site occurred around 1830, which is approximately when changes in fire regime, or in some cases the end of the hiatus, happened in several other areas. For example, Stephens et al. (2003) noted less frequent and more synchronous fires after ~1830 in the Sierra San Pedro Mártir in northern Baja California. Sakulich and Taylor (2007) also documented a shift from frequent small burns to less frequent larger burns after 1800 in their study area in western Texas. The reasons and the precise dates for the shift in fire regime, or in some cases "the gap," are still unresolved. Hypotheses include decreased amplitude and/or frequency of ENSO, a cool phase of the AMO, a cool phase of the PDO, and lower variability in climate in general (Donnegan et al. 2001, Kitzberger et al. 2001, Heyerdahl et al. 2002, Grissino-Mayer et al. 2004, Brown and Wu 2005, Sibold and Veblen 2006, Kitzberger et al. 2007, Brown et al. 2008a, Skinner et al. 2008). It is possible that at Peña Nevada one or more of these hypotheses could explain the change in ENSO effects in approximately 1830 and the change after the 1970s as well.

The change in ENSO effects at Peña Nevada in the late twentieth century (around 1970) is more dramatic than the early 1800s change. After centuries of receiving above-average precipitation during El Niño events, Peña Nevada experienced the second-driest year in almost 500 years during the El Niño event of 1998 (Villanueva-Diaz et al. 2007). The year 1983, when another El Niño event occurred, was also dry at Peña Nevada according to the local tree-ring record. Some scientists attribute the unprecedented amplitudes of the 1983 and 1998 El Niño events to anthropogenically induced global climate changes, while others do not (Fedorov and Philander 2000). Global warming is likely to affect El Niño by altering the background climate, but of the several projections that have been made about details of these changes, it is currently impossible to know which, if any, are correct (Fedorov and Philander 2000, Tudhope and Collins 2003). In an analysis from 1948 to 1999, the number and extent of fires in the Everglades were greater during La Niña years than El Niño years (Beckage et al. 2003). In 1998, however, more than 500,000 acres in Florida burned, which is much higher than the 1981-2008 average of 205,000 acres (Florida Department of Agriculture and Consumer Services Division of Forestry; http://www.fl-dof.com/wildfire/stats_daily_reports.html). The anomalous effects on fire of the 1998 El Niño may have had an impact reaching well beyond northeastern Mexico.

Were the fires in the 1998 El Niño an anomaly?

At our sites on Peña Nevada, we have evidence of both top-down and bottom-up control of fires, including the anomalously severe fire of 1998. The severity of this fire was probably due in large part to top-down influences of climate: low precipitation and high temperatures. In 1998, Peña Nevada received very little precipitation. The year 1998 was also the warmest year of the 20th century (McPhaden 1999), which may have influenced the area burned globally that year, as well as area burned in Mexico and the Sierra Madre Oriental. Unusually severe wildfires like the one that burned Peña Nevada in 1998 will probably occur again if projections of warming and drying are realized (Westerling et al. 2006, Seager et al. 2007, Seager et al. 2009).

Changes in the bottom-up influences of fuels and forest structure also may have had an impact on the large size and severity of the El Niño fire of 1998. The forests in our sites, adapted to fairly frequent surface fire, had not experienced wildfires for over 40 (and in some cases almost 70) years before 1998. The resulting buildup of fuels and changes in canopy structure over time may have contributed to the severe impacts that occurred when a fire finally did burn during a dry year.

The low-intensity surface fires that historically burned in our sites were also likely influenced by both top-down and bottom-up effects. Evidence for bottom-up control is the dominance of small, asynchronous fires that occurred at only one of the three sites from 1645 to 1929, suggesting that differences in fuels, ignitions, and site characteristics were important at this small scale.

Top-down influence on the historical low-intensity surface fires is evidenced by the strong relationship of fire with dry years, throughout the period of record. In addition, before the 1830s, ENSO also had a strong relationship with fire occurrence. Prior to the 1920s, when fire exclusion began, bottom-up controls like fuel availability probably moderated top-down climatic influences. However, the bottom-up control that fuel exerted was eliminated when fire exclusion began and fuels became more homogeneous and probably more dense. This may have allowed top-down extreme climatic controls to dominate fire behavior in the late 20th century. We conclude that fires at this site are under the influence of top-down, regional to global influences as well as site-specific factors.

The dominant trees at Peña Nevada survived multiple fires over centuries, but an event of mass mortality occurred in our study area in 1998, probably due to a combination of fuel buildup and extreme dryness. Considering possible changes in future climate and the biological importance of the Sierra Madre Oriental, including the high number of local endemics, this merits concern and the development of new strategies for conservation. In some parts of Mexico, excessive human-originated fire has contributed to deforestation or forest structure changes in pine forests. Public education campaigns have been implemented throughout the country to reduce excessive burning (Rodríguez-Trejo and Fulé 2003). However, in the Sierra Madre Occidental in northwestern Mexico, there are areas where fire frequency today is similar to historical fire frequency and areas where fires, historically frequent, have been absent or rare for decades (Rodríguez-Trejo and Fulé 2003). Based on our reconstruction of fire history at Peña Nevada, fires occurred much less frequently after the 1920s than in the previous several centuries. Fire suppression in areas with fire regimes historically characterized by frequent surface fires is not the best management tool, as it may contribute to forest change, fuel buildup and increased risk of catastrophic crown fires. It is useful to understand the historical fire regimes of these forests to design the best management approaches for these areas. In addition, understanding how ENSO and other climate factors influence precipitation and fire is important; ENSO may no longer be a reliable indicator of precipitation or fire occurrence or behavior in this part of Mexico. It will be valuable to expand the network of fire-climate sites to enhance our understanding of fire-climate relationships and to further investigate whether ENSO effects on precipitation and fire are changing throughout the region or whether it is a site-specific phenomenon.

Acknowledgements

We thank Ejido La Encantada and Davíd Medellín for permission to work on Peña Nevada. Gustavo Medellín Pérez provided invaluable assistance in the field, as did Armando Becvort, Erica Bigio, Vicenta Constante García, and Cameron Fulé. Many thanks also to Don Normandin, Ian Hyp, Joe Crouse, and other staff at the Ecological Restoration Institute. This research was supported by the National Science Foundation (DEB-0640351) and the Ecological Restoration Institute at Northern Arizona University. We also thank Emily Heyerdahl and one anonymous reviewer for their helpful comments on the manuscript.

Literature Cited

Baisan, C. H. and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research **20**:1559-1569.

Beckage, B., W. J. Platt, M. G. Slocum, and B. Panko. 2003. Influence of the El Niño Southern Oscillation on fire regimes in the Florida Everglades. Ecology **84**:3124-3130.

Belsky, A. J. and D. M. Blumenthal. 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior West. Conservation Biology **11**:315-327.

Brown, P. M., E. K. Heyerdahl, S. G. Kitchen, and M. H. Weber. 2008. Climate effects on historical fires (1630-1900) in Utah. International Journal of Wildland Fire **17**:28-39.

Brown, P. M. and R. Wu. 2005. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology **86**:3030-3038.

Caso, M., C. González-Abraham, and E. Ezcurra. 2007. Divergent ecological effects of oceanographic anomalies on terrestrial ecosystems of the Mexican Pacific coast. Proceedings of the National Academy of Sciences **104**:10530-10535.

Cook, E. R. 2000. Nino 3 Index Reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series #2000-052. NOAA/NGDC Paleoclimatology Program, Boulder, CO.

Donnegan, J., T. T. Veblen, and J. S. Sibold. 2001. Climatic and human influences on fire history in Pike National Forest, central Colorado. Canadian Journal of Forest Research **31**:1526-1539.

Drury, S. A. and T. T. Veblen. 2008. Spatial and temporal variability in fire occurrence within the Las Bayas Forestry Reserve, Durango, Mexico. Plant Ecology **197**:299-316.

Duncan, B. N., R. V. Martin, A. C. Staudt, R. Yevich, and J. A. Logan. 2003. Interannual and seasonal variability of biomass burning emissions constrained by satellite observations. J. Geophys. Res. **108**.

Farjon, A. and B. T. Styles. 1997. Pinus (Pinaceae). The New York Botanical Garden, Bronx, NY.

Fedorov, A. V. and S. G. Philander. 2000. Is El Niño changing? Science **288**:1997-2002.

Ferrusquía-Villafranca, I. 1993. Geology of Mexico: A synopsis. Pages 3-108 *in* T. P. Ramamoorthy, R. Bye, A. Lot, and J. Fa, editors. Biological Diversity of Mexico: Origins and Distribution. Oxford University Press, New York.

Fulé, P. Z. and W. W. Covington. 1994. Fire-regime disruption and pine-oak forest structure in the Sierra Madre Occidental, Durango, Mexico. Restoration Ecology **2**:261-272.

Fulé, P. Z. and W. W. Covington. 1999. Fire regime changes in La Michilía Biosphere Reserve, Durango, Mexico. Conservation Biology **13**:640-652.

Fulé, P. Z., J. Villanueva-Díaz, and M. Ramos-Gómez. 2005. Fire regime in a conservation reserve in Chihuahua, Mexico. Canadian Journal of Forest Research **35**:320-330.

González Tagle, M. A., L. Schwendenmann, J. Jiménez Pérez, and W. Himmelsbach. 2007. Reconstrucción del historial de incendios y estructura forestal en bosques mixtos de pino-encino en la Sierra Madre Oriental. Madera y Bosques **13**:51-63.

Grissino-Mayer, H. D. 1999. Modeling fire interval data from the American Southwest with the Weibull distribution. International Journal of Wildland Fire **9**:37-50.

Grissino-Mayer, H. D. 2001. FHX2 - Software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research **57**:113-122.

Grissino-Mayer, H. D., W. H. Romme, M. L. Floyd, and D. D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology **85**:1708-1724.

Grissino-Mayer, H. D. and T. W. Swetnam. 1997. Multi-century history of wildfire in the ponderosa pine forests of El Malpais National Monument. New Mexico Bureau of Mines & Mineral Resources, Bulletin **156**:163-171.

Heyerdahl, E. K. and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. Pages 196-217 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer-Verlag, New York.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. The Holocene **12**:597-604.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurements. Tree-Ring Bulletin **43**:69-78.

IMTA. 2007. Extractor Rápido de Información Climatológica, version 3 (ERIC III); compact disc. Instituto Mexicano de Tecnología del Agua, Veracruz, Mexico.

Kaib, J. M. 1998. Fire history in riparian canyon pine-oak forests and the intervening desert grasslands of the Southwest Borderlands: a dendroecological, historical, and cultural inquiry. The University of Arizona, Tucson, AZ.

Keeley, J. E. and P. H. Zedler. 1998. Evolution of life histories in *Pinus*. Pages 219-249 *in* D. M. Richardson, editor. Ecology and Biogeography of *Pinus*. Cambridge University Press, New York, NY.

Kipfmueller, K. F. and W. L. Baker. 2000. A fire history of a subalpine forest in south-eastern Wyoming, USA. Journal of Biogeography **27**:71-85.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Sciences **104**:543-548.

Kitzberger, T., T. W. Swetnam, and T. T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Global Ecology and Biogeography **10**:315-326.

Magaña, V. O., J. L. Vásquez, J. L. Pérez, and J. B. Pérez. 2003. Impact of El Niño on precipitation in Mexico. Geofísica Internacional **42**:313-330.

Margolis, E. Q., T. W. Swetnam, and C. D. allen. 2007. A stand-replacing fire history in upper montane forests of the southern Rocky Mountains. Canadian Journal of Forest Research **37**:2227-2241.

McDonald, A. K. 2009. personal communication.

McDonald, J. A. 1990. The alpine-subalpine flora of northeastern Mexico. Sida **14**:21-28.

McDonald, J. A. 1993. Phytogeography and history of the alpine-subalpine flora of Northeastern Mexico Pages 681-705 *in* T. P. Ramamoorthy, R. Bye, A. Lot, and J. Fa, editors. Biological diversity of Mexico: origins and distribution. Oxford University Press, Oxford.

McPhaden, M. J. 1999. Genesis and evolution of the 1997-98 El Niño. Science **283**:950-954.

Rodríguez-Trejo, D. A. and P. Z. Fulé. 2003. Fire ecology of Mexican pines and a fire management proposal. International Journal of Wildland Fire **12**:23-37.

Rodríguez-Trejo, D. A. and S. J. Pyne. 1999. Mexican fires of 1998. International Forest Fires News **20**:61-63.

Román-Cuesta, R. M., J. Retana, and M. Gracia. 2004. Fire Trends in Tropical Mexico: A Case Study of Chiapas. Journal of Forestry **102**:26-32.

Romme, W. H. 1980. Fire history terminology: report of the ad hoc committee.*in* Proceedings of the Fire History Workshop, Oct 20-24, 1980. USDA Forest Service, Tucson, AZ.

Sakulich, J. and A. H. Taylor. 2007. Fire regimes and forest structure in a sky island mixed conifer forest, Guadalupe Mountains National Park, Texas, USA. Forest Ecology and Management **241**:62-73.

Seager, R., M. Ting, M. Davis, M. Cane, N. Naik, J. Nakamura, C. Li, E. Cook, and D. W. Stahle. 2009. Mexican drought: an observational modeling and tree ring study of variability and climate change. Atmósfera **22**:1-31.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science **316**:1181-1184.

Sibold, J. S. and T. T. Veblen. 2006. Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. Journal of Biogeography **33**:833-842.

Skinner, C. N., J. H. Burk, M. G. Barbour, E. Franco-Vizcaíno, and S. L. Stephens. 2008. Influences of climate on fire regimes in montane forests of north-western Mexico. Journal of Biogeography **35**:1436-1451.

Stahle, D. W. and M. K. Cleaveland. 1993. Southern Oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and southern Great Plains. Journal of Climate **6**:129-140.

Stephens, S. L., C. N. Skinner, and S. J. Gill. 2003. Dendrochronology-based fire history of Jeffrey pine - mixed conifer forests in the Sierra San Pedro Martir, Mexico. Canadian Journal of Forest Research **33**:1090-1101.

Swetnam, T. W. 1990. Fire history and climate in the southwestern United States. Pages 6-17 *in* Proceedings of the Symposium "Effects of fire managment of southwestern natural resources". USDA Forest Service General Technical Report RM-191, Tucson, AZ.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. Science **262**:885-889.

Swetnam, T. W. and J. L. Betancourt. 1990. Fire - Southern Oscillation relations in the southwestern United States. Science **249**:1017-1020.

Swetnam, T. W. and J. L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate **11**:3128-3147.

Therrell, M. D. 2005. Tree rings and 'El Año del Hambre' in Mexico. Dendrochronologia **22**:203-207.

Thoms, C. A. and D. R. Betters. 1998. The potential for ecosystem management in Mexico's forest ejidos. Forest Ecology and Management **103**:149-157.

Touchan, R., T. W. Swetnam, and H. D. Grissino-Mayer. 1993. Effects of livestock grazing on pre-settlement fire regimes in New Mexico.*in* Proceedings: Symposium on fire in wilderness and park management. US Department of Agriculture Forest Service, Missoula, MT.

Tudhope, S. and M. Collins. 2003. The past and future of El Niño. Nature **424**:261-262.

Van Horne, M. L. and P. Z. Fulé. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forest. Canadian Journal of Forest Research **36**:855-867.

Villanueva-Diaz, J., D. W. Stahle, B. H. Luckman, J. Cerano-Paredes, M. D. Therrell, M. K. Cleaveland, and E. Cornejo-Oviedo. 2007. Winter-spring precipitation reconstructions from tree rings for northeast Mexico. Climatic Change **83**:117-131.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science **313**:940-943.

TABLE 2.1. Fire interval characteristics at three sites on Peña Nevada in the Sierra Madre Oriental, Mexico.

	Site, years of analysis			
Characteristics	San Onofre (SO) 1641-1920	El Diferencial (DI) 1645-1929	Mesa Acuña (MA) 1774-1928	Three sites combined 1645-1929
Total fires	113	188	103	408
Number (proportion) with season	72 (0.64)	108 (0.57)	42 (0.41)	224 (0.55)
Number (proportion) DE fires	70 (0.97)	106 (0.98)	39 (0.93)	217 (0.97)
Total no. intervals				
All fires	30	33	16	53
25%	15	21	13	19
Mean fire interval (yr)				
All fires	9.3	8.6	9.6	5.4
25%	18.6	13.5	11.9	14.5
Median fire interval (yr)				
All fires	7.5	8	10	5
25%	13	12	11	12
Weibull Median Interval (yr)				
All fires	7.9	8.1	9.6	4.6
25%	18.1	13.0	11.6	13.6
Weibull Modal Interval (yr)				
All fires	4.1	6.8	9.7	2.6
25%	16.7	11.7	11.0	11.7
Minimum interval (yr)				
All fires	1	1	3	1
25%	10	6	6	1
Maximum interval (yr)				
All fires	32	19	16	19
25%	33	32	23	32

Note: The Weibull distribution provides a standard way to compare fire regimes across ecological gradients (Grissino-Mayer 1999). Number with season means the number of fire scars for which an intra-ring position could be determined. DE fires are those that occur during the dormant period or when the tree is putting on its first earlywood (early earlywood).

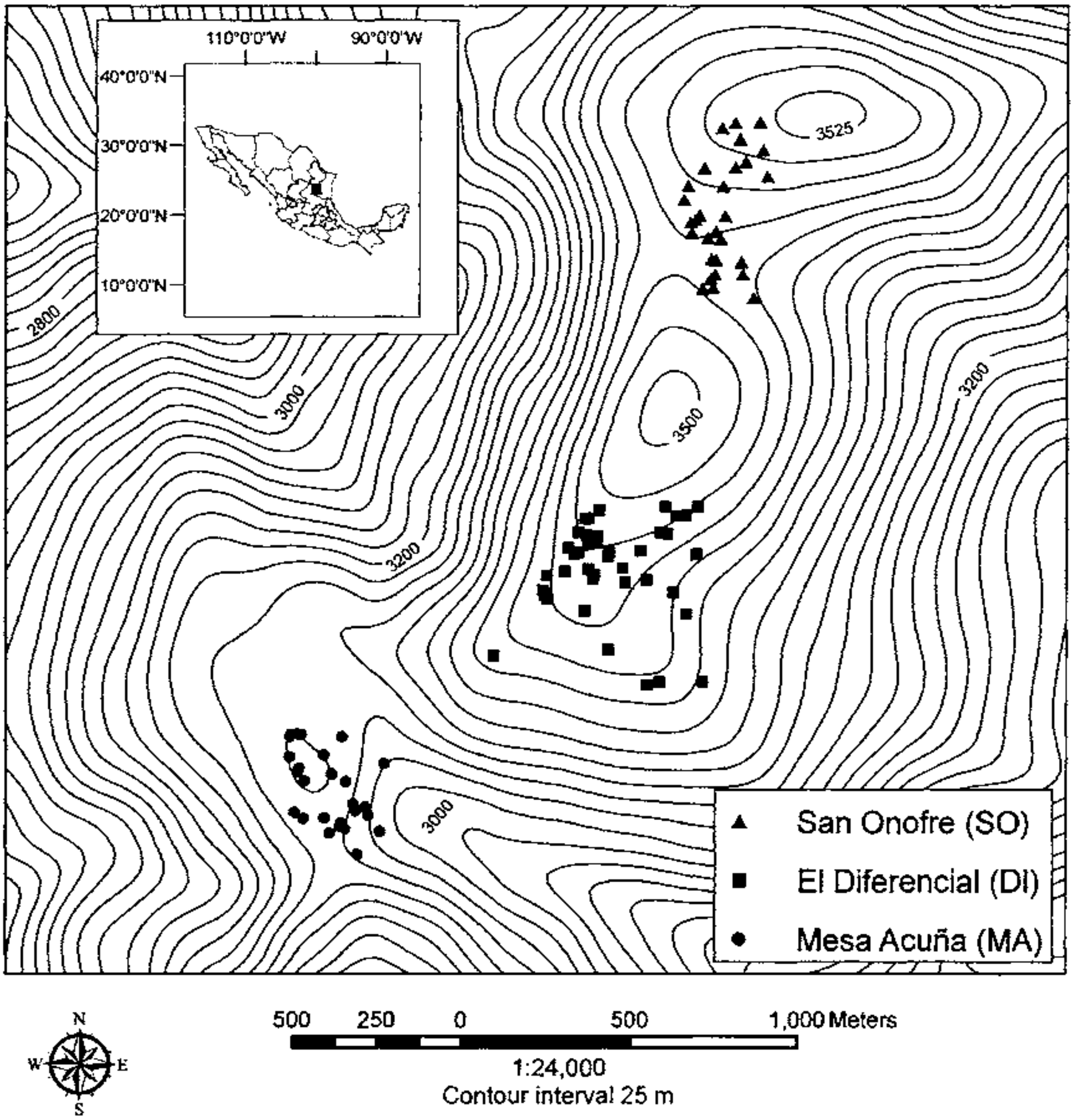

FIGURE 2.1. Map of the three study sites arrayed along the ridge north of Peña Nevada peak, Nuevo León, Mexico.

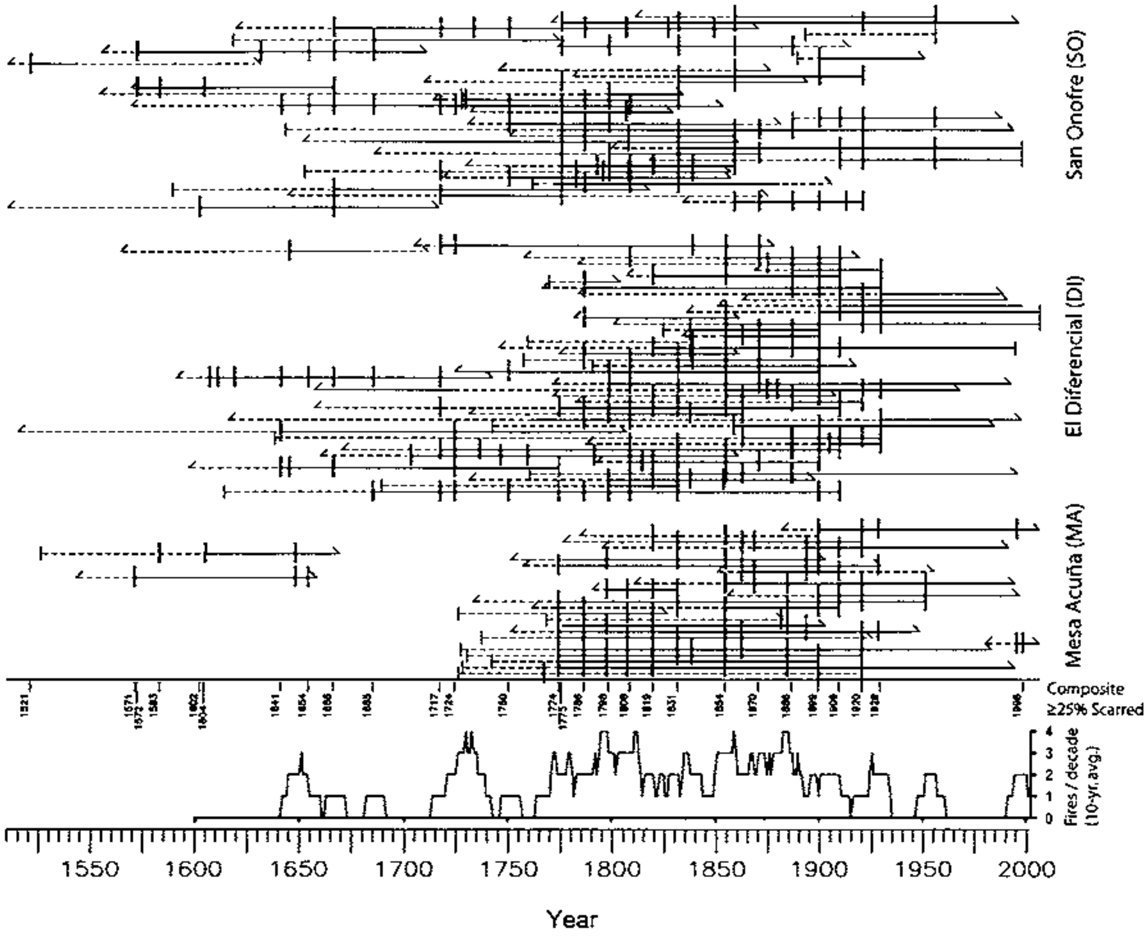

FIGURE 2.2. Fire history chart of Peña Nevada, 1510-2006. Horizontal lines represent samples and vertical lines represent fire scars. The composite record (filtered to include only those fires that scarred at least 25% of recording trees in all three sites) is shown with dates below the chart. Software: FHX2 v. 3.2 (Grissino-Mayer 2001). Also shown is a running (10-year) average of fires per decade (bottom).

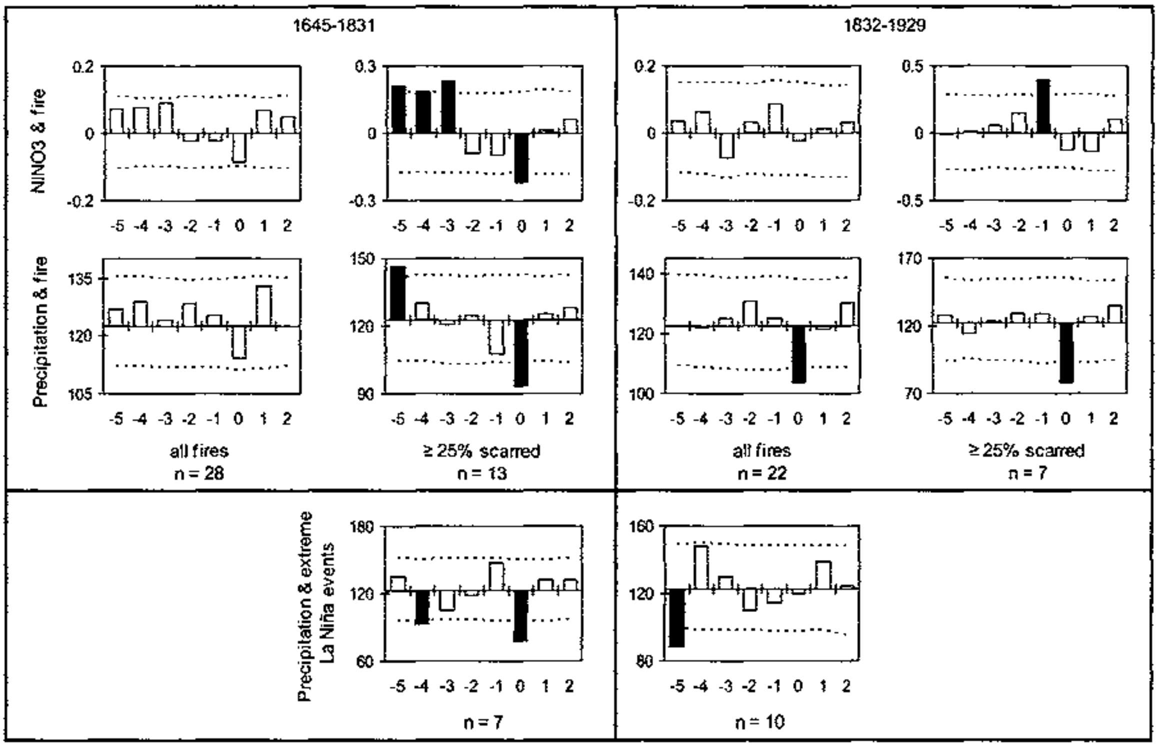

FIGURE 2.3. Top: superposed epoch analysis before 1831 and after 1832 showing departure from the mean value of NIÑ03 SST (top; sea surface temperatures; Cook 2000) and precipitation (middle; local reconstruction; Villanueva et al. 2007) for fire years in which all and ≥25% of samples were scarred. Fire years are indicated by 0, and values are also given for 5 years prior to fire years and 2 years after fire years. Black bars are those that pass the 95% confidence interval. Bottom: superposed epoch analysis showing departure from the mean value of precipitation for extreme La Niña years before 1831 and after 1832. La Niña years are indicated by 0.

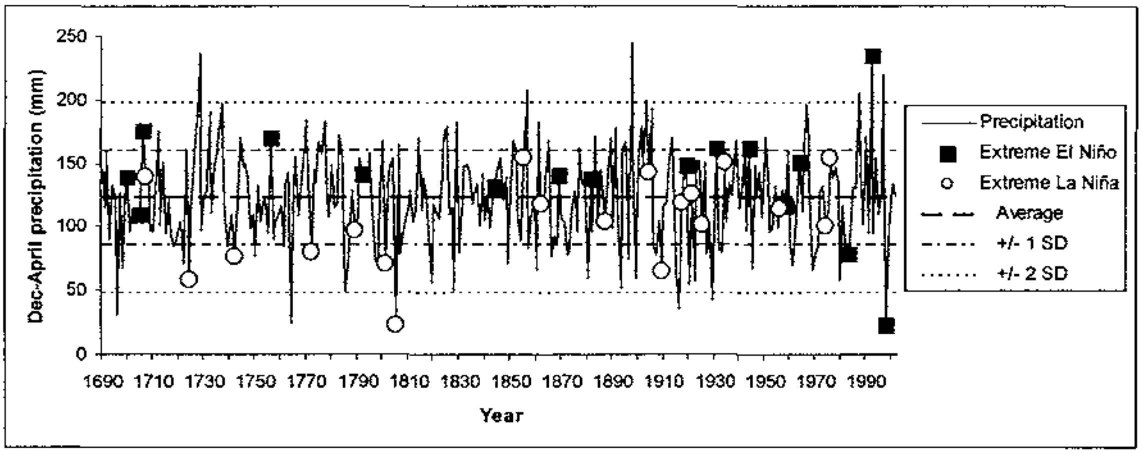

FIGURE 2.4. Relationship between reconstructed precipitation at Peña Nevada and extreme El Niño and La Niña years (extreme years 1699-1971 from Stahle and Cleaveland [1993]).

CHAPTER 3: COMPARING THE RELATIVE INFLUENCE OF BROAD-SCALE AND FINE-SCALE FACTORS ON FIRE OCCURRENCE IN NORTHEASTERN MEXICO

Abstract

Factors that affect fire occurrence operate on a continuum of scale, from fine-scale microsite variation in topography to broad-scale global climate oscillations. Fine-scale factors interrupt fire synchrony across landscapes, while broad-scale factors are influential in synchronizing fire across landscapes and even continents. In northeastern Mexico, we selected a study area with useful characteristics for distinguishing the influence of broad-scale vs. fine-scale factors. We worked in 9 sites on three parallel mountain ranges that receive nearly identical broad-scale climatic influence, but between which fires could unlikely spread. Our objectives were to 1) characterize the historical fire regime and describe the occurrence of low-severity and high-severity fire in our sites, 2) assess the relative influence of broad-scale and fine-scale factors by quantifying synchrony of fire dates within and among sites and mountain ranges, and 3) determine what influence the El Niño-Southern Oscillation (ENSO) had on fire occurrence and assess the stability of the relationship over time. We collected and cross-dated 383 fire-scarred samples and identified years in which fires occurred. We found that surface fires were the dominant fire type in our study area over the past several centuries, although there is evidence of high-severity disturbance at the scale of <25 ha. We also found low fire synchrony among mountains, indicating a strong influence of fine-scale factors on fire occurrence. Finally, La Niña events were associated with fire over time, although not significantly since the 1830s. Our results highlight the importance of scale in describing

fire regimes and suggest that we can use fire history to understand the controls on complex ecosystem processes.

Introduction

The relative influence of broad-scale and fine-scale controls on fire regimes depends on the scale of analysis and on the strength of the controls in a given area (Falk et al. 2007, Kellogg et al. 2008). Climate is a significant driver of wildfire synchrony at regional to continental scales (e.g. Swetnam and Betancourt 1990, Swetnam 1993, Heyerdahl et al. 2002, Kitzberger et al. 2007, Heyerdahl et al. 2008). Synchronous regional fire years, in which widely separated sites burn in the same year, can result from periods of widespread drought associated with regional-scale climate patterns. Human activity has also been described as a broad-scale influence on fire (Brown et al. 2001); for example, large landscapes in the southwestern USA were affected by humans between 1870 and 1900 when surface fire regimes were interrupted due to the introduction of livestock, logging, predator control, land use changes, and fire suppression (Swetnam and Baisan 2003).

Fine-scale variation in factors such as ignitions, topography, and fuel type, amount, and connectivity may reduce synchrony in fire between sites because they exert independent influences on a site-by-site basis, increasing heterogeneity in burn patterns (Brown et al. 2001, Kellogg et al. 2008, Iniguez et al. 2009). Controls may shift depending on the relative strength of forcing factors; fine-scale topographic influences or factors such as human ignition sources may be stronger in years with mild climate, but severe fire weather can override local factors and result in widespread synchrony of fire occurrences (Flatley et al. 2011).

Our understanding of the scales at which fine-scale and broad-scale factors influence fire occurrence is incomplete, although several studies have examined controls on fire at multiple scales (Falk et al. 2007). For example, Heyerdahl et al. (2001) inferred the influence of broad-scale factors using among-watershed variation in fire regime and the influence of fine-scale factors using within-watershed variation, and concluded that both broad-scale and fine-scale factors are influential on fire frequency, size, and season in the interior western United States. In another example from the Klamath Mountains, variation in fire frequency was related to aspect, and topographic features that acted as barriers to fire spread were important in defining spatial patterns of fire on the landscape (Taylor and Skinner 2003). Finally, Hessl et al. (2004) found that in the state of Washington, climate (summer drought and the positive phase of the Pacific Decadal Oscillation) was linked to fire, but these relationships were overridden by land use changes in the twentieth century.

Various studies have also explored the controls on fire using models. Parisien et al. (2010) found in a modeling exercise that weather-related variables had a larger effect on mean burn probability, while fuels and ignitions had a larger effect on the variability of burn probability, but the authors noted that cleanly separating broad-scale and fine-scale factors is not possible. Other modeling exercises have demonstrated that broad-scale controls are more important in topographically simple landscapes, while fine-scale controls are more important in topographically complex landscapes (Kellogg et al. 2008, Kennedy and McKenzie 2010).

Understanding how climate, as the most broad-scale factor affecting fire, interacts with controls at different scales and with fire occurrence itself, can help us anticipate changes that might occur as climate change progresses. Fire-climate information is also important from a management perspective, as one of the ways managers influence fire occurrence and severity is through the manipulation of fine-scale factors of fuels and prescribed ignitions. If fire is mostly controlled by broad-scale climate patterns, such management will be less effective (Westerling et al. 2006).

Fire/climate relationships in temperate pine forests of Mexico are among the least-studied in North America (Heyerdahl and Alvarado 2003). In northwestern Mexico, some studies have found a relationship between the El Niño Southern Oscillation (ENSO) negative phase (La Niña), drought, and fire occurrence (Heyerdahl and Alvarado 2003, Skinner et al. 2008). Another study documented a lag-year effect where fires tend to occur one year after a wet El Niño (positive ENSO phase) year (Drury and Veblen 2008). Only one long-term fire/climate study has been carried out previously in northeastern Mexico (although see González Tagle et al. 2007 for another fire reconstruction in the area), at Peña Nevada, a peak dominated by high-elevation *Pinus hartwegii* (Lindl.) forests (Yocom et al. 2010). There, Yocom et al. (2010) found patterns of frequent fire and a strong relationship between drought and fire years. The relationship between ENSO and fire changed in the 1830s: before the 1830s, La Niña events were strongly associated with fire occurrence, but the relationship disappeared after the 1830s and in recent years fires have burned at Peña Nevada during both strong El Niño and La Niña events. Also at Peña Nevada, Yocom et al. (2010) found one stand to be composed mostly of even-aged trees, with several synchronous pith (center) dates. Synchronous pith dates can be evidence of high-severity fire or other disturbance, which opens up growing space for a cohort of seedlings to establish (Brown and Wu 2005, Brown 2006).

The northern end of the Sierra Madre Oriental, in northeastern Mexico, provides a "natural experiment" to investigate the relative influences of broad-scale and fine-scale controls. This part of the Sierra consists of a series of east-west oriented, high, parallel forested mountain ranges separated by deep, non-forested valleys (Fig. 3.1). The distinctive topography allowed us to examine fire patterns in sites on mountain tops separated by only ~10 km. Because the mountain ranges are in such close proximity to each other, they experience the same broad-scale climatic influences, such as ENSO and regional drought. However, fire starts on individual mountain ranges are independent because fires would be unlikely to spread between them. Quantifying fire synchrony between sites and among mountain ranges thus allows us to differentiate between broad-scale and fine-scale controls on fire regimes. Broad-scale influence would be indicated by high fire synchrony among sites and among mountain ranges, suggesting that climate events (e.g. regional droughts, El Niño or La Niña events) strongly affected fire occurrence. Fine-scale control would be indicated by highly asynchronous fire occurrence among sites and among ranges, suggesting that fine-scale factors such as topography, fuels, and ignition sources were more important in determining the occurrence of fire. At the finest scale, differences among sites within mountain ranges could be attributable to local variation in topography or fuels. Intermediate levels of synchrony would indicate combinations of controlling factors at a given scale.

Our objectives were to 1) characterize the historical fire regime and describe the occurrence of low-severity and high-severity fire in our sites, 2) assess the relative influence of broad-scale and fine-scale factors by quantifying synchrony of fire dates among sites and mountain ranges, and 3) determine the influence the El Nino-Southern

Oscillation (ENSO) on fire occurrence and assess the stability of the relationship over time.

Methods

Study Area

We sampled nine sites on three different mountain ranges: San Antonio (southernmost; referred to as South), La Viga (middle; Central), and Rancho Nuevo (northernmost; North; Fig. 3.1). Three sites on each of these ranges were selected based on the presence of old trees or old remnant wood, in an effort to compile the longest possible tree-ring record. South Mountain had a shallow bowl with a meadow at the top; the three sites on South Mountain surrounded this meadow and faced south or southwest (Table 3.1). Average elevation of sites on South Mountain was 3259 m and average slope was 29%. The Central and North Mountains had sharp east-west ridgelines and the three sites on each of these mountains were located on the steep northern slopes. Sites on Central Mountain had an average elevation of 3388 m and average slope of 44%, and sites on North Mountain had an average elevation of 3144 m and average slope of 42%. The three mountain ranges were dominated by various mixtures of *Pinus hartwegii*, *Pinus strobiformis* (Engelmann), *Abies vejarii* (Martínez), and *Pseudotsuga menziesii* (Mirb.) Franco (Farjon 1990, Farjon and Styles 1997). The mountains in this region are the result of uplift and folding and exposed rock is limestone (Ferrusquía-Villafranca 1993). Weather data from San Antonio de las Alazanas (25° 16'N, 100° 37' W), near our study sites but at a lower elevation (2,170 m), indicated a yearly temperature average of 13° C and average yearly precipitation of 437 mm (1954 – 1999). Given the dry adiabatic lapse rate of 9.8 °C per 1000 m in elevation, yearly average temperature at our sites was between 1 and 3.5 °C. Average precipitation was likely higher than 437 mm at our study sites. Forests in this area have been used for centuries by local people for timber, fuelwood, and resin production (Ortega-Jiménez 2008). Fire suppression began in earnest with the publication in 1930 of regulations organizing the suppression of wildfires in this region (Ortega-Jiménez 2008).

Field Sampling

We collected fire-scarred tree samples from the study sites in 2001 (a pilot study done as part of the North American Dendroecological Fieldweek; Speer et al. 2006), 2007 and 2008. We established three 25-ha sites on each mountain, for a total of 9 sites. Sites on South Mountain are referred to as S1, S2, and S3, and so on (Fig. 3.1). On each mountain, study sites were spaced at a minimum of 0.5 km and a maximum of 2 km apart. We systematically searched each site and took fire-scarred samples that would provide good spatial distribution throughout the site, and we collected between 24 and 61 samples per site. We sampled dead trees of any species with the largest numbers of well-preserved fire scars (Van Horne and Fulé 2006), but we also sampled live trees, which often had only one or two scars, to ensure that the fire history extended up to the present. We used chain saws to remove partial cross sections of fire-scarred trees. We recorded the location of each tree to map the sample locations in each site.

In a companion study, to characterize forest species composition, we established and sampled 20 plots each in S2, C1, and N1. Overstory trees and stumps were measured in 200 m^2 circular plots. Data recorded for each tree included species, dbh, and height. Stumps were identified to species and diameter was recorded. We also took sections of several stumps from site S2 for dendrochronological analysis to determine when they were cut.

Laboratory Methods

In the laboratory, samples were sanded with increasingly finer grits of sandpaper until individual cells were clearly visible under a microscope. We visually crossdated each sample using a *Pseudotsuga menziesii* tree-ring chronology from Central Mountain (Villanueva-Diaz et al. 2007). The crossdating of a 10% subset of the samples was confirmed by a second dendrochronologist. We also measured the ring widths of each sample and checked the crossdating with the COFECHA software program (Holmes 1983). We identified fire scars to the year of formation by noting the crossdated ring in which the fire injury occurred (Baisan and Swetnam 1990). When possible, fire scars were determined to be located in the early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L), or on the boundary between rings (indicating a dormant (D) season fire). We assigned dormant season fires to the subsequent calendar year. We grouped fires into spring (D + EE) and summer (ME + LE + L) categories for seasonal evaluation.

Analysis

To quantify the historical fire regime, we calculated surface fire interval distributions for periods in which there was an adequate tree-ring record (Table 3.1), defined as beginning in the first fire year when at least 3 samples in that site were recording. The period of analysis for each site ended on the last year when at least 3 samples were scarred in order to describe the historical fire regime prior to a dramatic drop in fire frequency in the 19th or 20th centuries. The only exception was site 3b: although 8 samples were scarred in 1982, this fire followed an unprecedented period of 73 years without a fire that scarred more than one tree, and therefore was not included in the period of analysis. To assess the possibility of historical high-severity fire occurrence, which would have killed trees and opened up growing space for seedling establishment, we identified periods in each site with multiple pith dates, by identifying groups of pith dates clustered in 30-year periods.

We calculated fire interval statistics with FHX2 version 3.2 software (Grissino-Mayer 2001). For each site, we calculated the composite mean fire interval between all fires (hereafter referred to as "all fires"), and also between more widespread fires that scarred at least 25% of recording trees (hereafter referred to as "widespread fires"). Recording trees are those that have been scarred at least once; after an initial wound, trees of most species are more likely to scar in subsequent fires (Romme 1980) and therefore become "recording trees." We used the Kolmogorov-Smirnov goodness-of-fit test (α=0.05) to determine whether the Weibull median probability intervals (WMPI) fit the data adequately. The WMPI is the fire interval associated with the 50% exceedance probability of a modeled Weibull function fit to an empirical fire interval distribution (Grissino-Mayer 2001). Using JMP software, we also used Tukey's HSD (α=0.05) to test whether there were significant differences in mean fire interval among sites and among mountains.

To test whether fires occurred synchronously among sites and among mountains more often than would be expected by chance, we used chi-square tests. We used a 2x2 contingency analysis to compare observed vs. expected values of fire co-occurring on 0, 1, 2, or 3 mountains, since we did not expect that fires would spread between ranges due to the topography, vegetation differences between mountain ranges and valleys, and human settlements in the valleys (Grissino-Mayer 1995). We combined the 2 and 3 mountain categories to achieve a cell value greater than 5, which is necessary for the test. Expected values were estimated from joint probabilities of fire occurring or not occurring on the mountains. A 2x1 analysis was used to test synchrony between pairs of sites within each mountain since fire could easily spread between sites on each mountain.

We also evaluated the synchrony of fire occurrence patterns over time among sites on each mountain using the program K1D, which uses a modified Ripley's *K* function to test synchrony over time (Gavin et al. 2006). K1D determines the dependence between two or more types of events that are ordered in one dimension by calculating the multivariate Ripley *K*-function simplified for one dimension (Gavin 2010). In K1D, the *K* function is transformed to the *L* function, $\hat{L}_{AB}(t)$ where values near 0 suggest independence, values >0 suggest synchrony, and values <0 suggest asynchrony of fire occurrence within a window of *t* years. K1D also constructs 95% confidence envelopes for the $\hat{L}_{AB}(t)$ function from 1000 randomized simulations of the records.

To evaluate the influence of ENSO on fire occurrence at our study sites, we used superposed epoch analysis (SEA) in FHX2 (Grissino-Mayer 1995) to compare fire occurrence with an independently derived ENSO index. The SEA compared reconstructed NINO3 values (December-February, 1408-1978; Cook 2000) during superposed fire years, five years prior to fire years, and two years after fire years. To address temporal autocorrelation in the NINO3 index, we fit autoregressive integrated moving average models based on lowest Akaike's information criterion and significant but uncorrelated parameter estimates (Brown et al. 2008a) and used the resulting white noise residuals in our analyses. To assess statistical significance of the SEA results, we calculated 95% confidence intervals using bootstrapped distributions of climate data in 1000 trials. We compared ENSO with the occurrence of all fires regardless of size, as well as widespread fires that scarred at least 25% of recording trees in any of the nine sites. We analyzed ENSO association with fire before 1831 and after 1832 to evaluate whether the relationship changed at the same time that the ENSO/fire relationship changed 200 km to the south, at Peña Nevada. We considered evaluating the relationship between fire and local reconstructed Palmer Drought Severity Index (PDSI), obtained from the North American Drought Atlas (Cook and Krusic 2004). However, the PDSI reconstruction at the closest gridpoint to our study area had a consistent negative verification reduction in error (RE) statistic, which is generally interpreted to mean that the reconstruction is unreliable (Cook and Krusic 2004).

Results

Forest composition

S2 was dominated by a fairly even mixture of *Pinus hartwegii* (Lindl.), *Pinus strobiformis*, and *Abies vejarii* with small numbers of *Pseudotsuga menziesii* (Farjon and Styles 1997). Stumps in site S2 were cut in the mid-20th century. C1 was dominated by *P. hartwegii* with a smaller component of *A. vejarii*. N1 had mostly *A. vejarii* and *Pseudotsuga menziesii* trees with very small numbers of *P. hartwegii* and *P. strobiformis*. In our sites we also found small pockets of *P. culminicola* (Andresen et Beaman), an endangered pinyon pine endemic to the Sierra Madre Oriental, as well as isolated populations of *Populus tremuloides* (Michx.), and *Prunus* sp. Cut stumps in S2 and C1 were mostly *P. hartwegii*, and mostly *Pseudotsuga menziesii* in N1.

Fire regime

We collected a total of 383 fire-scarred samples in 2001, 2007, and 2008, most from pines (*Pinus hartwegii* and *P. strobiformis*) and a minority from *Pseudotsuga menziesii* and *Abies vejarii*. We were able to crossdate 357 of the samples (93.2%) and 1357 fire scars in total (Table 3.1). The earliest fire scar identified in any of the sites was from 1422, and the last fire scars formed in 1998. Of the fire scars where intra-ring position could be determined, 88% were formed in the dormant season.

Fires were relatively frequent at all sites over the past several centuries. Mean fire interval (MFI) for all fires ranged in individual sites from 7.8 to 16.4 years (Table 3.2). The Weibull function fit the data adequately in every site; the WMPI ranged from 6.7 to 13.9 years. For widespread fires (≥ 25% of recording trees scarred), MFI per site ranged from 12.7 to 27.6 years. Minimum fire interval in sites ranged from 1 to 4 years and maximum fire interval ranged from 19 to 79 years. On average, values of central tendency (MFI and WMPI) for all fires and for widespread fires were longest on Central Mountain and shortest on South Mountain. However, the differences in MFI between mountains were not significant. The only significant difference in MFI among sites was found for all fires between S1 and C1.

Several of our sites had pulses of tree regeneration in the past, based on pith dates of fire-scarred samples that are clustered within a 30-year period. South Mountain had the least evidence of pulses of regeneration, with few clusters of pith dates and only 3-6 trees per cluster (Fig. 3.2a). Pulses were most pronounced in sites on Central Mountain (C1, C2, and C3). Each of the sites had a pulse of regeneration in the mid-1700s (Fig. 3.2b). Thirteen samples in site C1 had pith dates between 1745-1758, 11 samples in site C3 had pith dates between 1736-1763, and 4 samples in site C2 had pith dates between 1741-1754. In addition, site C1 had a pulse of regeneration between 1564-1593 (9 samples), and site C2 had a pulse of regeneration between 1636-1662 (13 samples). There was evidence of clumps of regeneration on North Mountain as well, but there were fewer trees in each pulse (Fig. 3.2c).

A change in the fire regime occurred in the twentieth century, but the timing of the change varied between sites and between mountains (Fig. 3.2). On South Mountain, the last multiple-scar fires in sites S1, S2, and S3 were in 1918, 1887, and 1962, respectively. All three sites on Central Mountain (C1, C2, and C3) were consistent in the timing of fire exclusion, with the last multiple-scar fire occurring in each site in 1917. On North Mountain, the last multiple-scar fire in site N1 was in 1909, site N2 had a multiple-scar fire in 1909 and not again until 1982, and site N3 last experienced a multiple-scar fire in 1962.

Fire synchrony

Between 1622 and 2009, there were six years in which all three mountains recorded a fire (1622, 1654, 1689, 1785, 1797, and 1838) (Fig. 3.3). The years of highest synchrony among sites were 1785 and 1797, when 8 out of the 9 sites recorded fire.

Results of chi-square tests indicate that the level of synchrony among mountains and among sites is no higher than would be expected by chance ($p>0.05$).

Levels of within-mountain synchrony over time were different among mountains, as shown by graphs of the *L* function as a function of time (Fig. 3.4). Sites on South Mountain showed significant synchrony at 0 and 1-year time frames, and trended toward asynchrony at longer time windows. Central Mountain had significant synchrony between sites at 0-4 years, and significant synchrony at around 13, 17, 22, and 33 year windows. North Mountain exhibited intermediate levels of synchrony between South and Central Mountains. Significant synchrony was shown from 0-2 years and at around 36 and 64 years.

Fire-climate

La Niña events were significantly associated with the occurrence of fire in our study region before 1831 ($p<0.05$) and were associated strongly but not significantly after 1832 (Fig. 3.5). We found some slight differences between ranges and between sites in the relationship between fire and ENSO, but splitting the dataset by mountain and site reduced the sample size of fire events in the SEA analyses, so the results are not robust and are not shown here.

Discussion

High-elevation frequent fire regime

Overall, the three mountains historically had very similar fire regimes in terms of fire frequency and seasonality. In general, the fire regime on all three mountains was characterized by moderately frequent surface fire. However, there is variation among the mountains. MFI for all fires and widespread fires, WMPI, and maximum interval were all longer on average in Central Mountain sites than in sites on the other two mountains. South Mountain tended to have the shortest intervals of the three mountains. The mountain highest in elevation, Central Mountain, had more pulses of regeneration, which could be evidence of small patches of high-severity fire, but we found no evidence in our sites of high-severity fire at the scale of 25 ha or greater. Brown et al. (2008b) did not consider multi-aged stands with recruitment pulses that overlapped living trees (such as our sites) to indicate evidence of high-severity fire. However, we argue for the possibility that small patches of high-severity fire may have opened up gaps within our sites, at the scale of <25 hectares.

Fine-scale factors more influential than broad-scale factors

Low fire synchrony among mountain ranges suggests that fine-scale factors were most important in regulating fire regimes, with only six shared fire dates on all three mountains between 1622 and 2007, out of 126 total fire years during that period (~5%). Synchrony in our sites is much lower than in similar settings elsewhere; for example, in the Chiricahua Mountains in southeastern Arizona, fire history studies have been done in Sara Deming Canyon (Morino and Baisan 2000) and Rustler Park (Seklecki et al. 1996), two areas separated by 13 km of rugged terrain. Those two areas shared 16 fire dates (out of 66 total fire dates; 24%) between 1708 and 1894. At a larger scale, a regional analysis of fire dates in the Madrean Archipelago (SE Arizona, SW New Mexico, and NW Sonora) revealed that there were 30 years between 1648 and 1886 when at least 5 sites recorded fire (Swetnam 2005). This is a much higher level of synchrony, over a much larger region, than we found in our study area. However, synchrony among sites in our study area is comparable to synchrony among sites in El Malpais National Monument in New Mexico, another study location where some sites were separated by lava flows that act as natural barriers. In a 230-year period, 13 fire years coincided at four or more of the nine sites (Grissino-Mayer and Swetnam 1997). In comparison, in a 218-year period at our study sites, 10 fire years coincided at four or more of the nine sites. Fire synchrony among mountains at our site is no more than would be expected by chance alone, which indicates strong fine-scale influence on fire occurrence and little synchronization due to broad-scale climatic factors. We will discuss possible explanations for the surprisingly weak climatic entrainment of fire regimes at this scale in the next section.

We also found differences among mountains in terms of within-mountain synchrony, as shown in the K1D graphs. Central Mountain shows several periods of significant synchrony at longer time windows. This indicates that the three sites on Central Mountain share a decadal-scale pattern in common. The trend toward asynchrony on South Mountain indicates that the three sites on South Mountain, at the decadal and multi-decadal scales, are acting independently in terms of fire occurrence patterns.

The three mountains were not consistent in the timing of fire exclusion. Sites on Central Mountain were uniform; the last multi-scar fire at all three sites was in 1917. However, sites on North Mountain had their last multi-scar fires in 1909 or 1952, and sites on South Mountain were the least consistent, with last multi-scar fire dates in 1887, 1918, and 1962 in the three sites. This lack of synchrony in the onset of fire exclusion is unusual in comparison to many fire history studies from the western United States, where the onset of fire exclusion was not only consistent across study areas but fairly consistent across much of the western United States because of the onset of grazing, logging, and fire suppression. In western Mexico and in the only other published long-term fire history study in the Sierra Madre Oriental, the cessation of frequent fire was coincident with the formation of *ejidos*, which are rural communities living on and managing commonly-held land (Heyerdahl and Alvarado 2003, Yocom et al. 2010). In the area of our study sites, *ejidos* were formed in the mid- to late-1930s, which does not align exactly with the dates of last fires in our study sites. However, this area has a long history of human use of the forest (Ortega-Jiménez 2008); regardless of *ejido* formation, human influence was probably a factor in the cessation of fire at our sites.

Humans are sometimes considered a broad-scale influence in the western U.S. rather than a fine-scale influence because the influx of livestock, large-scale logging by settlers, and national fire suppression policies affected much of the region at around the same time (Swetnam and Baisan 2003). The lack of consistency at our study sites in northeastern Mexico suggests that, unlike in most of the western United States, humans influence fire occurrence at finer scales in northern Mexico. The difference could be due to differences in infrastructure and economy in the two countries. Railroad building in the western United States coincided with a massive increase in livestock grazing, because railroads allowed for an export economy. Settlers had incentive to graze as many animals as possible because the animals were not for personal use but could be shipped east for profit. Huge livestock herds ate the fine fuels necessary for the continuation of surface fires and helped cause the cessation of fire somewhat synchronously across the southwestern United States (Belsky and Blumenthal 1997). In addition, early grazing in the western United States was followed by an ambitious and generally successful policy of fire suppression that maintained fire exclusion (Pyne 1982). Although Mexico had similar policies (Rodríguez-Trejo 1996), the resources for effective backcountry fire suppression were much less.

Why do fine-scale factors prevail?

Our results suggest that at the scale of our study region, fine-scale factors predominate. Climate as a broad-scale factor was not strong enough to synchronize fire throughout the region any more than would be expected by chance. Why would this occur?

We do not have conclusive evidence but we can suggest some potential reasons. First, some level of stochasticity cannot be ruled out. Lertzman et al. (1988) found in a modeling exercise that substantial variability in fire regime can result from purely stochastic processes, with no underlying ecological causes. For example, although fine-scale patterns of lightning strikes actually may not be stochastic, we do not know enough about the regulating mechanisms to precisely model lightning at a fine scale and therefore we treat it as part of the unexplained variation in fire regimes.

Second, the high frequency of fire in this study region indicates that fires do not burn only in the most extreme climate years. A fire occurred somewhere in the nine sites every three years or less in the period common to all nine sites. Climatically, opportunities for fires to burn are fairly common; years with NINO3 values equal to or less than the average NINO3 value for all fires occurred in 140 out of 381 years between

1622 and 2002. If severe La Niña conditions were required for a fire to carry, fires would likely be more synchronous throughout the study area.

There are also several fine-scale factors that vary among the three mountain ranges, including elevation, topography, forest species composition, and land use history. These are interlinked factors that cannot be untangled; for example, elevation and forest species composition are highly correlated. First, elevation varies among mountain ranges. Central Mountain is the highest in elevation of the three mountains, with sites on average 130 m higher than sites on South Mountain and 244 m higher than on North Mountain. Central Mountain had the longest fire intervals, the most synchronous fires, and the strongest, most synchronous pulses of regeneration, which could indicate a history of higher-intensity disturbance. Many other studies have found longer fire intervals, more synchronous fires, and more stand-replacing disturbance with increasing elevation (Brown et al. 2001, Fulé et al. 2003, Margolis and Balmat 2009). Brown et al. (2001) note that fire severity and fire extent generally increase at higher elevations because of longer time periods between fires due to moister conditions, greater fuel loadings, higher fuel moisture, and more continuous fuel across a landscape. South Mountain, at intermediate elevation, has a fire regime characterized by higher fire frequency than the other mountains, lower synchrony among sites, and the least evidence of stand-replacing disturbances. North Mountain is the lowest in elevation but has an intermediate pattern of fire intervals, synchrony, and evidence for stand-replacing disturbance. Clearly, although elevation may play a role, it does not fully explain the differences in fire regimes.

Topography may be an important fine-scale influence on fire as well. While sites on Central and North Mountains were arranged on steep north-facing slopes, sites on

South Mountain were on three less sloping, mostly south-facing sides of a wet meadow. This difference in topography may also affect fuels. Average slopes varied; South Mountain sites were the least steep with average slopes of 28%. Sites on Central Mountain averaged 44% slope, and sites on North Mountain averaged 42% slope. It is possible that the steep slopes and lack of a barrier on Central and North Mountains result in more synchronous fires across the mountains; slopes have been shown to differ from flat areas in terms of fire occurrence (Gavin et al. 2003). South Mountain may experience smaller, more stochastic fires because of its flatter topography and the wet meadow in the center of the sites. In a study of fire history in the Santa Catalina Mountains in southern Arizona, Iniguez et al. (2008) also found that differences in fire history patterns were related to landscape-scale topography and differences between vegetation and fuels on north vs. south facing slopes.

Another potential fine-scale factor influencing fire is different species composition of the forests on the three mountains. Variation in species composition is probably related to elevation and land use history differences among the three mountains. There is only one other published report of *Pinus hartwegii* fire history: mean fire intervals for all fires in that study ranged from 8.6 to 9.6 years (Yocom et al. 2010), slightly shorter than the mean fire intervals on Central Mountain, which is also dominated by *P. hartwegii*. Composite mean fire intervals in mixed *Pseudotsuga menziesii* forests were less than 10 years in Texas (Sakulich and Taylor 2007). There are no published reports of fire history in *A. vejarii* mixed forests; *Abies* has examples of surface-fire-adapted species such as *A. concolor* and species adapted to high-severity fire like *A.*

lasiocarpa. However, it is well-documented that fire characteristics change with both elevation and vegetation (e.g. Margolis and Balmat 2009).

Differences in land use history may also have played a role in influencing fire. As elsewhere in Mexico, certainly humans have used fire in this region for various reasons over centuries. However, we do not know how many fires humans started in the area throughout history, nor whether human ignition patterns were different on the three mountains. We also do not know the full history of logging on these mountains, although we know from plot measurements that the tree species favored for cutting was different on North Mountain compared to South Mountain and Central Mountain. All three mountains have roads leading to the top. We saw evidence of grazing on South Mountain and seasonal human habitation on South Mountain and Central Mountain, but we don't know how much grazing currently takes place and we have no information on historical grazing activities. All three mountains are close to small human population centers in the valleys below and have probably been visited and used for centuries (Ortega-Jiménez 2008).

Kellogg et al. (2008) hypothesized that broad-scale controls are stronger in topographically simple landscapes, while bottom-up controls are more important in more topographically complex landscapes. This hypothesis was supported by modeling work by Kennedy and McKenzie (2010) using fire-scar data, and it is supported by our findings of strong bottom-up controls in a topographically very complex area. Flatley et al. (2011) concluded that topography is an important influence on fire but also that it can be overridden by climate. In our study region, there were only six years when all three mountains recorded fires, which indicates that in this case the synchronizing effect of climate rarely overrides the strong influence of topography.

The role of ENSO in our study region

Despite the lack of fire synchrony we found among the three mountains, there is a relationship between climate and fire occurrence in our study region. La Niña events were significantly or strongly associated with fire occurrence over time. There was a change in the relationship in the 1830s at this study area, but it was nuanced: La Niña events were still strongly associated with fire occurrence after the 1830s although the association was no longer significant at the 95% confidence level. This contrasts with previous results from Peña Nevada, where after the 1830s there was no relationship at all between ENSO and fire (Yocom et al. 2010). Our results suggest that these study sites, being farther north, are not as squarely in the transition zone where ENSO effects change over time. To fully investigate this point, we need a network of climate reconstructions and fire-climate sites in this region.

Our results highlight the importance of scale in describing fire regimes and suggest that we can use fire history to understand the controls on complex ecosystem processes. The three different mountains that we studied are heterogeneous in terms of forest composition, topography and elevation, and fires were asynchronous on the three mountains despite their close proximity. This emphasizes the importance of limiting inferences about a heterogeneous region based on a small sampled area. Our results suggest that fine-scale factors may lead to heterogeneous responses to climate change, even within a small region like our study area. Given these conclusions, further exploration of fire-climate relationships in the Sierra Madre Oriental is merited.

Acknowledgements

We thank local *ejidos* and landowners for permission to work on their land. We thank Dan Gavin for the development and help with the K1D software. Armando Becvort, Erica Bigio, Walker Chancellor, Julián Charles, Vicenta Constante García, Osvaldo Turlán Medina, and Cameron Fulé provided valuable assistance in the field. Many thanks also to Don Normandin, Charles Machula and other staff and students at the Ecological Restoration Institute. The pilot study in site S1 in 2001 was done as part of the North American Dendroecological Fieldweek. This research was supported by the National Science Foundation (DEB-0640351) and the Ecological Restoration Institute at Northern Arizona University.

Literature Cited

Baisan, C. H. and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research **20**:1559-1569.

Belsky, A. J. and D. M. Blumenthal. 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior West. Conservation Biology **11**:315-327.

Brown, P. M. 2006. Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. Ecology **87**:2500-2510.

Brown, P. M., E. K. Heyerdahl, S. G. Kitchen, and M. H. Weber. 2008a. Climate effects on historical fires (1630-1900) in Utah. International Journal of Wildland Fire **17**:28-39.

Brown, P. M., M. W. Kaye, L. S. Huckaby, and C. H. Baisan. 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: Influences of local patterns and regional processes. Ecoscience **8**:115-126.

Brown, P. M., C. L. Wienk, and A. J. Symstad. 2008b. Fire and forest history at Mount Rushmore. Ecological Applications **18**:1984-1999.

Brown, P. M. and R. Wu. 2005. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology **86**:3030-3038.

Cook, E. R. 2000. Nino 3 Index Reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series #2000-052. NOAA/NGDC Paleoclimatology Program, Boulder, CO.

Cook, E.R. and P.J. Krusic. 2004. The North American Drought Atlas. Lamont-Doherty Earth Observatory and the National Science Foundation.

Drury, S. A. and T. T. Veblen. 2008. Spatial and temporal variability in fire occurrence within the Las Bayas Forestry Reserve, Durango, Mexico. Plant Ecology **197**:299-316.

Falk, D. A., C. Miller, D. McKenzie, and A. E. Black. 2007. Cross-scale analysis of fire regimes. Ecosystems **10**:809-823.

Farjon, A. 1990. Pinaceae - drawings and descriptions of the genera Abies, Cedrus, Keteleeria, Nothotsuga, Tsuga, Cathaya, Pseudotsuga, Larix and Picea. Koeltz Scientific Books, Königstein.

Farjon, A. and B. T. Styles. 1997. Pinus (Pinaceae). Flora Neotropica Monograph 75. The New York Botanical Garden, Bronx, NY.

Ferrusquía-Villafranca, I. 1993. Geology of Mexico: A synopsis. Pages 3-108 *in* T. P. Ramamoorthy, R. Bye, A. Lot, and J. Fa, editors. Biological Diversity of Mexico: Origins and Distribution. Oxford University Press, New York.

Flatley, W. T., C. W. Lafon, and H. D. Grissino-Mayer. 2011. Climatic and topographic controls on patterns of fire in the southern and central Appalachian Mountains, USA. Landscape Ecology **26**:195-209.

Fulé, P. Z., J. E. Crouse, T. A. Heinlein, M. M. Moore, W. W. Covington, and G. Verkamp. 2003. Mixed-severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA. Landscape Ecology **18**:465-486.

Gavin, D. G. 2010. User's guide: K1D: Multivariate Ripley's K-function for one-dimensional data. University of Oregon.

Gavin, D. G., L. B. Brubaker, and K. P. Lertzman. 2003. Holocene Fire History of a Coastal Temperate Rain Forest Based on Soil Charcoal Radiocarbon Dates. Ecology **84**:186-201.

Gavin, D. G., F. S. Hu, K. Lertzman, and P. Corbett. 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology **87**:1722-1732.

González Tagle, M. A., L. Schwendenmann, J. Jiménez Pérez, and W. Himmelsbach. 2007. Reconstrucción del historial de incendios y estructura forestal en bosques mixtos de pino-encino en la Sierra Madre Oriental. Madera y Bosques **13**:51-63.

Grissino-Mayer, H. D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. University of Arizona, Tucson.

Grissino-Mayer, H. D. 2001. FHX2 - Software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research **57**:113-122.

Grissino-Mayer, H. D. and T. W. Swetnam. 1997. Multi-century history of wildfire in the ponderosa pine forests of El Malpais National Monument. New Mexico Bureau of Mines & Mineral Resources, Bulletin **156**:163-171.

Hessl, A. E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications **14**:425-442.

Heyerdahl, E. K. and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. Pages 196-217 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer-Verlag, New York.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology **82**:660-678.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurements. Tree-Ring Bulletin **43**:69-78.

Iniguez, J. M., T. W. Swetnam, and C. H. Baisan. 2009. Spatially and temporally variable fire regime on Rincon Peak, Arizona, USA. Fire Ecology **5**:3-21.

Iniguez, J. M., T. W. Swetnam, and S. R. Yool. 2008. Topography affected landscape fire history patterns in southern Arizona, USA. Forest Ecology and Management **256**:295-303.

Kellogg, L.-K., D. McKenzie, D. Peterson, and A. Hessl. 2008. Spatial models for inferring topographic controls on historical low-severity fire in the eastern Cascade Range of Washington, USA. Landscape Ecology **23**:227-240.

Kennedy, M. C. and D. McKenzie. 2010. Using a stochastic model and cross-scale analysis to evaluate controls on historical low-severity fire regimes. Landscape Ecology.

Lertzman, K., J. Fall, and B. Dorner. 1988. Three kinds of heterogeneity in fire regimes: at the crossroads of fire history and landscape ecology. Northwest Science **72**:4-23.

Margolis, E. Q. and J. Balmat. 2009. Fire history and fire-climate relationships along a fire regime gradient in the Santa Fe Municipal Watershed, NM, USA. Forest Ecology and Management **258**:2416-2430.

Morino, K. A. and C. H. Baisan. 2000. Final Report: Fire history in Chiricahua National Monument.

Ortega-Jiménez, S. 2008. Reconstrucción histórica del uso del bosque de San Antonio de las Alazanas, Arteaga, Coahuila. Universidad Autónoma Agraria Antonio Narro, Saltillo, Mexico.

Parisien, M.-A., C. Miller, A. A. Ager, and M. A. Finney. 2010. Use of artificial landscapes to isolate controls on burn probablity. Landscape Ecology **25**:79-93.

Pyne, S. J. 1982. Fire in America: A Cultural History of Wildland and Rural Fire. Princeton University Press, Princeton, NJ.

Rodríguez-Trejo, D. A. 1996. Incendios Forestales. Mundi Prensa-UACH-INIFAP, México, D.F.

Romme, W. H. 1980. Fire history terminology: report of the ad hoc committee. Pages 135-137 *in* Proceedings of the Fire History Workshop, Oct 20-24, 1980. USDA Forest Service, Tucson, AZ.

Sakulich, J. and A. H. Taylor. 2007. Fire regimes and forest structure in a sky island mixed conifer forest, Guadalupe Mountains National Park, Texas, USA. Forest Ecology and Management **241**:62-73.

Seklecki, M. T., H. D. Grissino-Mayer, and T. W. Swetnam. 1996. Fire history and the possible role of Apache-set fires in the Chiricahua Mountains of southeastern Arizona. In: Ffolliott, P.F., DeBano, L.F., Maker, Jr., M.B., Gottfried, G.J., Solis-Garza, G., Edminster, C.B., Neary, D.G., Allen, L.S., and Hamre, R.H., tech. coord., Effects of Fire on Madrean Province Ecosystems: A Symposium Proceedings. . USDA Forest Service General Technical Report RM 289: 238-246.

Speer, J. H., P. M. Brown, P. J. Krusic, and H. D. Grissino-Mayer. 2006. Professional fieldweeks as an educational experience and a venue for explorative research: Case study of the North American Dendroecological Fieldweek. Indiana State University, Department of Geography, Geology, and Anthropology:Professional Paper Series #23.

Swetnam, T. W. 2005. Fire histories from pine-dominant forest in the Madrean Archipelago. USDA Forest Service Proceedings RMRS-P-36.

Swetnam, T. W. and C. H. Baisan. 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. Pages 158-195 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and climate in temperate ecosystems of the western Americas. Springer-Verlag, New York.

Taylor, A. H. and C. N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications **13**:704-719.

Villanueva-Diaz, J., D. W. Stahle, B. H. Luckman, J. Cerano-Paredes, M. D. Therrell, M. K. Cleaveland, and E. Cornejo-Oviedo. 2007. Winter-spring precipitation reconstructions from tree rings for northeast Mexico. Climatic Change **83**:117-131.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science **313**:940-943.

Yocom, L., P. Z. Fulé, P. M. Brown, J. Cerano-Paredes, J. Villanueva, E. Cornejo-Oviedo, and D. A. Falk. 2010. El Niño-Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time. Ecology **91**:1660-1671.

TABLE 3.1. Characteristics and fire scar information for the 9 sites sampled in this study.

Mountain	Code	Site	Average Elevation (m)	Average Slope (%)	Average Aspect	Samples dated	Number of fire scars	Period of analysis
South: San Antonio	S1	La Armenia	3270	41	SW	39	248	1614-1918
	S2	Las Bateas	3253	22	SW	29	141	1648-1887
	S3	Las Manzanas	3253	22	S	22	80	1666-1962
Central: La Viga	C1	La Viga	3463	34	N	54	200	1654-1917
	C2	Musgoso	3414	52	N	42	159	1696-1917
	C3	Paraíso	3286	46	N	44	150	1709-1917
North: Rancho Nuevo	N1	Rancho Nuevo	3140	35	N	48	135	1729-1909
	N2	El Tarillal	3081	47	NE	31	122	1755-1909
	N3	Puerto El Tarillal	3211	44	N	48	122	1710-1952
Total						357	1357	

TABLE 3.2. Measures of fire frequency. Fire intervals are for all fire dates recorded at each site during each site's period of analysis unless otherwise indicated. MFI is mean fire interval, "all fires" refers to any fire regardless of size, and "25% fires" refers to more widespread fires that scarred ≥25% of recording trees. WMPI is Weibull Median Probability Interval.

Site	# Intervals	Mean fire interval: all fires (yr)	WMPI: all fires (yr)	Mean fire interval: 25% fires (yr)	Minimum fire interval (yr)	Maximum fire interval (yr)
S1	39	7.8	6.7	12.7	1	28
S2	25	9.6	7.9	14.1	1	29
S3	23	12.9	11.4	17.4	2	32
C1	16	16.4	13.9	23.9	2	47
C2	14	15.8	11.1	27.6	1	79
C3	19	11.0	9.0	16.0	1	37
N1	14	12.9	12.0	13.9	3	28
N2	12	12.8	12.3	15.4	4	24
N3	25	9.7	8.7	20.2	1	19

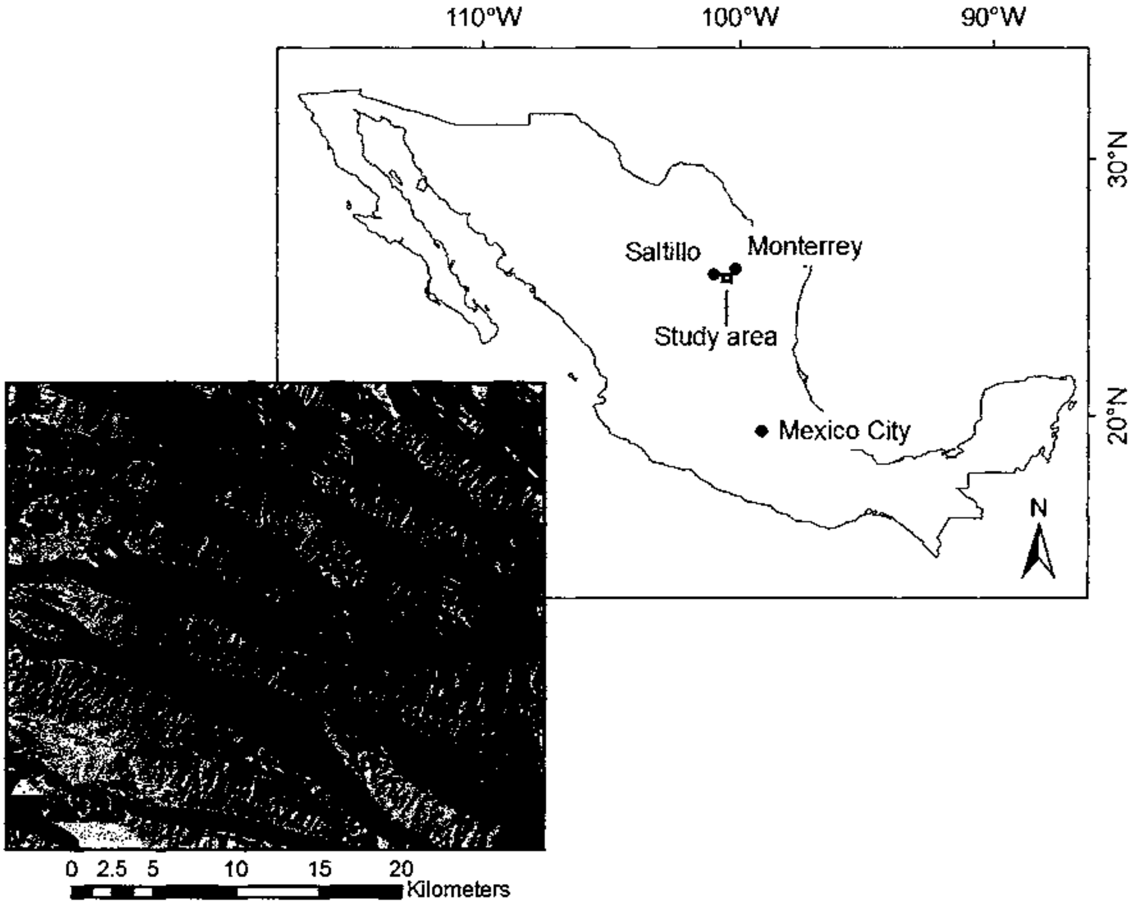

FIGURE 3.1. Top: location of study area in Mexico. Bottom: Location of nine sites on three mountain ridges. Elevations of the sites on the three mountains average 3259 m (South), 3388 m (Central), and 3144 m (North).

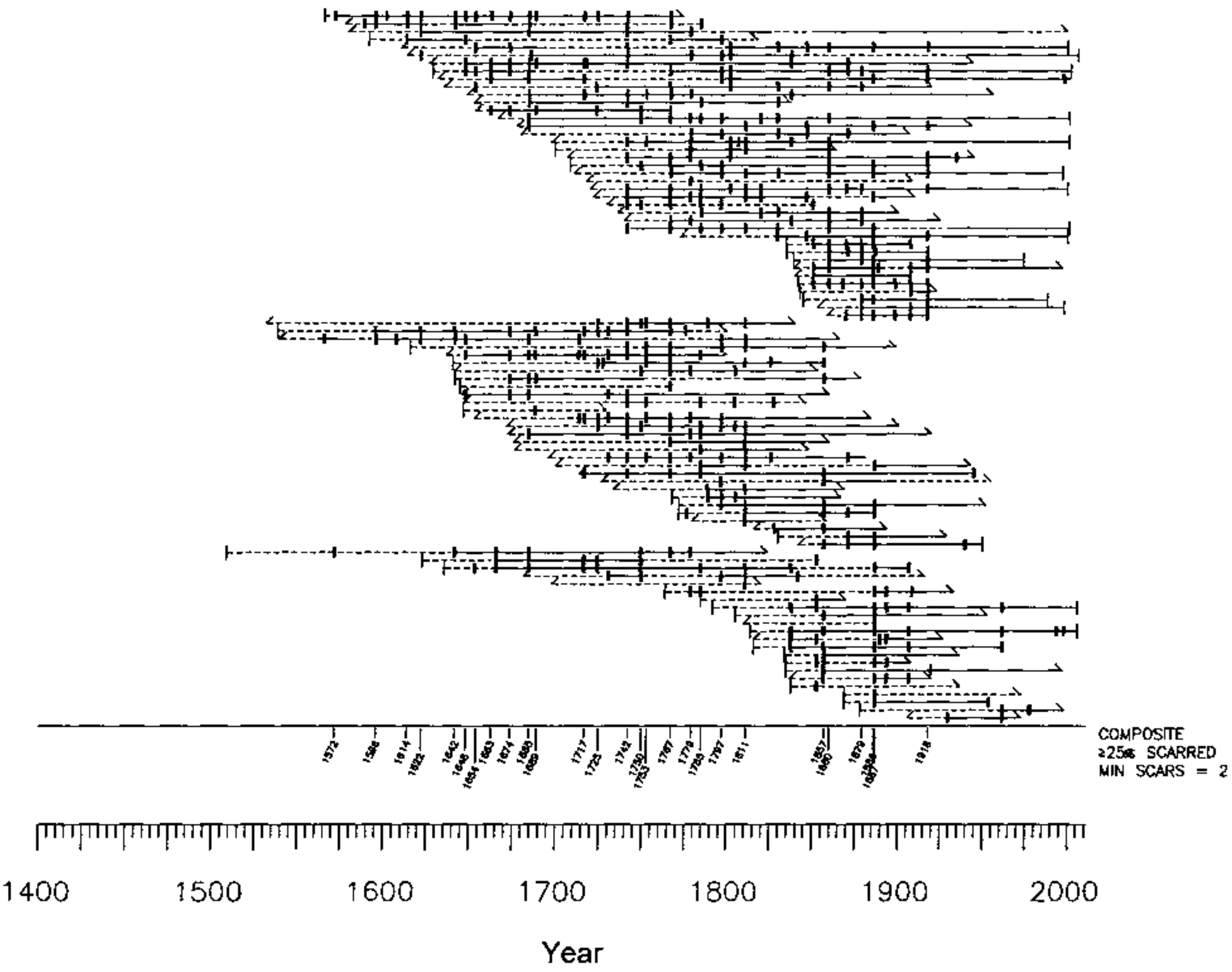

FIGURE 3.2A. Fire history graph for South Mountain. Horizontal lines represent individual tree samples; solid horizontal lines represent periods when the sample was recording and dashed horizontal lines represent periods when the sample was not recording. Bold vertical tick marks represent precisely dated fire scar dates. Vertical lines to the left represent pith dates, and slanted lines to the left represent inside ring dates (i.e., unknown number of years to pith).

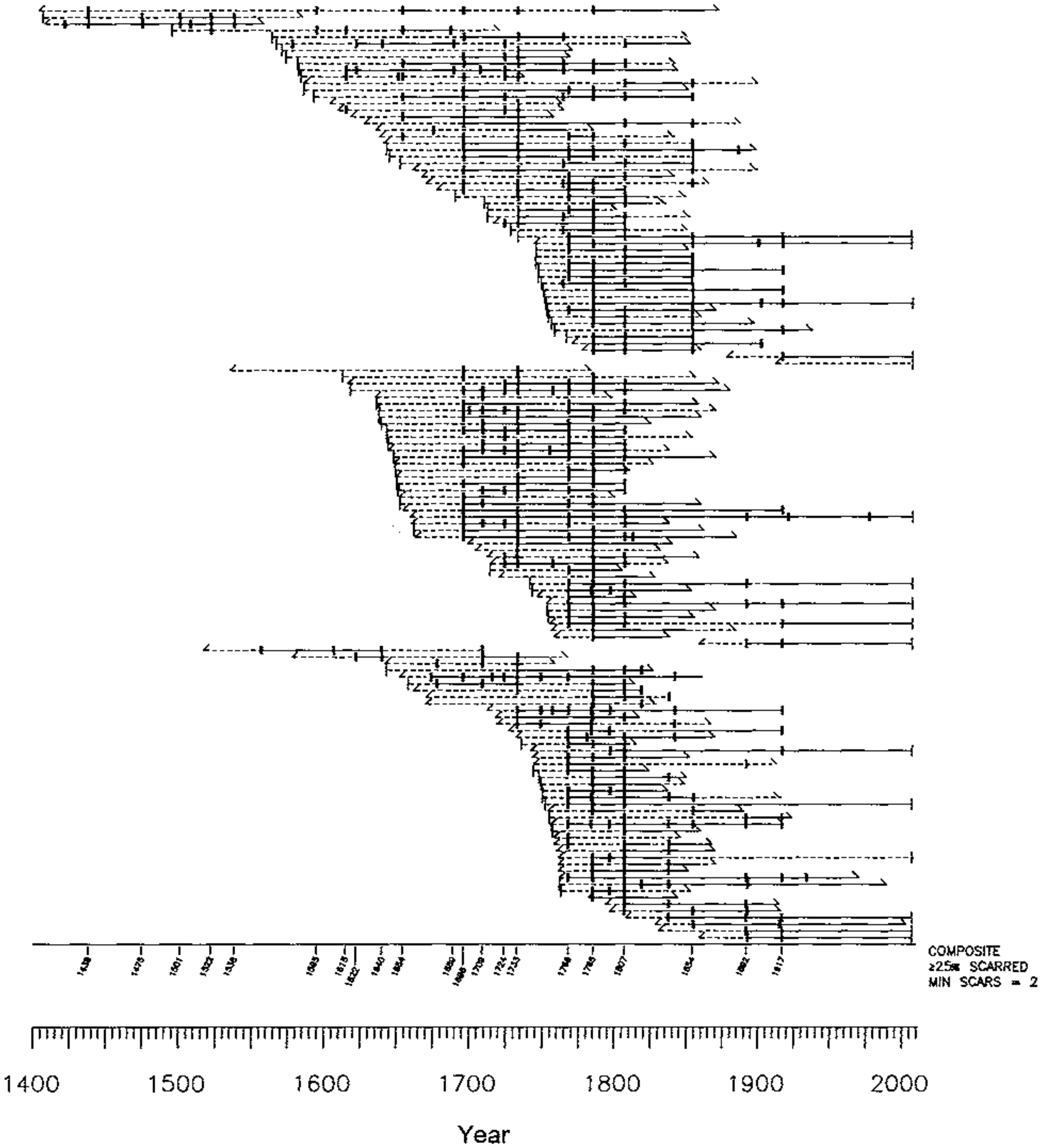

FIGURE 3.2B. Fire history graph for Central Mountain. Horizontal lines represent individual tree samples; solid horizontal lines represent periods when the sample was recording and dashed horizontal lines represent periods when the sample was not recording. Bold vertical tick marks represent precisely dated fire scar dates. Vertical lines to the left represent pith dates, and slanted lines to the left represent inside ring dates (i.e., unknown number of years to pith). Grey boxes indicate 30-year periods with ≥8 pith dates.

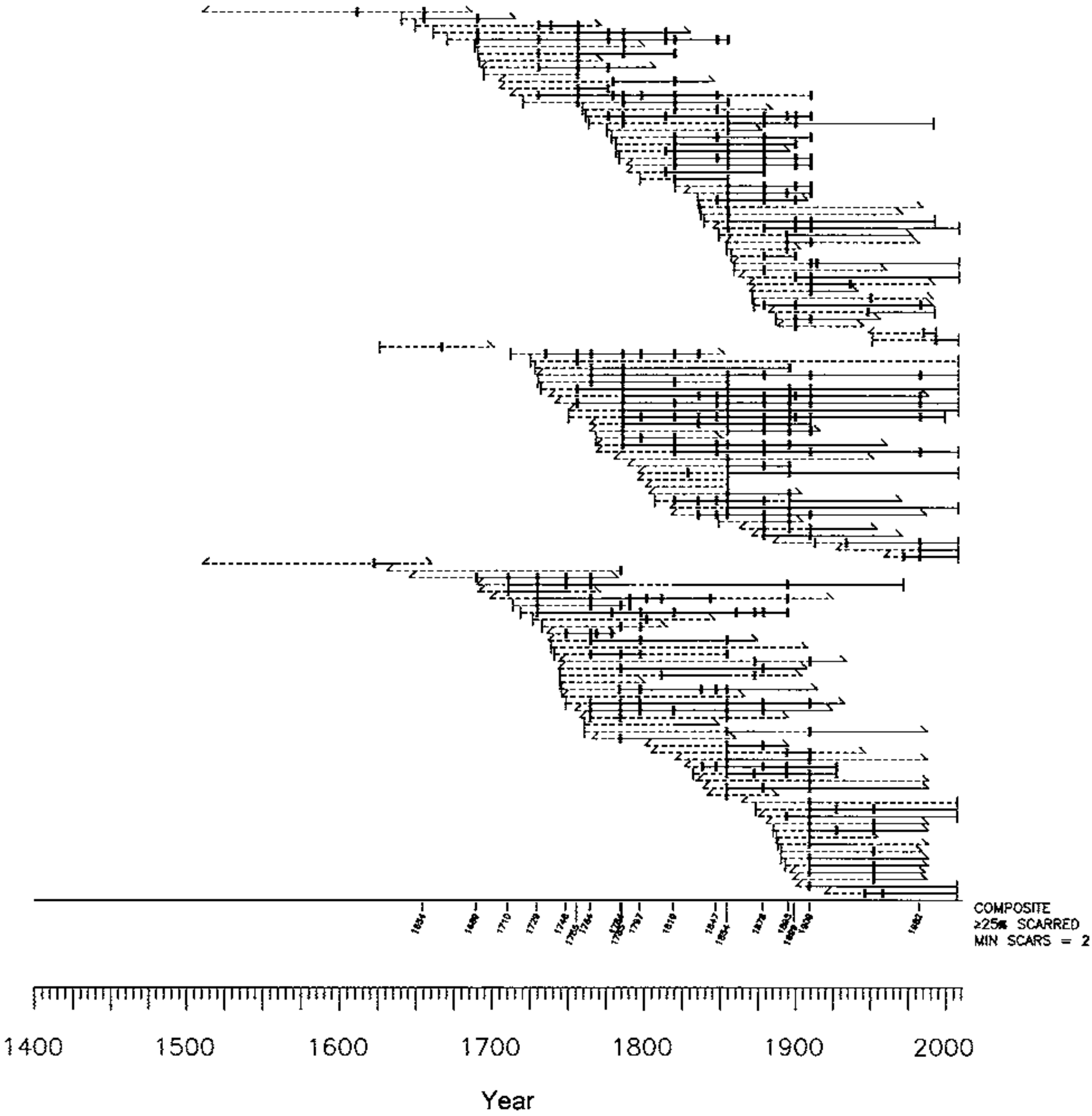

FIGURE 3.2C. Fire history graph for North Mountain. Horizontal lines represent individual tree samples; solid horizontal lines represent periods when the sample was recording and dashed horizontal lines represent periods when the sample was not recording. Bold vertical tick marks represent precisely dated fire scar dates. Vertical lines to the left represent pith dates, and slanted lines to the left represent inside ring dates (i.e., unknown number of years to pith). Grey boxes indicate 30-year periods with ≥8 pith dates.

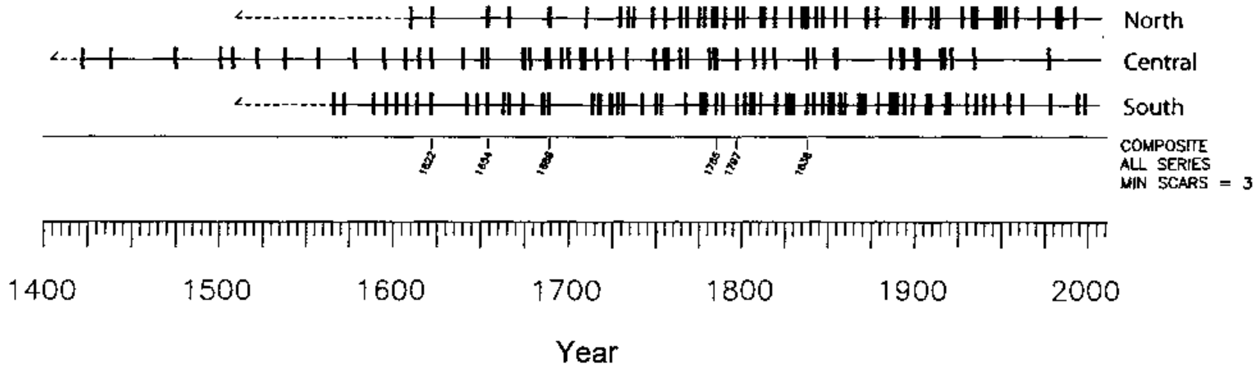

FIGURE 3.3. Graph showing all fires on each mountain. The six years listed at the bottom of the figure are the only years in which all three mountain ranges recorded fire simultaneously.

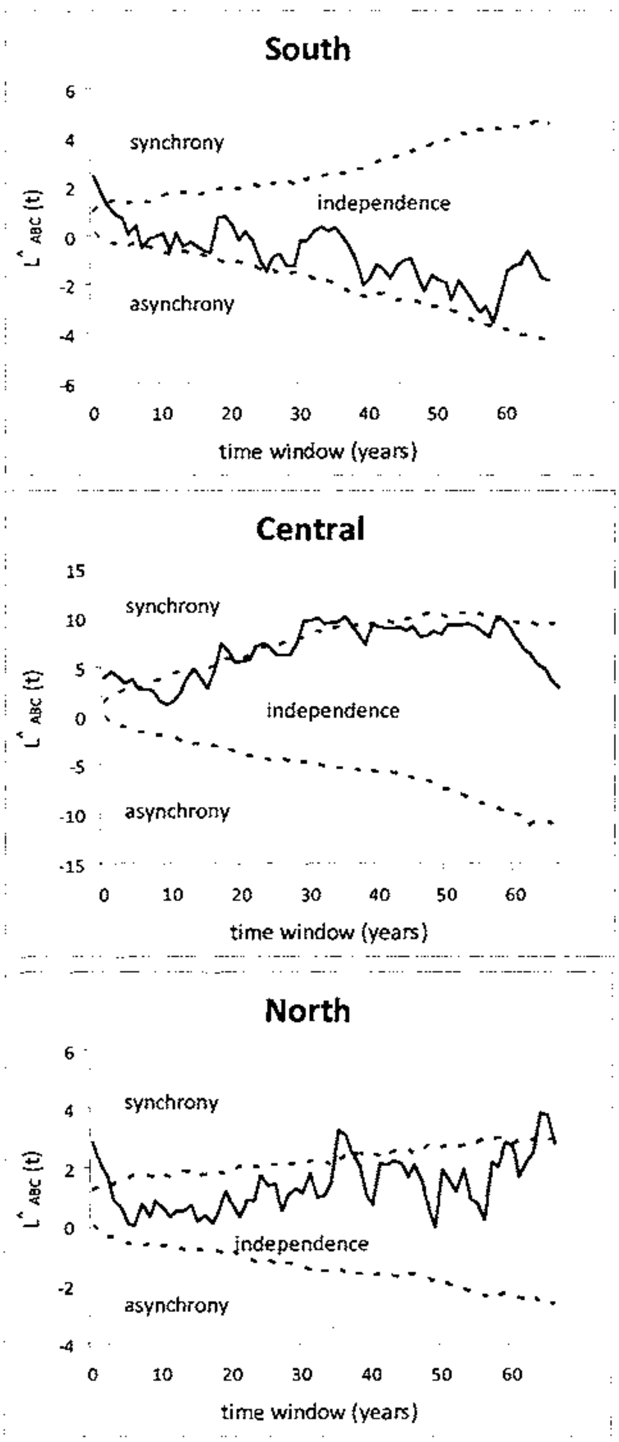

FIGURE 3.4. *L* function graphs generated in K1D for South, Central, and North mountains. The graphs show the temporal windows (t) in which fire episodes are independent or synchronous between the three sites on each mountain. Thin lines are 95% confidence envelopes based on 1000 randomizations of shifting records relative to each other.

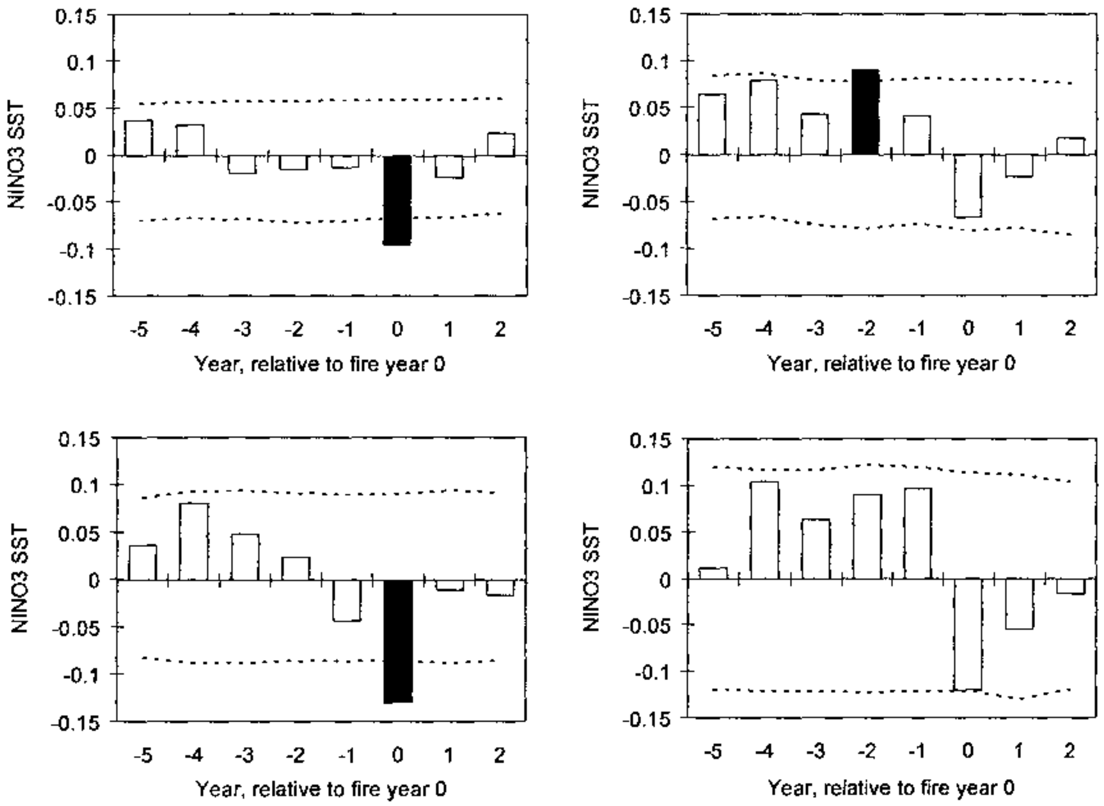

FIGURE 3.5. Superposed epoch analysis before 1831 (left) and after 1832 (right) showing departure from the mean value of prewhitened NINO3 SST (sea surface temperatures; Cook 2000) for all fire years (top) and fire years in which ≥25% of samples were scarred in any of the nine sites (bottom). Fire years are indicated by 0, and values are also given for five years prior to fire years (negative values) and 2 years after fire years. The black bars pass the 95% confidence interval.

CHAPTER 4: OLD FOREST SUPPORTS VERY FREQUENT SURFACE FIRE: PICO DE ORIZABA NATIONAL PARK, MEXICO

Abstract

Pico de Orizaba in southeastern Mexico is North America's third-tallest peak, supporting timberline forests of *Pinus hartwegii* that are highly isolated from other *P. hartwegii* populations. In 1975, researchers reported that increased human-caused burning was degrading the forests on this peak. We measured forest structure and fire history to test the hypothesis that human-caused fires have changed the fire regime and degraded the forest by increasing mortality and decreasing regeneration. In contrast to northern Mexico, where La Niña events are associated with fire, we hypothesized that fire occurrence at Pico de Orizaba, which is south of the Tropic of Cancer, is associated with El Niño events. We established 6 sites of 12 ha each in Pico de Orizaba National Park, measured forest structure and age distribution, and collected fire-scarred samples. We found that the forest was uneven-aged and contained many large and old trees (basal area range 16.3 to 34.5 m^2 ha^{-1}, maximum age 483 years). In the twentieth century, a fire scarred at least one tree in at least one of our sites in 90 of 100 years: a very frequent surface fire regime, although most fires were small and asynchronous. We found no increase in fire frequency or evidence of recent degradation of the forest, so our first hypothesis was not supported, at least for this region of the Park. Inter-annual climatic variability was not an influential driver of fire, and ENSO was not significantly related to the occurrence of widespread fire, although there was a weak trend toward a fire relationship with La Niña events. Our second hypothesis was not supported by these results. We conclude that for the portion of Pico de Orizaba National Park that we

studied, the old forest has supported very frequent fire, not associated with ENSO oscillations, for at least 150 years. A trend in the 21st century toward decreased fire could be cause for concern, as a decrease in frequent fire could lead to an increase in tree density and a loss of resilience in the face of climate change and other future disturbance.

Introduction

Old forests around the world are rare and valuable relicts. Threats to old forests include timber cutting, climate change, and disturbance such as severe fire (Abella et al. 2007). In central Mexico, a series of tall volcanic peaks form a chain of geographically isolated "islands" of high-elevation forest. These peaks are of high conservation value because they support unique species and are often less disturbed by people than low-elevation ecosystems that are close to dense populations. They are also important for the region's water supply. At the treeline on these peaks, the forests form monospecific stands of *Pinus hartwegii* (Lindl.), Mexico's highest-elevation pine. Since *P. hartwegii* is restricted to the timberline, its populations are highly isolated. In a study of four populations of *P. hartwegii* in Mexico, it was found that each had diverged significantly since they were isolated, the isolation was ancient rather than recent, and there is no evidence of gene flow between the populations on different mountains (Schaal and Leverich 1996). High levels of geographic isolation can lead to demographic and genetic instability (Schaal and Leverich 1996).

Pinus hartwegii has several fire adaptations, including the ability to regenerate well in a fire-created seed bed, thick bark, a self-pruning capacity, the ability to recover from crown scorch, and the capacity to resprout (Rodríguez-Trejo and Fulé 2003). It also may exhibit the grass stage (Rodríguez-Trejo 2008), another characteristic of fire-adapted species. Two fire history studies have been completed in *P. hartwegii* forests, both in the Sierra Madre Oriental of northeastern Mexico, several hundred kilometers north of Pico de Orizaba. The results of those studies indicate that the historical fire regime was characterized by frequent surface fires (mean fire intervals ranged from 8.6 to 16.4 years). In those studies, there was no evidence of resprouting in any of the *P. hartwegii* trees (Yocom et al. 2010, Yocom et al. in prep.). However, the range of *P. hartwegii* extends from northern Mexico south to Guatemala and Honduras, and it is possible that other populations of this species, including those that have been documented to resprout, may experience different fire regimes.

The fire regime in these high-altitude forests is relatively unknown. Rodríguez-Trejo and Fulé (2003) suggested that three categories of forest exist in Mexico: (1) forests that have been altered to experience relatively little fire in recent decades as compared to historical fire occurrence, due to human-induced fire exclusion, (2) forests that have continued to burn at frequencies and severities similar to historical patterns, and (3) forests that have received excessive fire with deleterious ecological consequences due to human practices of setting fire for agricultural or other uses. Fire history studies that have been conducted in Mexico to date have found either a history of regular, frequent fires continuing up to the present with little human interference (e.g. Fulé et al. in press), or an abrupt cessation of fires, correlated with increased human land use including livestock grazing, road building, and timber harvesting, often associated with the formation of *ejidos* (e.g. Heyerdahl and Alvarado 2003, Yocom et al. 2010). No dendrochronological fire history studies have found that human-caused fires are excessive to the point of degrading the forest, but all of the quantitative fire history studies that have been done in Mexico to date were carried out in the more sparsely populated northern part of the country.

In central and southern Mexico, some forests have been degraded by an excess of human-caused fires (Román-Cuesta et al. 2004). One forest that has been reported to have experienced degradation due to human-caused fires is on Pico de Orizaba, a high volcanic peak in a national park in southeastern Mexico (Fig. 4.1). Lauer and Klaus (1975), who studied the timberline at Pico de Orizaba in the 1970s, observed that people using the lower slopes of the mountain for animal grazing set fires for agricultural reasons. Although Lauer and Klaus (1975) did not quantitatively study the fire regime, they speculated that human-ignited fires on these volcanoes were different in several ways from natural lightning-caused fires: 1) they take place almost every year, whereas natural fires were estimated to occur every 6-7 years, 2) they are set most often in February and March while natural fires occurred at the beginning of the rainy season in May, and 3) they are started below the timberline and swept up into the crowns of trees by the upslope wind, while natural fires typically started at timberline and moved downslope as surface fires. They also speculated that the timberline at Pico de Orizaba had become lower in elevation due to human-caused fire (Lauer and Klaus 1975, Lauer 1978). The present study is designed to test several of their ideas. If the hypothesis that humans have altered the fire regime by causing an increased number of fires in recent decades is correct, this would be the first long-term, dendrochronology-based documentation of increased fire due to human activities in Mexico.

The geographical location of Pico de Orizaba National Park is also ideal for testing fire relationships with El Niño Southern Oscillation (ENSO). The dipole between northern Mexico, where La Niña events tend to be correlated with dry conditions, and southern Mexico, where El Niño events tend to be correlated with dry conditions, is located close to the Tropic of Cancer (Fig. 4.1). Pico de Orizaba National Park is located in the region where El Niño conditions are associated with below-average precipitation, based on precipitation-ENSO index correlations. In northwestern Mexico, several studies have linked fire occurrence to La Niña events (Fulé and Covington 1999, Heyerdahl and Alvarado 2003, Fulé et al. 2005, Skinner et al. 2008). In northeastern Mexico, the situation is more complicated, with a finding at Peña Nevada in the Sierra Madre Oriental that there was a changing relationship between El Niño/La Niña phases, precipitation, and fire over time, with one change occurring around 1830 and another occurring in the late twentieth century (Yocom et al. 2010). At the northern end of the Sierra Madre Oriental, there has been a more consistent trend toward an association between La Niña events and fire (Yocom et al. in prep.), but the association is not as strong as it is in the Sierra Madre Occidental. In contrast to northern Mexico, fire in southern Mexico is more likely to occur during El Niño events such as the El Niño events of 1983 and 1998 (Román-Cuesta et al. 2003). However, there have been no previous fire history reconstruction studies done in this region.

The objectives of this study were to test the following hypotheses and sub-hypotheses:

1) Humans have altered the fire regime, which has resulted in degradation of the forest.

a. Fire regime changes included an increase in fire frequency, a change in fire type from surface fire to crown fire, and a change in seasonality of fire.

b. Forest degradation is evidenced by high tree mortality and little regeneration.

c. Forest structure, demographics, or fuel loads put the forest at risk of severe disturbance.

2) ENSO is related to fire occurrence at this location.

a. El Niño events are associated with fire occurrence.

b. The relationship between ENSO and fire has been consistent over time.

Methods

Site Description

The study area, Pico de Orizaba National Park, was chosen based on its unique characteristics, including its status as a national park (high conservation value and potential), its geographical location in Mexico, and because more than thirty years ago, scientists noticed what they considered to be changed fire ecology due to human activities.

Pico de Orizaba, (also called Citlaltépetl, meaning "star mountain" in the Náhuatl language), is the highest peak in Mexico and the third highest peak in North America. Pico de Orizaba is a dormant volcano; the last known eruption, which was a minor ash eruption, was in 1846. The last major eruption was over 4000 years ago (de la Cruz-Reyna and Carrasco-Núñez 2002). The volcano is located on the border of the states of

Veracruz and Puebla at the eastern end of the Trans-volcanic Belt, a chain of high volcanoes that stretches across central Mexico. The peak has an elevation of 5,675 m above sea level. Its companion peak, Sierra Negra, approximately 7 km to the southwest, is at 4,600 m above sea level. The forest at the timberline, which is between 3,900 and 4,200 m, is dominated by *Pinus hartwegii* (Fig. 4.2), which has been lightly impacted by tree cutting or wood gathering. The understory consists mostly of thick bunch grasses including *Calamagrostis tolucensis* (Kunth) Trin. ex Steud., *Festuca tolucensis* (Kunth), and *Muhlenbergia quadridentata* (Kunth) trin. (Lauer and Klaus 1975).

Using temporary weather stations, Lauer and Klaus (1975) estimated that mean annual temperature at 4000 m above sea level on the north side of Pico de Orizaba was 5° C with an average 6° C mean daily range. Mean annual precipitation was 900 mm, which was a decrease from the 1300 mm per year estimated at 3300 m above sea level.

ENSO-Precipitation Correlation Map of Mexico

To characterize the relationship between ENSO and precipitation over time in Mexico, we created a map of correlations between weather station precipitation data and the Southern Oscillation Index (SOI) (see Caso et al. 2007 for a similar map, but restricted to the Pacific coast of Mexico). SOI is the difference in surface air pressure between Darwin, Australia, and Tahiti and is a measure of ENSO. From the ERICIII database, we extracted data for weather stations that had $\geq 90\%$ complete data for ≥ 30 years. We calculated correlations between precipitation data from these "high-quality" weather stations and SOI and mapped the results, coding each weather station on the map by direction and strength of the correlation (Fig. 4.1).

Field methods

We established 6 sites of 12 ha each at timberline in Pico de Orizaba National Park in 2009. The sites are arrayed in the saddle between Pico de Orizaba and Sierra Negra (Fig. 4.1). We chose the six sites based on the presence of old trees or old remnant wood, with the goal of compiling the longest possible tree-ring record for the analysis of fire history and fire-climate relationships. Because of our emphasis on finding old wood, this area does not necessarily represent the whole park. The average elevation of the six sites ranges from 3912 m to 4132 m above sea level and the average slope ranges from 38.0% to 60.7% (Table 4.1).

Fire history

We collected fire-scarred tree samples from the study sites. We systematically searched each site and took fire-scarred samples that would provide good spatial distribution throughout the site and the longest fire record possible. We used chain saws to remove partial cross-sections of fire-scarred trees, both live and dead. We recorded the following data for each sample: tree species, diameter at breast height (DBH), and status (live, stump, snag, or log).

In the laboratory, samples were sanded with increasingly finer grits of sandpaper until individual cells were clearly visible under a microscope. We visually crossdated each sample, measured the ring widths, and checked the crossdating with the COFECHA software program (Holmes 1983). We identified fire scars to the year of formation by noting the crossdated ring in which the fire injury occurred (Baisan and Swetnam 1990).

Where possible, we also noted the position of each fire scar within the annual growth ring.

Fire interval statistics were calculated with FHX2 version 3.2 software (Grissino-Mayer 2001). For each site, we calculated the twentieth-century composite mean fire interval between all fires, including fires that only scarred one tree, between fires that scarred at least 2 trees, and between more widespread fires that scarred at least 25% of recording trees (with a minimum of 2 scars). Recording trees are those that have been scarred at least once; after an initial wound, injured trees are more likely to scar in subsequent fires (Romme 1980) and therefore are "recording trees." We used the twentieth century period to compare statistics between sites because all six sites have excellent sample depth during that period. We also calculated fire interval statistics for each site starting when that site had at least 3 recording samples: those dates for sites 1-6 are 1888, 1853, 1818, 1902, 1805, and 1849. We also used the Kolmogorov-Smirnov goodness-of-fit test to determine whether the Weibull distribution fit the data adequately. The Weibull median probability interval (WMPI) is the fire interval associated with the 50% exceedance probability of a modeled Weibull function fit to an empirical fire interval distribution (Grissino-Mayer 2001).

To assess the possibility of historical high-severity fire occurrence, we identified fire-free periods in each site with multiple pith dates, by identifying groups of pith dates clustered in 30-year periods. Finally, to assess whether human-caused changes have altered the fire regime, we looked for trends in fire frequency over time, altered seasonality of fires over time, and differences in the percentage of recording trees scarred over time.

Forest structure and fuels

To measure forest structure and age, we established 5 permanent plots in each of the 6 sites for a total of 30 plots. Based on a grid, UTM coordinates were chosen for each plot center, and we found the center of each plot in the field using a hand-held GPS device. We marked each plot with a metal stake and a tree tag. We counted seedlings (trees under 1.3 m in height) in 5.64 m circular plots. We measured trees taller than 1.3 m in 11.28 m circular plots, and we also measured the four additional closest live trees over 1.3 m in height in order to increase our sample depth of measured and cored trees. This method resulted in plots with radii ranging from 11.95 m to 26.6 m and a total area ranging from .045 ha to 0.22 ha. For each tree over 1.3 m in height we recorded height, DBH, and diameter at stump height. We also took increment cores from all trees over 1.3 m in height in order to determine tree ages. We cored trees as close as possible to their bases in order to determine tree ages most accurately. We re-cored trees when we estimated that the first core missed the center of the tree by 10 or more rings. We measured fuels, including litter and duff depth and 10-hr, 100-hr, and 1000-hr sound and rotten woody debris, using a 15 m planar transect running in a random direction from the center of each plot. We measured canopy cover with a vertical densiometer at 15 points along the same line that we used for measuring fuels.

We calculated trees per hectare and basal area per hectare for each plot. Distances to the 4 closest trees were not recorded in plot 4-2, so for that plot we used the average plot size in Site 4, which was 0.070 ha (diameter 14.8 m).

In the laboratory, cores were affixed to core mounts and sanded. We crossdated cores when possible and counted rings when necessary in order to obtain an estimate of each tree's age. When a core did not pass through the center of a tree, we used a template of concentric, appropriately-sized circles to estimate the number of rings to the center. We grouped tree ages into 10-year classes for analysis.

Fire and climate

To evaluate climate conditions related to fire occurrence at our study sites, we used superposed epoch analysis (SEA) in FHX2 version 3.2 (Grissino-Mayer 2001) to compare an independently derived index of ENSO during fire years, for five years prior to fire years, and for two years after fire years. We used an instrumentally-measured index of winter NINO3 (Kaplan et al. 1998, Reynolds et al. 2002). We were not able to compare fire occurrence with local precipitation or temperature records because the records are short, incomplete and not reliable. To assess statistical significance in the SEA analyses, confidence intervals (95%) were calculated using bootstrapped distributions of climate data in 1000 trials. To compare climate patterns with more widespread fires, we identified fire years in which at least 3 sites had the formation of at least 2 fire scars. This gave us a list of 32 fire years. We also plotted the same 32 widespread fire years on an index of winter (DJF) instrumentally measured NINO3 (Kaplan et al. 1998, Reynolds et al. 2002).

Finally, we compared a list of extreme ENSO events in the 20^{th} century with fire occurrence in our study area. ENSO winter Southern Oscillation Index (SOI) values were identified between 1699 and 1971 by Stahle and Cleaveland (1993), using tree-ring records from Mexico and the United States. Stahle and Cleaveland used two methods to reconstruct extreme SOI values, regression and classification, and considered the most accurate list of extremes to be a list of years when both methods obtained the same results for extreme winter SOI values. This is the list we used. After 1971, we determined extreme winter SOI values to be December-January-February (DJF) average values (SOI data from NCAR's Climate Analysis Section Data Catalog (http://www.cgd.ucar.edu/cas/catalog/climind/) that were >1.5 standard deviations from the average DJF values from 1935 to 2006. Using this method, extreme winter SOI values after 1971 were in 1974 and 1976 (La Niña events) and 1983, 1992, and 1998 (El Niño events).

Results

Fire history

We collected 142 fire-scarred samples in the 6 sites, of which 102 (72%) were from live trees, 21 (15%) were from snags, 10 (7%) were from logs, and 9 (6%) were from stumps. All samples were from *P. hartwegii* trees. We were able to crossdate 118 of the samples (83.1%).

The first scar that we identified occurred in 1764, and the last scars were formed in 2002 (Fig. 4.3). The majority (95.2%) of fire scars for which we could determine seasonality (57%) were formed in the dormant period. During the period of excellent sample depth in every site (twentieth century), fires were very frequent. The mean fire interval for all fires ranged from 2.1 to 3.5 years, the mean fire interval for fires that scarred at least two trees ranged from 3.3 to 5.8 years, and the mean fire interval for fires that scarred ≥25% of recording trees ranged from 6.5 to 9.5 (Table 4.2). The Weibull distribution fit our data except for two cases (indicated in Table 4.2). Weibull median probability interval values were similar but in each case slightly smaller than corresponding mean fire interval values, indicating that the distribution of fire intervals is skewed toward small intervals.

In the twentieth century, a fire scarred at least one tree in the 6 sites in 90 out of 100 years. There were two years in the twentieth century when ≥2 trees in all 6 sites were scarred: 1902 and 1907. Five sites had the formation of at least 2 scars in 1943 and 1960. Prior to 1900, the sample depth was substantially lower in most sites. However, calculations of MFI that include data prior to 1900 result in values within 1.2 years of the MFI during 1900-2009. The fire frequency changed abruptly after 2000: only one fire was recorded, in one site, during the period 2000-2009. This is exceptional compared to the twentieth century, when fire was recorded in at least one site in 90% of years. At no time did we find changes in seasonality of fires or differences in the percentage of recording trees scarred over time.

Forest structure

We measured a total of 305 live trees and 24 dead trees in the 30 plots. All but one were *P. hartwegii*; the one exception was a *Juniperus* species. We were able to estimate ages using cores for 274 of those trees; the other cores were either lost (10 cores) or did not come close to the pith (21 cores) so we were not able to estimate age.

Mean tree density ranged from 67.6 to 242.5 trees ha^{-1} in the six sites, while basal area ranged from 16.3 to 34.5 m^2 ha^{-1} (Table 4.3). Snags were present in 10 of the 30 plots, and snags per hectare values per site ranged from 3.6 to 15.6. We found only 7 cut stumps in our 30 plots, in sites 1, 3, and 4. Stumps densities per site ranged from 0 to 5.9

stumps ha^{-1}. Seedling and sapling density ranged from 0-260 seedlings ha^{-1}, and there was no correlation between seedling and sampling density and overstory tree density or basal area. The median tree height across all sites was 19.5 m, and there was a weak trend toward decreasing height with elevation; the correlation coefficient between height and elevation of plot center was -0.38.

All sites were uneven-aged (Fig. 4.4). Site 3 was the only site where we did not have trees in our sample with center dates prior to 1880. However, we had one core from site 3 with an inner date of 1637; this core was broken off near the center and we were not able to estimate the center date of the tree. In the other sites, cores which we could not use for age estimation had inner dates ranging from 1719 to 1963. If we had been able to estimate center dates from these cores, in general they would have increased values in the older age classes. The tree size distribution mirrored the age distribution closely (Fig. 4.5). Age and size of individual trees were highly correlated, with a correlation coefficient of 0.81 for all trees that were aged.

Fuel loading was fairly low. Average litter depth ranged from 1.1 to 2.2 cm, and average duff depth ranged from 1.7 to 4.9 cm (Table 4.3). Total woody debris ranged from 1.5 to 13.4 mg ha^{-1}.

Fire-climate

In the SEA analysis, winter NINO3 values tended to be below average during fire years, indicating a trend toward a fire relationship with La Niña events (Fig. 4.6). This trend was also apparent in the plotting of widespread fire years on the winter NINO3 index over time (Fig. 4.7). However, the trends were not significant, and it appears that widespread fires have occurred in both El Niño and La Niña years in the past. No change could be observed in the 1830s due to the short fire record that we reconstructed.

In 1902 and 1907, the years of most widespread fire across our sites, winter NINO3 values were close to average. Comparing a list of twentieth-century ENSO extremes (Stahle and Cleaveland 1993) with fire occurrence in our sites reveals that in extreme El Niño years of the 20th century (n=8), an average of 1.75 sites recorded fire, while in the extreme La Niña years of the 20th century (n=9) an average of 0.89 sites recorded fire. The difference between the mean number of sites recording fire in extreme El Niño and extreme La Niña years is close to significant (p=0.050).

Discussion

Not found: altered fire regime and degradation of the forest

Changes to the fire regime

Our first sub-hypothesis was that an increase in fire frequency occurred, that there was a change in fire type from surface fire to crown fire, and that there was a change in seasonality of fire. We did not find an increase in fire frequency during the period that we were able to analyze. However, it is possible that humans have been partially responsible for the very high number of fires over the past 150 years. Perhaps Lauer and Klaus's (1975) assessment that humans had increased fire frequency was correct but the influence has been felt much longer than over the past half-century. Mean fire intervals in this forest of *P. hartwegii* were much shorter than mean fire intervals found in *P. hartwegii* forest farther north in Mexico (Yocom et al. 2010). If the *P. hartwegii* population in Pico de Orizaba National Park has adapted to an evolutionary environment that was characterized by as frequent fire as we documented in the past 150 years, it is possible that different fire frequencies in different populations of *P. hartwegii* have contributed to the genetic differentiation among populations found by Schaal and Leverich (1996). The interaction of disturbance regimes and genetic divergence in geographically isolated populations would be an interesting avenue for further research.

The fire scar record indicates that fires were usually very small and asynchronous. When the 2-scar filter was used, between 14 and 55% of fire dates were eliminated from the analysis, depending on the site. The very small size of many fires suggests that they are probably not fires that have escaped from agricultural burns on the slopes below. Human-started fires in agricultural fields below the timberline would be more likely to fan out as they spread upslope and scar more trees, although this is something for which we have no conclusive evidence. The small size of many fires is probably not due to limited fuel, given the abundant and continuous grasses, and we speculate that it could be due to the low partial pressure of oxygen at the altitude of the timberline. Controlled experimental burning at elevations ranging from 400 to 3000 m above sea level has indicated that fires develop more slowly at high altitude (Wieser et al. 1997) and experimental burning at 50 m and 3658 m above sea level indicated that burning rate, radiation heat flux, and flame temperature are lower at high altitude than at low altitude (Li et al. 2009). Perhaps burning conditions, including fuel moisture and temperature, are also not normally ideal for fire spread.

The overwhelming majority of scars in our sites were formed on ring boundaries, when trees were dormant. Most of our samples, collected in April and May, did not have any current-year ring growth yet, meaning that dormancy in wood growth lasts through at least the beginning of May. This means that dormant-period fires could have occurred in any month from the fall, when trees enter dormancy, through approximately May. Because the vast majority of fire scars were formed in the dormant season, we were not able to assess whether humans or other factors changed the seasonality of most fires from immediately before the rainy season to earlier in the dry season.

We did not find evidence of high-severity fire in the area that we worked based on patterns of mortality or past pulses of even-aged regeneration. This is in contrast to *P. hartwegii* forests in the Sierra Madre Oriental, where we found clusters of pith dates in fire-scarred samples that could be evidence for small patches of high-severity disturbance that opened up growing space for pulses of recruitment (Yocom et al. 2010, Yocom et al. in prep.). In the present study, tree center dates did not appear to be episodic but instead were fairly steady through time.

To summarize the evidence related to our first sub-hypothesis, we did not find evidence of an increase in fire frequency, although we found that fires were very frequent through time; we were not able to assess whether humans have changed the seasonality of most fires because almost all scars were formed in the dormant period; and we found no evidence of crown fire in our sites. We cannot conclude that humans have not changed the fire regime at all, because fire frequency and/or seasonality may have changed prior to the twentieth century. However, humans have not changed the dominant fire type from surface fire to crown fire in our study area.

Although we did not see an increase in fire frequency during the period we analyzed, we did note a decrease in fire frequency in the last decade. We do not know if the drop in fire frequency is due to increased fire suppression or decreased human-caused ignitions. In the mid-1990s a telescope was built on Sierra Negra, and with that came people who monitor the telescope full time. Also, although Pico de Orizaba National Park was officially designated a national park in 1937, it did not have management until 2004. Since 2004, an effort has been made to extinguish fires immediately when they start.

Forest degradation

Our second sub-hypothesis was related to forest degradation through increased fire frequency: that high mortality has occurred and there is little regeneration. Our results do not support this hypothesis. The forest in our study area has been unaffected by timber harvest, severe fire, or other major disturbances. We found old, large trees in every site, few snags, and no evidence of fire-caused mortality of overstory trees. Abella et al. (2007) gave examples of change that affect old-growth, frequent-fire forests of the western United States: fire exclusion, increased fire severity, livestock grazing, fragmentation, watershed disruption, large-tree removal, road building, fuelwood harvest, predator control, exotic plants, urban development, and climate change. Of these, we saw evidence only for road building, although it is not extensive, and some timber cutting, also not extensive. Climate change is also a potential factor of change in these forests that we did not measure.

Regeneration varied substantially among sites and among plots. Measured values of seedling density range from 0 to 260 seedlings per hectare, and all plots together averaged 113.3 seedlings per hectare. The data reflect the patchiness of regeneration that occurred everywhere throughout our sites. In addition, there is a peak of small, young trees in the size and age distributions from our sites. Estimating mortality rates compared to regeneration rates can provide a benchmark of whether regeneration is sufficient to replace mortality. In the simplest calculation (see Mast et al. 1999), maintenance of 119 trees/ha (±20%) in a distribution with a maximum age of 270 years (±20%) predicts a mortality rate range of 3.0 – 6.5 trees ha $^{-1}$ decade $^{-1}$. Tree establishment rates in the 1990s and 2000s were well above that mortality rate (9.6 and 11.3 trees ha $^{-1}$ decade $^{-1}$) but were lower in the 1970s and 1980s (1.7 trees ha $^{-1}$ decade $^{-1}$ in both decades). Although the 1970s and 1980s had low establishment, overall our results suggest that, contrary to our second sub-hypothesis, forest degradation as we defined it here has not occurred in our sites: we found low mortality, the presence of old large, trees, and sustained recruitment over time evidenced by the presence of trees in every age category beginning in 1740.

Forest sustainability

Our third sub-hypothesis was related to forest sustainability: that current forest structure, demographics, or fuel loads put the forest at risk from severe disturbance. Forest structure characteristics in our sites are comparable to characteristics of other old-growth fire-adapted conifer forests that have not been subjected to fire exclusion. The Sierra San Pedro Martir (SSPM) in northern Baja California, Mexico, is an example (Stephens and Gill 2005). Live tree density on Pico de Orizaba (average across all sites) was 119.2 trees ha^{-1}, slightly less than the 145.3 trees ha^{-1} reported in the SSPM. Basal area in our sites averaged 23.9 m^2 ha^{-1}, slightly more than the 19.9 m^2 ha^{-1} reported in the SSPM (Stephens and Gill 2005). Canopy cover in our sites in Pico de Orizaba National

Park ranged from 32 to 52%, which can be characterized as moderate canopy cover. In the SSPM, Stephens et al. found an average canopy cover of 26.8% (Stephens et al. 2007).

The size and age distributions of the forest were similar to each other, with a peak in the middle-sized and middle-aged regions and another peak in the small, young tree range. The relatively high density of small, young trees is found in most forests, and the forest age and size distributions may have been very similar throughout the past century. However, the high density of young, small trees may also be related to the unusual lack of fire in the 2000s and to some degree in the 1990s. Many of the small young trees established prior to the recent drop in fire frequency, but the recent lull in fire may be helping them to survive (Mast and Wolf 2004, Brown and Wu 2005). Overall, the forest that we measured has an uneven-aged distribution with populations of old, middle-aged, and young trees. This suggests that the population is demographically stable and is unlikely to be at risk of a population crash or irruption due to demographic imbalances.

Fuels in our study area were fairly light. This is expected, given the frequent fire regime that characterized our study areas. Coarse woody debris tends to be lower in areas with a continued fire regime (Stephens et al. 2007). We can conclude that our third hypothesis regarding forest sustainability is not supported; the intrinsic characteristics of the forest itself, including forest demographics, structure, and fuels do not put the forest at risk of negative impacts from disturbance.

Quantitative measurements of the fire regime and forest structure do not support Lauer and Klaus's assessment in the 1970s; it appears that humans have not altered the fire regime during the time period we could assess, or caused forest degradation.

However, it should be stressed that we studied a small portion of the timberline between Pico de Orizaba and Sierra Negra. We chose our study area because one of our goals was to find old trees and old wood in order to extend the climate-fire record as far back as possible. In our exploration of the park, we did see evidence of more timber cutting and patchy high-severity fire on the north side of Pico de Orizaba, and the trees appeared to be younger. The north side of the mountain should be further explored; the hypothesis that human-caused fires have altered the fire regime and degraded the forest might be supported there. This study should be regarded as a first step in understanding the dynamics of climate, fire, and human activities in Pico de Orizaba National Park and the eastern Trans-volcanic Belt.

Not found: ENSO events associated with fire

Inter-annual climatic variability was not a strong driver of fire occurrence at this location. Small fires were recorded in 90 of 100 years in the twentieth century, indicating that climate conditions were almost always suitable for burning. Our first sub-hypothesis, that El Niño events are associated with fire events, was not supported. Neither El Niño nor La Niña events were significantly associated with fire. There was a weak trend in the SEA results towards an association between fire and La Niña. On the other hand, a slightly higher number of sites recorded fire, on average, during the extreme El Niño events during the twentieth century than during the extreme La Niña events.

During the strong El Niño event of 1998, central and southern Mexico experienced a record number of fires. It was also a record year in terms of area and biomass burned, smoke released, cost of suppression, and firefighter lives lost

(Rodríguez-Trejo and Pyne 1999, Duncan et al. 2003). In our study area in Pico de Orizaba National Park, most samples in site 5 were scarred in 1998. However, 1997 was a big fire year in site 2 and 1999 was a big fire year in sites 1, 4, and 6. Clearly the El Niño event of 1998, which synchronized fires across much of Mexico, did not synchronize fire events within our sites in Pico de Orizaba National Park. Our results, indicating that fires are not conclusively associated with El Niño or even with ENSO, were unexpected given that in southern Mexico El Niño events tend to be associated with below-average precipitation (Fig. 4.1) and above-average fire occurrence.

We were not able to test our second sub-hypothesis, that ENSO events have been consistently related to fire occurrence over time, because our fire scar record did not extend back past the 1830s, the time period we documented a change in ENSO-fire relationships in the Sierra Madre Oriental. Although one of our objectives in selecting sites was to locate areas with old trees and old wood in order to allow the extension of the fire-climate record back in time, we did not find very much old wood with conserved fire scars. This may be related to the very high frequency of fires in the study area; remnant wood is probably difficult to find because it has been consumed by frequent fire over the centuries.

High-elevation forests around the world are threatened by human impacts and climate change; additionally, in central Mexico, relatively undisturbed forests are rare. The forests in our sites on Pico de Orizaba continued to coexist with very frequent fire through the twentieth century, probably ignited by both lightning and humans. During the last decade, fire occurrence has abruptly diminished. It is our hope that information from this study will support planning and decision-making by managers, scientists, and government officials; our findings can be used for management and conservation in the Park and in other similar ecosystems. Because very frequent fire has not degraded the forest over the past century and it is possible that the forest has adapted to this frequent fire regime over millennia, the historical disturbance regime should be allowed to continue as much as possible to maintain these rare and valuable forests' capacity for resilience in the face of climate change.

Acknowledgements

We thank CONANP, Hector Rojas and the Pico de Orizaba National Park for permission to work in the park. Dante Arturo Rodríguez provided support to the project. Rafael de Jesús Amador, Oscar Hernández de la Torre, Keith Kent, Iván Zamudio, and Conrado Vásquez García were terrific assistants in the field. We appreciate Scott Curran's assistance with the ERICIII database. Rachel Sheridan's help in the lab was greatly appreciated. Thanks also to Don Normandin, other staff, and students at the Ecological Restoration Institute. This research was supported by a National Science Foundation Doctoral Dissertation Enhancement Project grant (OISE- 1003845) and grant DEB-0640351, and the Ecological Restoration Institute at Northern Arizona University.

Literature Cited

Abella, S. R., W. W. Covington, P. Fulé, L. B. Lentile, A. J. Sánchez Meador, and P. Morgan. 2007. Past, present, and future old growth in frequent-fire conifer forests of the western United States. Ecology and Society **12**:16.

Baisan, C. H. and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research **20**:1559-1569.

Brown, P. M. and R. Wu. 2005. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology **86**:3030-3038.

Caso, M., C. González-Abraham, and E. Ezcurra. 2007. Divergent ecological effects of oceanographic anomalies on terrestrial ecosystems of the Mexican Pacific coast. Proceedings of the National Academy of Sciences **104**:10530-10535.

de la Cruz-Reyna, S. and G. Carrasco-Núñez. 2002. Probabilistic hazard analysis of Citlaltépetl (Pico de Orizaba) Volcano, eastern Mexican Volcanic Belt. Journal of Volcanology and Geothermal Research **113**:307-318.

Duncan, B. N., R. V. Martin, A. C. Staudt, R. Yevich, and J. A. Logan. 2003. Interannual and seasonal variability of biomass burning emissions constrained by satellite observations. J. Geophys. Res. **108**.

Fulé, P. Z. and W. W. Covington. 1999. Fire regime changes in La Michilía Biosphere Reserve, Durango, Mexico. Conservation Biology **13**:640-652.

Fulé, P. Z., M. Ramos-Gómez, C. Cortés-Montaño, and A. M. Miller. in press. Fire regime in a Mexican forest under indigenous resource management. Ecological Applications.

Fulé, P. Z., J. Villanueva-Díaz, and M. Ramos-Gómez. 2005. Fire regime in a conservation reserve in Chihuahua, Mexico. Canadian Journal of Forest Research **35**:320-330.

Grissino-Mayer, H. D. 2001. FHX2 - Software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research **57**:113-122.

Heyerdahl, E. K. and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. Pages 196-217 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer-Verlag, New York.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurements. Tree-Ring Bulletin **43**:69-78.

Kaplan, A., M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, and B. Rajagopalan. 1998. Analyses of global sea surface temperature 1856-1991. Journal of Geophysical Research **103**:18567-18589.

Lauer, W. 1978. Timberline studies in central Mexico. Arctic and Alpine Research **10**:383-396.

Lauer, W. and D. Klaus. 1975. Geoecological Investigations on the Timberline of Pico de Orizaba, Mexico. Arctic and Alpine Research 7:315-330.

Li, Z.-h., Y. He, H. Zhang, and J. Wang. 2009. Combustion characteristics of *n*-heptane and wood crib fires at different altitudes. Proceedings of the Combustion Institute **32**:2481-2488.

Mast, J. N., P. Z. Fulé, M. M. Moore, W. W. Covington, and A. E. M. Waltz. 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. Ecological Applications **9**:228-239.

Mast, J. N. and J. J. Wolf. 2004. Ecotonal changes and altered tree spatial patterns in lower mixed-conifer forests, Grand Canyon National Park, Arizona, U.S.A. Landscape Ecology **19**:167-180.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang. 2002. An Improved In Situ and Satellite SST Analysis for Climate. Journal of Climate **15**:1609-1625.

Rodríguez-Trejo, D. A. 2008. Fire regimes, fire ecology, and fire management in Mexico. Ambio **37**:548-556.

Rodríguez-Trejo, D. A. and P. Z. Fulé. 2003. Fire ecology of Mexican pines and a fire management proposal. International Journal of Wildland Fire **12**:23-37.

Rodríguez-Trejo, D. A. and S. J. Pyne. 1999. Mexican fires of 1998. International Forest Fires News **20**:61-63.

Román-Cuesta, R. M., M. Gracia, and J. Retana. 2003. Environmental and human factors influencing fire trends in ENSO and non-ENSO years in tropical Mexico. Ecological Applications **13**:1177-1192.

Román-Cuesta, R. M., J. Retana, and M. Gracia. 2004. Fire Trends in Tropical Mexico: A Case Study of Chiapas. Journal of Forestry **102**:26-32.

Romme, W. H. 1980. Fire history terminology: report of the ad hoc committee. Pages 135-137 *in* Proceedings of the Fire History Workshop, Oct 20-24, 1980. USDA Forest Service, Tucson, AZ.

Schaal, B. A. and W. J. Leverich. 1996. Molecular variation in isolated plant populations. Plant Species Biology **11**:33-40.

Skinner, C. N., J. H. Burk, M. G. Barbour, E. Franco-Vizcaíno, and S. L. Stephens. 2008. Influences of climate on fire regimes in montane forests of north-western Mexico. Journal of Biogeography **35**:1436-1451.

Stahle, D. W. and M. K. Cleaveland. 1993. Southern Oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and southern Great Plains. Journal of Climate **6**:129-140.

Stephens, S. L., D. L. Fry, E. Franco-Vizcaíno, B. M. Collins, and J. M. Moghaddas. 2007. Corase woody debris and canopy cover in an old-growth Jeffrey pine-mixed conifer forest from the Sierra San Pedro Martir, Mexico. Forest Ecology and Management **240**:87-95.

Stephens, S. L. and S. J. Gill. 2005. Forest structure and mortality in an old-growth Jeffrey pine-mixed conifer forest in north-western Mexico. Forest Ecology and Management **205**:15-28.

Wieser, D., P. Jauch, and U. Willi. 1997. The influence of high altitude on fire detector test fires. Fire Safety Journal **29**:195-204.

Yocom, L., P. Z. Fulé, P. M. Brown, J. Cerano-Paredes, J. Villanueva, E. Cornejo-Oviedo, and D. A. Falk. 2010. El Niño-Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time. Ecology **91**:1660-1671.

Yocom, L., P. Z. Fulé, D. A. Falk, E. Cornejo-Oviedo, P. M. Brown, J. Villanueva, J. Cerano-Paredes, C. García-Domínguez, and C. Cortés-Montaño. in prep. Comparing the influence of broad-scale and fine-scale factors on fire occurrence in northeastern Mexico.

TABLE 4.1. Characteristics of six sites at Pico de Orizaba National Park, Mexico. Average elevation and average slope are calculated from fire scar locations.

Site	Aspect	Average elevation (m)	Average slope (%)
1	N	3913	43.7
2	S	3942	60.7
3	E	4132	53.6
4	W	3912	40.1
5	S	4045	38.0
6	NE	4081	50.5

TABLE 4.2. Fire interval characteristics for the years 1900-2009 at six sites in Pico de Orizaba National Park, Mexico. [1]Weibull model does not fit the data. [2]Average sample mean fire interval calculations were calculated for the time period covered by each individual sample.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Number of intervals						
All fires	37	39	26	41	45	34
All fires, ≥2 scarred	21	17	16	23	29	29
25% scarred	11	10	10	15	11	14
Mean fire interval (yr)						
All fires	2.7	2.6	3.5	2.4	2.1	2.9
All fires, ≥2 scarred	4.7	5.6	5.8	4.2	3.3	3.4
25% scarred	8.9	9.5	9.2	6.5	8.6	6.6
Weibull median interval (yr)						
All fires	2.4	2.3[1]	3.3	2.2	2.0[1]	2.5
All fires, ≥2 scarred	4.4	4.9	5.4	3.9	3.1	3.0
25% scarred	8.6	9.0	8.9	5.7	7.2	6.1
Minimum interval (yr)						
All fires	1	1	1	1	1	1
All fires, ≥2 scarred	1	1	3	1	1	1
25% scarred	3	4	3	1	3	2
Maximum interval (yr)						
All fires	10	8	7	7	6	11
All fires, ≥2 scarred	11	15	12	10	11	11
25% scarred	16	23	16	18	30	17
Average sample mean fire interval[2] (yr)	14.6	14.2	14.5	15.4	16.9	12.3

TABLE 4.3. Forest structure and fuels characteristics for six timberline sites in Pico de Orizaba National Park, Mexico. Trees are classified as stems over 1.3 m in height and seedlings and saplings are classified as less than 1.3 m in height.

Site	Tree density (trees ha^{-1})	Basal area (m^2 ha^{-1})	Seedlings ha^{-1}	Canopy cover (%)	Litter depth (cm)	Duff depth (cm)	Total woody debris (mg ha^{-1})
1	95.7	26.3	260	48	1.1	4.0	3.4
2	80.3	16.3	80	37	1.4	2.6	13.4
3	209.1	25.4	140	47	2.4	3.2	1.8
4	105.7	26.9	60	32	1.7	3.6	1.5
5	67.7	20.6	0	37	2.2	1.7	1.7
6	242.5	34.5	140	52	2.5	4.9	8.3
Total	119.2	23.9	113.3	42	1.9	3.3	5.0

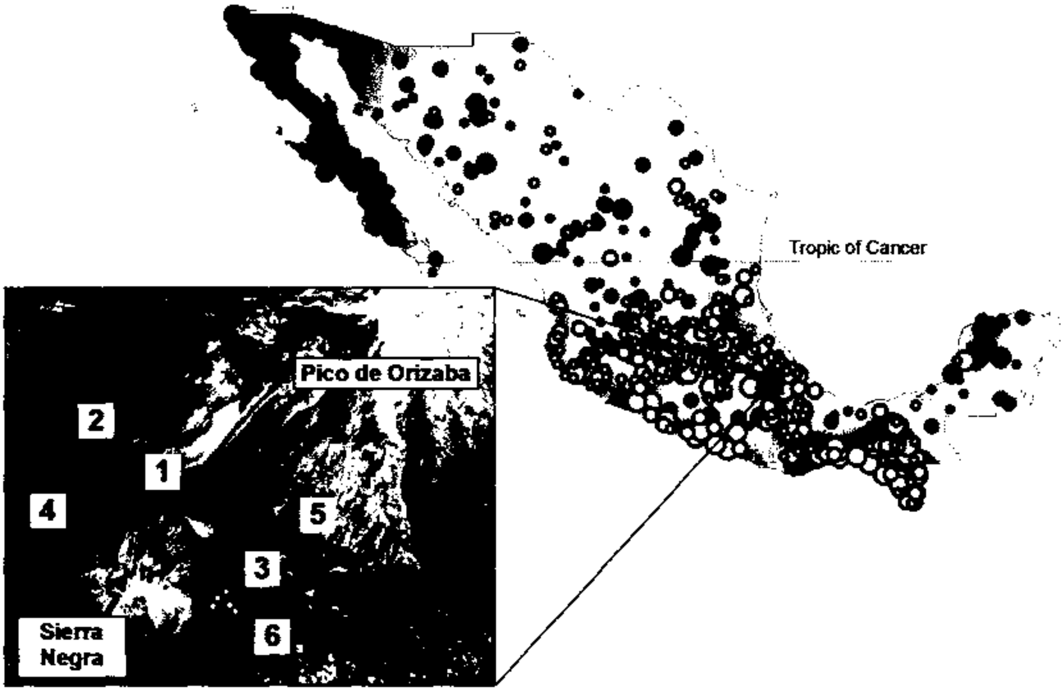

FIGURE 4.1. Overview: map of Mexico with a black square showing the location of Pico de Orizaba National Park (square is not to scale). Circles indicate 775 weather stations with at least 90% complete data for at least 30 years. Filled circles indicate a negative correlation (< -0.1) between precipitation and Southern Oscillation Index (SOI) values, and unfilled circles indicate a positive correlation (> 0.1). Note considerable intermixing of weather stations correlated with either phase of the Southern Oscillation in central Mexico. Inset: map showing timberline location of six sites between Pico de Orizaba and Sierra Negra in Pico de Orizaba National Park. Image from Google Earth.

FIGURE 4.2. Photo of Site 1 (Sierra Negra in the background) taken from Site 2.

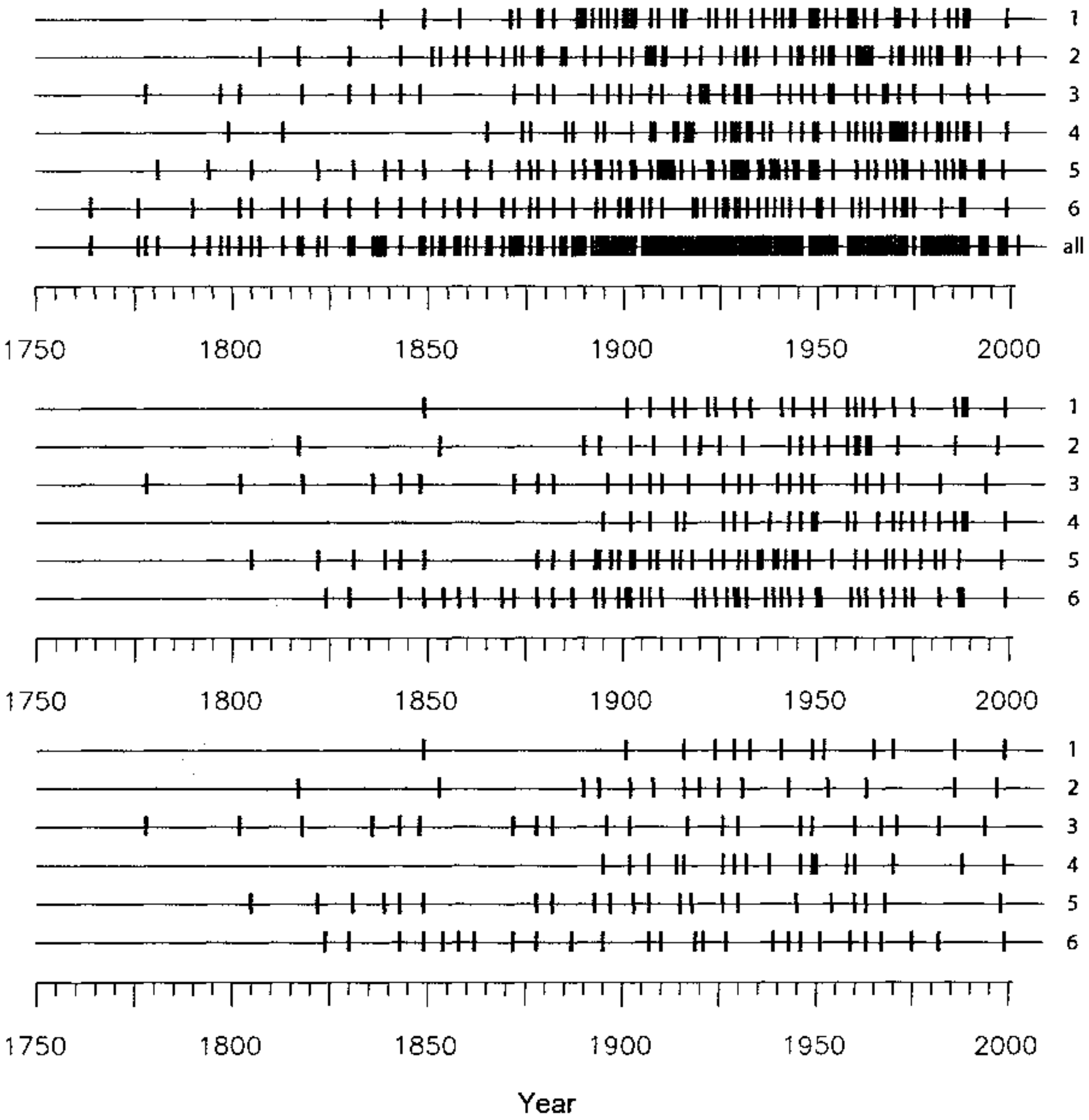

FIGURE 4.3. Top: all fires in each site and throughout all sites. Middle: years when a minimum of 2 samples were scarred in each site. Bottom: years when a minimum of 25% of recording samples and a minimum of 2 samples were scarred. The grey boxes on the left cover data that were not used in analyzing fire statistics, because the sample size decreased substantially before 1900.

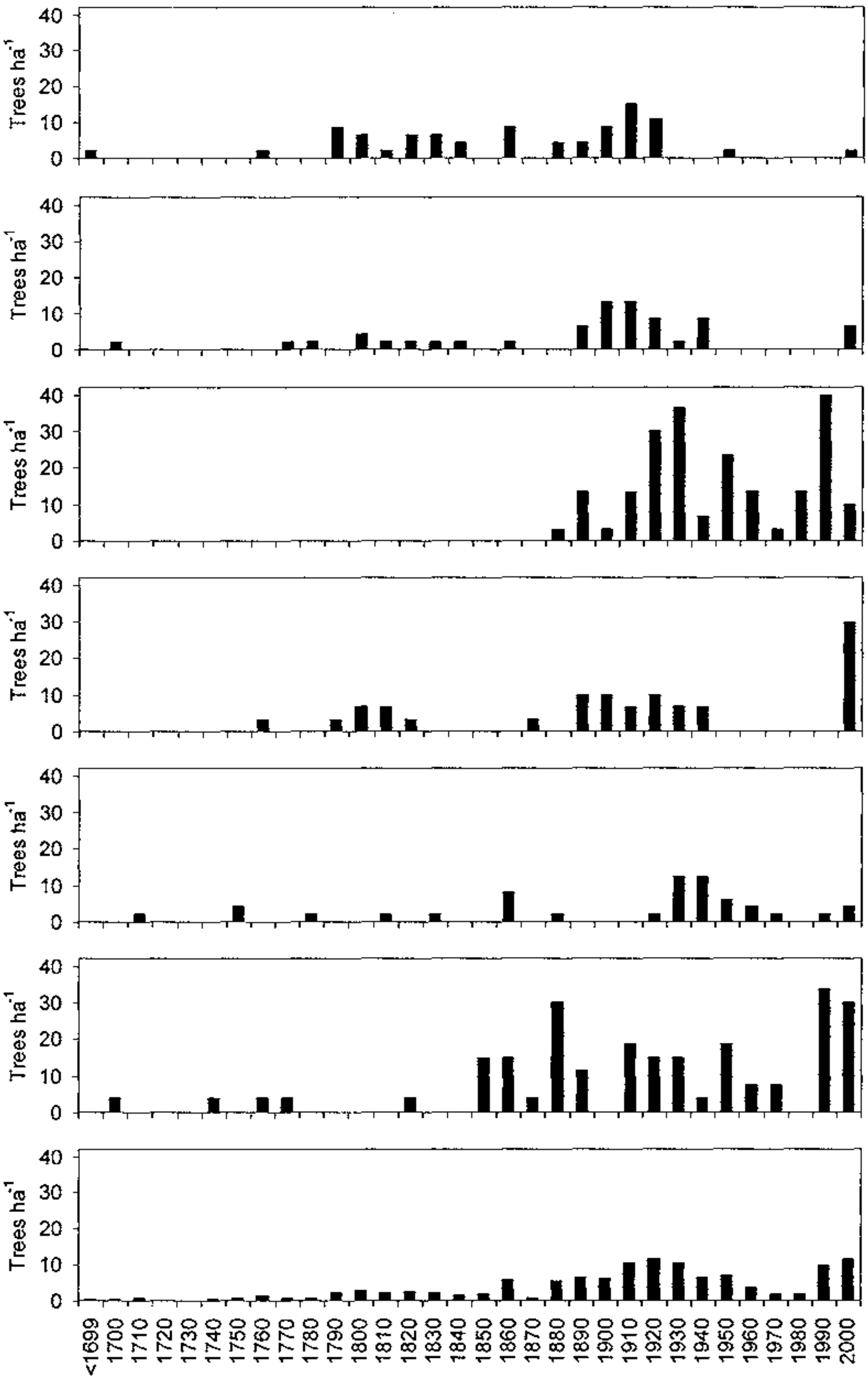

FIGURE 4.4. Forest density (trees ha^{-1}) in 10-year age classes in sites 1-6 as well as in all sites combined.

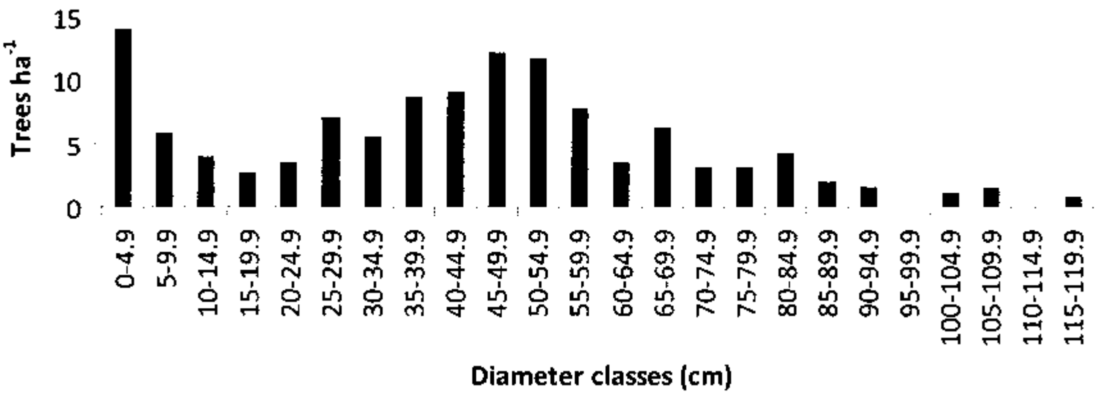

FIGURE 4.5. Tree density (trees ha^{-1}) in 5-cm diameter classes in all sites combined.

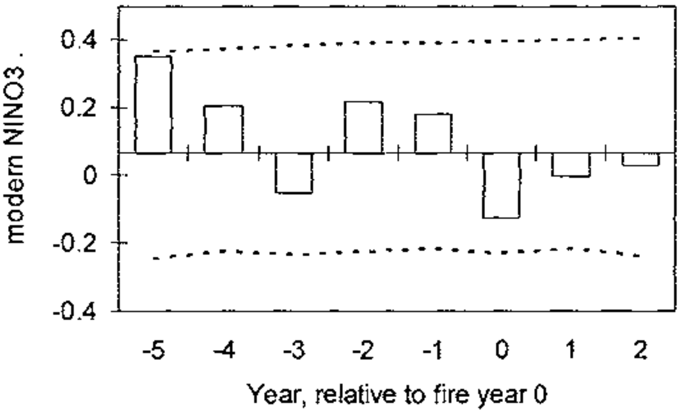

FIGURE 4.6. Superposed epoch analysis showing departure from the mean value of NINO3 SST for widespread fire years (at least 2 scars in at least 3 sites). Fire years are indicated by 0, and values are also given for five years prior to fire years (negative values) and two years after fire years.

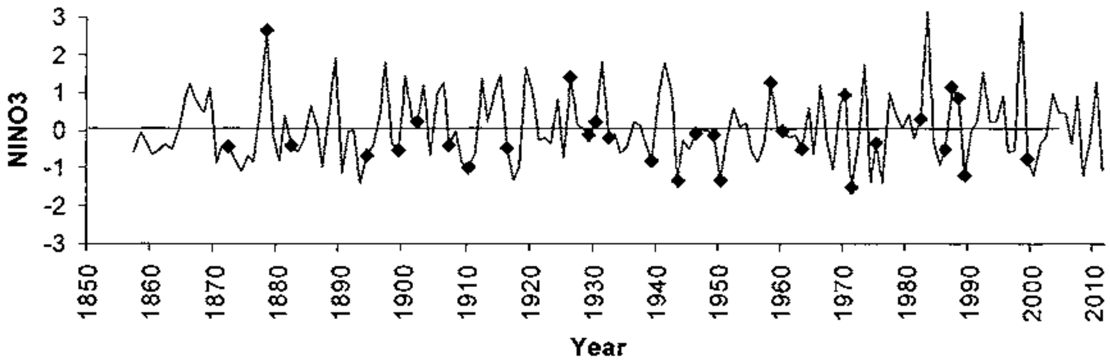

FIGURE 4.7. Widespread fire years (>3 sites with >2 fire scars) plotted on winter (December, January, February) NINO3 values (Kaplan et al. 1998, Reynolds et al. 2002).

CHAPTER 5: CLIMATE AND LAND-USE DRIVERS OF HISTORICAL FIRES IN NORTHERN MEXICO

Abstract

We investigated the influence of climate on the occurrence of fire in northern Mexico. Using a network of 52 sites in 5 regions in the Sierra San Pedro Martir, the Sierra Madre Occidental, and the Sierra Madre Oriental, we compared across-region and within-region fire synchrony with climate oscillations including El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), as well as combinations of these oscillations. We also compared dates of fire regime disruption across northern Mexico. Across-region fires in northern Mexico were more likely to occur during negative (La Niña) phases of ENSO and cool phases of PDO, and fire was significantly more likely to occur during the combination of the cool phases of ENSO and PDO than expected. AMO was not significantly associated with fire occurrence. In four of the five regions, La Niña phases of ENSO were significantly associated with fire occurrence, and in three regions fires were significantly associated with previous-year El Niño conditions. We found that dates of fire regime interruption across northern Mexico were highly variable within and among regions. This suggests that human land use change is the strong driver of fire regime interruption, and climate played little or no role in the widespread cessation of fire across much of western North America in the nineteenth and twentieth centuries.

Introduction

El Niño-Southern Oscillation (ENSO) is a climatic oscillation that affects fire patterns throughout western North and South America (e.g. Swetnam and Betancourt 1990, Kitzberger et al. 2001, Heyerdahl and Alvarado 2003, Fulé et al. 2005). Recently, climate phenomena that oscillate on longer time scales, such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), have been shown to interact with ENSO to reinforce or dampen historical fire occurrence patterns (Hessl et al. 2004, Schoennagel et al. 2005, Taylor and Beaty 2005, Sibold and Veblen 2006, Schoennagel et al. 2007). Warmer spring temperatures have been associated with an increase in fire activity across the western United States in the twentieth century (Westerling et al. 2006), and projections of further increases in temperature suggest a further increase in fire occurrence in the future (Westerling et al. 2006, Seager et al. 2007). To predict how current and future climate change will impact fire activity in western North America, it is necessary to explore historical climate-fire relationships at multiple scales across the region.

In the United States, regional-scale analyses of climate-fire relationships have been completed for the Southwest (e.g. Swetnam 1990, Swetnam and Betancourt 1990, Swetnam and Baisan 1996, Grissino-Mayer and Swetnam 2000), the Northwest (e.g. Hessl et al. 2004, Heyerdahl et al. 2008a), the northern Rockies (e.g. Heyerdahl et al. 2008b), and Utah (Brown et al. 2008), as well as a few studies at the scale of western North America (e.g. Kitzberger et al. 2001, Kitzberger et al. 2007, Trouet et al. 2010). Most of these studies are limited to analyzing climate-fire relationships before the 20th century, because in much of the United States fire regimes were interrupted in the mid- to late-nineteenth century by human influence, including livestock grazing and other land-use changes (Belsky and Blumenthal 1997, Heyerdahl et al. 2001, Hessl et al. 2004). To overcome the anthropogenic influence of the twentieth century and extend understanding of the historical relationships between climate and fire in North America, at least in part, we can look to northern Mexico. Human impacts in the mountains of northern Mexico followed a different history than the United States or Canada, with large-scale livestock introduction largely deferred until post-revolutionary land reforms in the mid-twentieth century. Comprehensive fire suppression was never achieved in some areas (Leopold 1937, Rodríguez-Trejo and Fulé 2003). Heyerdahl and Alvarado (2003) suggested that fire exclusion was closely associated with the formation of ejidos, which are lands held in common and managed by local people with the input of the government. When ejidos were granted as part of land reform in the early to mid twentieth century, fire regimes may have changed due to increased livestock grazing, road building, logging, and changing the traditional role of fire (Heyerdahl and Alvarado 2003). Although some sites experienced fire exclusion in the late 1800s, long before the formation of ejidos (Yocom et al. in prep.), and fire regimes at many sites were interrupted around the time of ejido formation (Heyerdahl and Alvarado 2003), other sites have fires continuing to the present (Fulé et al. in press). Due to the existence of many sites that did not experience fire exclusion until the mid-twentieth century and the presence of sites that have had continued fire regimes up to the present, Mexican forests comprise the most intact contemporary data source in North America for examining climate-fire interactions.

A network of fire history sites has been developed in northern Mexico over the past several decades, many of which have been used to explore fire-climate relationships as well as historical fire regimes. Northern Mexico is strongly affected by ENSO (Stahle and Cleaveland 1993), but ENSO links to fire occurrence have been studied only at the scale of individual sites or within mountain ranges. In the Sierra Madre Occidental in northwestern Mexico, past La Niña events were typically associated with the year of fire occurrence (Fulé and Covington 1999, Heyerdahl and Alvarado 2003, Fulé et al. 2005). However, in the southern part of the Sierra Madre Occidental, Drury and Veblen (2008) found that there was not a significant relationship between La Niña events and fire years but instead there was a significant lag relationship between El Niño and fire, with El Niño conditions typically occurring one year before fire years. In addition, dry conditions prevailing in fire years and wet conditions lagged one year prior to fire events were also common in northern Mexico (Heyerdahl and Alvarado 2003, Fulé et al. 2005), as they are in the southwestern US (Swetnam and Baisan 2003). In the Sierra San Mártir, located in Baja California, fire years were associated with La Niña conditions and also with a shifting of phase of the PDO (Skinner 2007). In the Sierra Madre Oriental, in northeastern Mexico, fire occurrence was associated with La Niña conditions, but in one area the relationship changed over time and La Niña was no longer associated with fire after the 1830s (Yocom et al. 2010). It is likely that ENSO, PDO, and AMO affected the occurrence of fire across northern Mexico. However, only now are new data sets being completed that expand the network to eastern Mexico (Yocom et al. 2010) and northern Chihuahua (Fulé et al. in press), and a large-scale analysis of interactions between these climate factors and fire has not been completed for this part of western North America.

Our objectives were to analyze the relationships between climate oscillations (ENSO, PDO, and AMO) and regionally synchronous fire years and to describe patterns of fire exclusion dates and their variability in sites across northern Mexico.

Methods

Study Area

We included all fire-history sites in northern Mexico for which we had data. The 52 sites included were originally sampled as individual research projects (Table 5.1; Fulé and Covington 1997, Heyerdahl and Alvarado 2003, Fulé et al. 2005, Cerano unpublished data, Fulé unpublished data, Yocom unpublished data, Skinner 2007, Yocom et al. 2010, Fulé et al. in press). The sites extend geographically from northern Baja California in the west, east to the Sierra Madre Oriental, north in the Sierra Madre Occidental to close to the U.S.-Mexico border, and south in the Sierra Madre Occidental to southern Durango (Fig. 5.1). All sites were north of the Tropic of Cancer and north of the dipole where the relationship between ENSO and precipitation changes. All sites were at 1950 m above sea level or higher and were forested. Tree species sampled in the sites varied across regions; they included *Abies vejarii*, *Pinus arizonica*, *Pinus ayacahuite*, *Pinus durangensis*, *Pinus engelmannii*, *Pinus hartwegii*, *Pinus herrerai*, *Pinus jeffreyii*, *Pinus leiophylla*, *Pinus lumholtzii*, *Pinus strobiformis*, *Pinus teocote*, and *Pseudotsuga menziesii*.

Fire chronologies

Fire chronologies were assembled from the IMPD or contributed by the original investigators. At each site, fire-scar data was sampled in an area ranging from 2 to 70 ha, and the number of crossdated fire-scarred tree samples from each site ranged from 6 to 54 (Table 5.1). We identified fire years at each site as those with scars on ≥2 trees, and these dates were compiled into site chronologies.

We divided the 52 sites into five regions, called Baja, Occidental North, Occidental Central, Occidental South, and Oriental (Fig. 5.1), to determine whether each region had different climate drivers of fire. We identified within-region synchronous fire years as those in which sites within each region recorded fire most synchronously. To do this, we aimed for a similar number of within-region synchronous fire years for each region, rather than defining a set number or percentage of sites recording fire, because each region had different numbers of sites and levels of synchrony (for example, Baja sites were very asynchronous and there were only 2 years when 5 sites recorded fire, but in Occidental South there were 23 years when 5 or more sites recorded fire). This approach resulted in a set of within-region synchronous fire years for each of the five regions, numbering 27, 21, 23, 19, and 31 in Baja, Occidental North, Occidental Central, Occidental South, and Oriental respectively.

We also identified across-region synchronous fire years as those when 4 or 5 regions recorded fire synchronously. We identified no-fire years as those when 0 regions recorded a fire, and we also identified years when 1, 2, or 3 regions recorded a fire.

Climate drivers of fire

We graphically and statistically compared our fire chronologies to independently derived tree-ring reconstructions of large-scale climate oscillations to assess potential climate forcing. We used the following reconstructions: winter NINO3 (December through February) SST index (Cook 2000), annual PDO (D'Arrigo et al. 2001), and annual AMO (Gray et al. 2004). To address temporal autocorrelation in the NINO3 index, we fit autoregressive integrated moving average models based on lowest Akaike's information criterion and significant but uncorrelated parameter estimates (Brown et al. 2008) and used the resulting white noise residuals in our analyses.

To evaluate the influence of climate drivers on fire occurrence at our study sites, we used superposed epoch analysis (SEA) in FHX2 (Grissino-Mayer 1995) to compare fire occurrence with climate indices including NINO3, PDO, and AMO. The SEA compared climate index values during fire years, five years prior to fire years, and two years after fire years. To assess statistical significance of the SEA results, we calculated 95% confidence intervals using bootstrapped distributions of climate data in 1000 trials.

We assessed the influence of two-way and three-way combinations of the phases of AMO, PDO, and ENSO on fire occurrence in northern Mexico. We used χ^2 goodness-of-fit tests (α=0.05) to compare the expected fire occurrence with observed fire occurrence to determine whether fires occurred disproportionately during particular phase combinations of large-scale climate oscillations (positive and negative phases of AMO, PDO, and ENSO). Expected values in each phase combination were calculated from the proportion of years from 1750-1978 in each of the combinations, and observed values were the number of across-region fire years in each phase combination.

Although the first fire in the sites was in 1438 and the last fire was in 2003, we analyzed the relationship between climate oscillations and fire across regions in the period from 1750 to 1978. We chose 1750 as a starting date for the climate-fire analysis because 35 of the 52 sites were recording at that time and all 5 regions had recorded at least one fire date before 1750, meaning that all 5 regions had the potential to contribute to regional fire years. We chose 1978 as an ending date for the climate-fire analysis because the period of overlap in the climate reconstructions we used ends in 1978.

Fire exclusion dates

To assess the variability of fire exclusion dates in the 52 sites, we created a fire history graph from the composite (≥2 fire scars) fire chronologies from each site and visually compared patterns of fire exclusion across sites and regions. For each site, we designated a year that the fire regime was interrupted: either the last year that fire was recorded in a site or the last year that fire was recorded in a site before an uncharacteristically large fire interval. We grouped the fire regime interruption dates into 20-year bins and graphed the results to assess patterns in fire regime interruption. We also graphed across-region synchronous fire dates on indices of ENSO, PDO, and AMO to look for changes in long-term climate patterns that could explain fire exclusion dates in northern Mexico.

Results

The 9 years of maximum synchrony of fire, when all 5 regions in northern Mexico recorded fire, were 1798, 1820, 1838, 1851, 1894, 1899, 1902, 1909, and 1917. There were an additional 36 years when 4 regions recorded fire, and we designated the 45 years when 4+ regions recorded fire as across-region synchronous fire years (Fig. 5.2). Fires were recorded in only 1 region in 59 years, 2 regions in 61 years, and 3 regions in 49 years. There were 45 years in which no fires were recorded in any of the regions.

ENSO was a significant driver of synchronous fire years. Average NINO3 values were significantly low in years when 3 or 4+ regions recorded fire, and significantly high in years when 0 or 1 region recorded fire (Fig. 5.3). Antecedent NINO3 values were significantly high prior to years when 4+ regions recorded fire, and significantly low prior to years when only 1 region recorded fire (Fig. 5.3). Average NINO3 values were significantly low in within-region fire years in Baja, Occidental North, Occidental Central, and Oriental, but not significantly low in Occidental South (Fig. 5.4). ENSO in antecedent years was important in some analyses as well: NINO3 values were significantly above-average one year prior to fire years in all three Occidental regions but not in Baja or the Oriental (Fig. 5.4). Baja showed a significantly above average NINO3 value 5 years prior to fire years.

PDO was also a significant driver of synchronous fire years. Average PDO index values were significantly low in across-region synchronous fire years (Fig. 5.5). There were no significant relationships between PDO and years when 0, 1, 2, or 3 regions recorded fire (not shown). Within regions, PDO was significantly low during fire years in Occidental North and Oriental: within-region synchronous fire years in the other three regions were not significantly associated with PDO (Fig. 5.5). AMO was not significantly correlated with fire years or no-fire years in any SEA analysis (not shown).

In the two-way combinations, there was a trend toward more fires than expected when both the PDO and ENSO were in negative phases (Fig. 5.6); the trend was very close to statistically significant. There were no combinations of AMO and PDO or AMO and ENSO in which observed fires were significantly different from expected. In the three-way combinations, there was a trend toward more fire than expected in the combinations where PDO and ENSO were both negative, especially when AMO was positive. Again, the Chi-square test for the three-way combinations was close to significant, but not significant. This result should be regarded with caution as more than 20% of the cells in the contingency table had values lower than 5.

A visual inspection of the fire history graph reveals high variability in when historical patterns of fire were interrupted (Fig. 5.2). Overall the Sierra Madre Oriental experienced fire regime interruption earliest of the five regions, although there is variation within the region, with fire interruption dates ranging from 1887 to 1962. In Baja California, fire regime interruption occurred in different sites between 1924 and 1981, with most sites having their last fire between the 1930s and the 1960s. In Occidental North, most sites had their last fire or the last fire before a long break in fire between 1945 and 1955, with one site experiencing frequent fire to the present (site rt, last fire recorded 2002). In Occidental Central, several sites have uninterrupted fire regimes, with last fires recorded in the late 1990s and 2003. Other sites had a change in fire regime as early as 1929 and scattered throughout the subsequent decades. In Occidental South, fire regime interruption dates were again scattered, ranging from 1930 through the subsequent decades. Two sites in this region (chi and alf) had a continuous record of fire up to the time that samples in those sites were collected. The graph of fire exclusion dates by region also shows that fire regime interruption dates, or dates of the last fire in uninterrupted sites, were spread throughout the twentieth century (Fig. 5.7).

Within-region and across-region fire dates graphed on indices of ENSO, PDO, and AMO reveal no patterns of climate that can be related to fire exclusion in sites or regions of Mexico (Fig. 5.8). For example, the amplitude and frequency of ENSO oscillations after the last within-region fire date (1956) do not appear to be different than before 1956.

Discussion

Synchronous fire years occurred in regions across northern Mexico frequently in the past. There were 45 years in which 4 or more regions recorded fire synchronously during the period of analysis, and there were also 45 years in which none of the regions recorded fire.

We found a significant association between La Niña conditions (negative phase of ENSO) and across-region synchronous fire years (4+ regions), as well as a significant association between La Niña years and within-region synchronous fire years in four of the five regions. It is notable that within-region synchronous years in Occidental South were not significantly related to La Niña years; this is the same result that Drury and Veblen (2008) found in their study in this region. Drury and Veblen (2008) speculated that perhaps in the southern Sierra Madre Occidental other climatic drivers were more important.

The positive phase of ENSO (El Niño) was significantly associated with the year prior to across-region synchronous fire years as well as with the year prior to within-region synchronous fire years in all three Sierra Madre Occidental regions. The previous-year El Niño association with fire occurrence has been found in many studies in the southwestern United States. El Niño events, which tend to be associated with above-average rainfall in the southwestern United States and northern Mexico, can enhance the growth of grasses and forbs, which then provide the fine fuel necessary for fire to spread during the following year (Swetnam and Betancourt 1990). However, we did not find the association between previous-year El Niño events and fire occurrence in the Baja and Oriental regions. This could be because fuel availability is not the limiting factor in the Baja and Oriental regions but rather low fuel moisture or ignitions are limiting. Fuel availability may not be a limiting factor as much in the Baja and Oriental regions because fires are less frequent than in the Sierra Madre Occidental regions (Fig. 5.2). Perhaps because there is more time on average for fuel to build up between fires, inter-annual precipitation variability and ensuing fuel build-up is not as important. On the other hand, in Baja, we found significantly above average NINO3 values five years prior to fire years. This result was also found by Skinner et al. (2008) in their analysis of this area. They speculated that the reason for this could be that needle production was enhanced during El Niño years, and the dominant tree in the region, *Pinus jeffreyii*, retains its needles for 4-6 years. When the needles were cast from the conifers, sufficient fine fuel would be on the ground for a surface fire to spread.

The PDO was a significant driver of fire synchrony at the scale of northern Mexico; across-region synchronous fires were significantly associated with the negative phase of PDO. In addition, the Occidental North and the Oriental regions showed significant relationships between negative PDO values and within-region synchronous fire years. However, the other three regions did not. The influence of the PDO was also seen in the contingency table analyses, where combined negative phases of the PDO and ENSO resulted in higher-than-expected occurrence of fire. The PDO has also been shown to be a significant driver of fire in the western United States (Kitzberger et al. 2007), and in regional studies in the Pacific Northwest (Hessl et al. 2004, Heyerdahl et al. 2008a), western Colorado (Schoennagel et al. 2007), and Utah (Brown et al. 2008).

AMO did not appear to have a significant impact on synchrony across northern Mexico. The only result that suggested that AMO was potentially a driver of fire was the in the three-way phase combinations. While the combination of a negative PDO and a negative ENSO resulted in higher-than-expected fire occurrence, it was highest when AMO was positive. However, the two-way combinations of AMO and PDO and AMO and ENSO did not produce significantly different observed vs. expected values of fire, so the AMO influence cannot be confirmed. If we had a longer record of fire in all five regions, we might be able to better assess the influence of AMO. Much of the analysis period is in a period of low AMO activity, and AMO may not have had a large influence on fire synchrony in that period.

Fire regime interruption dates were highly variable across sites. The Sierra Madre Oriental had the earliest fire regime interruption dates and the Sierra Madre Occidental Central region had the largest number of sites with uninterrupted fire regimes continuing to the present. The variability in fire regime interruption dates and the presence of only one site in northern Mexico with a fire regime interruption date before 1900 is in stark contrast to the southwestern United States, where fire regimes were typically interrupted between about 1870 and 1900 (Swetnam and Baisan 2003) due to the introduction of livestock (Belsky and Blumenthal 1997), other land use changes, and subsequent fire suppression policies.

The variability in fire regime interruption dates across northern Mexico strongly supports the idea that human land use, including livestock grazing, timber and fuel wood harvesting, and road building are the driving force behind changing fire regimes in western North America. If the changes were due to climate, the changes would be more synchronous across sites and regions. This is in contrast to findings from a recent study in southern Nevada, where a mainly climatic explanation was found for reduced fire frequency in the last century (Biondi et al. 2011). In northern Mexico, local land use history among sites is the likely reason for the variability in fire interruption dates. For example, the three sites at Pino Gordo, which have continuing fire up to the present, are very difficult to access, and internal political struggles have kept logging from occurring in these sites (Fulé et al. in press). In other sites, fire interruption was coincident with the formation of ejidos (Heyerdahl and Alvarado 2003). In La Michilía Biosphere Reserve, the previous owner of the land was a rancher with 7,000 cows (Fulé and Covington 1999). In contrast to the western United States, where a wave of settlers, livestock, and railways washed across much of the territory before 1900 and changed the fire regime of widespread areas within a short period of time, many sites in Mexico have their own individual story of land use, human interaction, and fire regime change.

Climate was a strong influence on fire regimes across northern Mexico historically. Given that climate variability affected fire occurrence in the past, future climate change could also affect fire occurrence. The climate in the Southwest and northern Mexico is projected to become more arid in the near future, with this transition potentially already underway (Seager et al. 2007). Drier conditions are conducive to fire occurrence, but fine fuel production may limit fire in a more arid environment. Longer, warmer summers have been linked to more fires in the western United States (Westerling et al. 2006), and the same relationship probably exists in northern Mexico as well. Additionally, although climate change is bound to change ENSO, it is difficult to predict exactly how (Fedorov and Philander 2000, Tudhope and Collins 2003). As our climate change projections improve and our understanding of how climate change will impact global climate oscillations develops, explorations of historical climate-fire relationships may be useful in providing insight into how fire occurrence will change in the future.

Acknowledgements

We thank Erica Bigio and the FACS project for advice on data management. This research was supported by National Science Foundation grant DEB-0640351, and the Ecological Restoration Institute at Northern Arizona University.

Literature Cited

Belsky, A. J. and D. M. Blumenthal. 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior West. Conservation Biology **11**:315-327.

Biondi, F., L. P. Jamieson, S. Strachan, and J. S. Sibold. 2011. Dendroecological testing of the pyroclimatic hypothesis in the central Great Basin, Nevada, USA. Ecosphere **2**:Article 5.

Brown, P. M., E. K. Heyerdahl, S. G. Kitchen, and M. H. Weber. 2008. Climate effects on historical fires (1630-1900) in Utah. International Journal of Wildland Fire **17**:28-39.

Cook, E. R. 2000. Nino 3 Index Reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series #2000-052. NOAA/NGDC Paleoclimatology Program, Boulder, CO.

D'Arrigo, R. D., R. Villalba, and G. Wiles. 2001. Pacific Decadal Oscillation Reconstruction. . IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2005-020. NOAA/NGDC Paleoclimatology Program, Boulder, CO.

Drury, S. A. and T. T. Veblen. 2008. Spatial and temporal variability in fire occurrence within the Las Bayas Forestry Reserve, Durango, Mexico. Plant Ecology **197**:299-316.

Fedorov, A. V. and S. G. Philander. 2000. Is El Niño changing? Science **288**:1997-2002.

Fulé, P. Z. and W. W. Covington. 1997. Fire regimes and forest structure in the Sierra Madre Occidental, Durango, Mexico. Acta Botánica Mexicana **41**:43-79.

Fulé, P. Z. and W. W. Covington. 1999. Fire regime changes in La Michilía Biosphere Reserve, Durango, Mexico. Conservation Biology **13**:640-652.

Fulé, P. Z., M. Ramos-Gómez, C. Cortés-Montaño, and A. M. Miller. in press. Fire regime in a Mexican forest under indigenous resource management. Ecological Applications.

Fulé, P. Z., J. Villanueva-Díaz, and M. Ramos-Gómez. 2005. Fire regime in a conservation reserve in Chihuahua, Mexico. Canadian Journal of Forest Research **35**:320-330.

Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson. 2004. Atlantic Multidecadal Oscillation (AMO) Index Reconstruction. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2004-062. NOAA/NGDC Paleoclimatology Program, Boulder, CO.

Grissino-Mayer, H. D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. University of Arizona, Tucson.

Grissino-Mayer, H. D. and T. W. Swetnam. 2000. Century-scale climate forcing of fire regimes in the American Southwest. The Holocene **10**:213-220.

Hessl, A. E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications **14**:425-442.

Heyerdahl, E. K. and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. Pages 196-217 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer-Verlag, New York.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology **82**:660-678.

Heyerdahl, E. K., D. McKenzie, L. D. Daniels, A. E. Hessl, J. S. Littell, and N. J. Mantua. 2008a. Climate drivers of regionally synchronous fires in the inland Northwest (1651-1900). International Journal of Wildland Fire **17**:40-49.

Heyerdahl, E. K., P. Morgan, and J. P. Riser II. 2008b. Multi-season climate synchronized historical fires in dry forests (1650-1900), northern Rockies, USA. Ecology **89**:705-716.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Sciences **104**:543-548.

Kitzberger, T., T. W. Swetnam, and T. T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Global Ecology and Biogeography **10**:315-326.

Leopold, A. 1937. Conservationist in Mexico. American Forests **37**:118-120.

Rodríguez-Trejo, D. A. and P. Z. Fulé. 2003. Fire ecology of Mexican pines and a fire management proposal. International Journal of Wildland Fire **12**:23-37.

Schoennagel, T., T. T. Veblen, D. Kulakowski, and A. Holz. 2007. Multidecadal climate variability and climate interactions affect subalpine fire occurrence, western Colorado (USA). Ecology **88**:2891-2902.

Schoennagel, T., T. T. Veblen, W. H. Romme, J. S. Sibold, and E. R. Cook. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests. Ecological Applications **15**:2000-2014.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science **316**:1181-1184.

Sibold, J. S. and T. T. Veblen. 2006. Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. Journal of Biogeography **33**:833-842.

Skinner, C. N. 2007. Silviculture and forest management under a rapidly changing climate. USDA Forest Service General Technical Report PSW-GTR-203.

Skinner, C. N., J. H. Burk, M. G. Barbour, E. Franco-Vizcaíno, and S. L. Stephens. 2008. Influences of climate on fire regimes in montane forests of north-western Mexico. Journal of Biogeography **35**:1436-1451.

Stahle, D. W. and M. K. Cleaveland. 1993. Southern Oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and southern Great Plains. Journal of Climate **6**:129-140.

Swetnam, T. W. 1990. Fire history and climate in the southwestern United States. Pages 6-17 *in* Proceedings of the Symposium "Effects of fire managment of southwestern natural resources". USDA Forest Service General Technical Report RM-191, Tucson, AZ.

Swetnam, T. W. and C. H. Baisan. 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. Pages 11-32 *in* C. D. Allen, editor. Fire Effects in Southwestern Forests: Proceedings of the Second La Mesa Fire Symposium, Los Alamos, NM March 29-31, 1994. General Technical Report RM-GTR-286. USDA Forest Service Rocky Mountain Forest & Range Experiment Station, Fort Collins, CO.

Swetnam, T. W. and C. H. Baisan. 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. Pages 158-195 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and climate in temperate ecosystems of the western Americas. Springer-Verlag, New York.

Swetnam, T. W. and J. L. Betancourt. 1990. Fire - Southern Oscillation relations in the southwestern United States. Science **249**:1017-1020.

Taylor, A. H. and R. M. Beaty. 2005. Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. Journal of Biogeography **32**:425-438.

Trouet, V., A. H. Taylor, E. R. Wahl, C. N. Skinner, and S. L. Stephens. 2010. Fire-climate interactions in the American West since 1400 CE. Geophysical Research Letters **37**:L04702.

Tudhope, S. and M. Collins. 2003. The past and future of El Niño. Nature **424**:261-262.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science **313**:940-943.

Yocom, L., P. Z. Fulé, P. M. Brown, J. Cerano-Paredes, J. Villanueva, E. Cornejo-Oviedo, and D. A. Falk. 2010. El Niño-Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time. Ecology **91**:1660-1671.

Yocom, L., P. Z. Fulé, D. A. Falk, E. Cornejo-Oviedo, P. M. Brown, J. Villanueva, J. Cerano-Paredes, C. García-Domínguez, and C. Cortés-Montaño. in prep. Comparing the influence of broad-scale and fine-scale factors on fire occurrence in northeastern Mexico.

TABLE 5.1. Sites used in analysis of fire-climate relationships in Mexico.

Region	Site	Code	Latitude (N)	Longitude (W)	Area (ha)	No. trees	Reference
Baja	Blan	bl	31.06	-115.48	4 to 20	6	Skinner et al. 2008
	West	we	31.04	-115.58	4 to 20	23	Skinner et al. 2008
	Pino	pi	31.02	-115.53	4 to 20	15	Skinner et al. 2008
	Vall	va	31.00	-115.48	4 to 20	19	Skinner et al. 2008
	Coro	co	30.99	-115.57	4 to 20	14	Skinner et al. 2008
	Puer	ski_pu	30.96	-115.58	4 to 20	13	Skinner et al. 2008
	Tasa	ski_ta	30.96	-115.52	4 to 20	12	Skinner et al. 2008
	Azul	az	30.96	-115.40	4 to 20	18	Skinner et al. 2008
	Grul	gr	30.90	-115.52	4 to 20	15	Skinner et al. 2008
	Pyra	py	30.87	-115.50	4 to 20	13	Skinner et al. 2008
Occidental North	Rincon de las Tinajas	rt	30.56	-108.64	12	47	Fulé et al. unpublished
	El Abeto	ab	30.53	-108.62	12	34	Fulé et al. unpublished
	Mesa Prieta	mp	30.50	-108.55	12	47	Fulé et al. unpublished
	Prieta Sur	ps	30.49	-108.54	12	29	Fulé et al. unpublished
	Tutuaca Low	tm	28.66	-108.28	25	20	Fulé et al. 2005
	Tutuaca High	ta	28.65	-108.27	25	25	Fulé et al. 2005
	Tutuaca Top	tp	28.65	-108.26	25	33	Fulé et al. 2005
	Salsipuedes	ssp	28.62	-108.24	2	18	Heyerdahl and Alvarado 2003

Table 5.1 continued on following page.

TABLE 5.1 (CONTINUED). Sites used in analysis of fire-climate relationships in Mexico.

Region	Site	Code	Latitude (N)	Longitude (W)	Area (ha)	No. trees	Reference
Occidental Central	Pino Gordo Bajo Corachi	pgbc	26.57	-107.03	15	29	Fulé et al. in press
	Pino Gordo Medio Corachi	pgmc	26.57	-107.02	15	28	Fulé et al. in press
	Pino Gordo Alto Corachi	pgac	26.56	-107.01	15	25	Fulé et al. in press
	Guachochi	gu	26.88	-107.12	15	13	Fulé et al. unpublished
	Mohinora Parte Baja	mpbaja	25.97	-107.03	40	41	Cerano et al. unpublished
	Mohinora Parte Alta	mpalta	25.95	-107.03	60	32	Cerano et al. unpublished
	Falda de la Cañada	fct	25.41	-106.95	4	25	Heyerdahl and Alvarado 2003
	Alto del Jiguital	ajt	25.45	-106.88	3	22	Heyerdahl and Alvarado 2003
	Salsipuedes	sl	25.25	-106.50	30	28	Fulé & Covington 1997
	Arroyo Verde	av	25.08	-106.22	70	26	Fulé & Covington 1997
	Arroyo Laureles	al	24.95	-106.22	70	30	Fulé & Covington 1997
	Cebadillas	cb	24.88	-106.00	30	21	Fulé & Covington 1997
	El Carpintero	car	24.49	-105.67	4	24	Heyerdahl and Alvarado 2003
	Mesa de los Ladrónes	mlc	24.47	-105.66	3	29	Heyerdahl and Alvarado 2003
Occidental South	Las Chivas	chi	23.67	-105.51	6	23	Heyerdahl and Alvarado 2003
	Arroyo de las Flores	alf	23.62	-105.25	5	22	Heyerdahl and Alvarado 2003
	Las Bayas	lba	23.46	-104.83	3	17	Heyerdahl and Alvarado 2003
	Playa Grande	pg	23.47	-104.30	70	32	Fulé & Covington 1999
	Arroyo Taray	at	23.42	-104.25	70	33	Fulé & Covington 1999
	Arroyo San Pedro North	aspn	23.38	-104.22	30	15	Fulé & Covington 1999
	Arroyo San Pedro South	asps	23.37	-104.22	30	6	Fulé & Covington 1999
	Cerro Almagre	ca	23.35	-104.12	30	26	Fulé & Covington 1999

Table 5.1 continued on following page.

TABLE 5.1 (CONTINUED). Sites used in analysis of fire-climate relationships in Mexico.

Region	Site	Code	Latitude (N)	Longitude (W)	Area (ha)	No. trees	Reference
Oriental	Puerto el Tarillal	pu	25.44	-100.54	25	48	Yocom et al. unpublished
	Rancho Nuevo	rn	25.43	-100.53	25	48	Yocom et al. unpublished
	El Tarillal	et	25.44	-100.52	25	31	Yocom et al. unpublished
	La Viga	lv	25.36	-100.55	25	54	Yocom et al. unpublished
	Muzgoso	mu	25.36	-100.54	25	42	Yocom et al. unpublished
	Paraiso	pa	25.36	-100.52	25	44	Yocom et al. unpublished
	Las Bateas	lb	25.28	-100.49	25	29	Yocom et al. unpublished
	Las Manzanas	lm	25.27	-100.49	25	22	Yocom et al. unpublished
	La Armenia	la	25.27	-100.47	25	39	Yocom et al. unpublished
	San Onofre	so	23.80	-99.85	25	33	Yocom et al. 2010
	El Diferencial	di	23.79	-99.85	25	42	Yocom et al. 2010
	Mesa Acuña	ma	23.78	-99.86	25	25	Yocom et al. 2010
	Total				1043	1405	

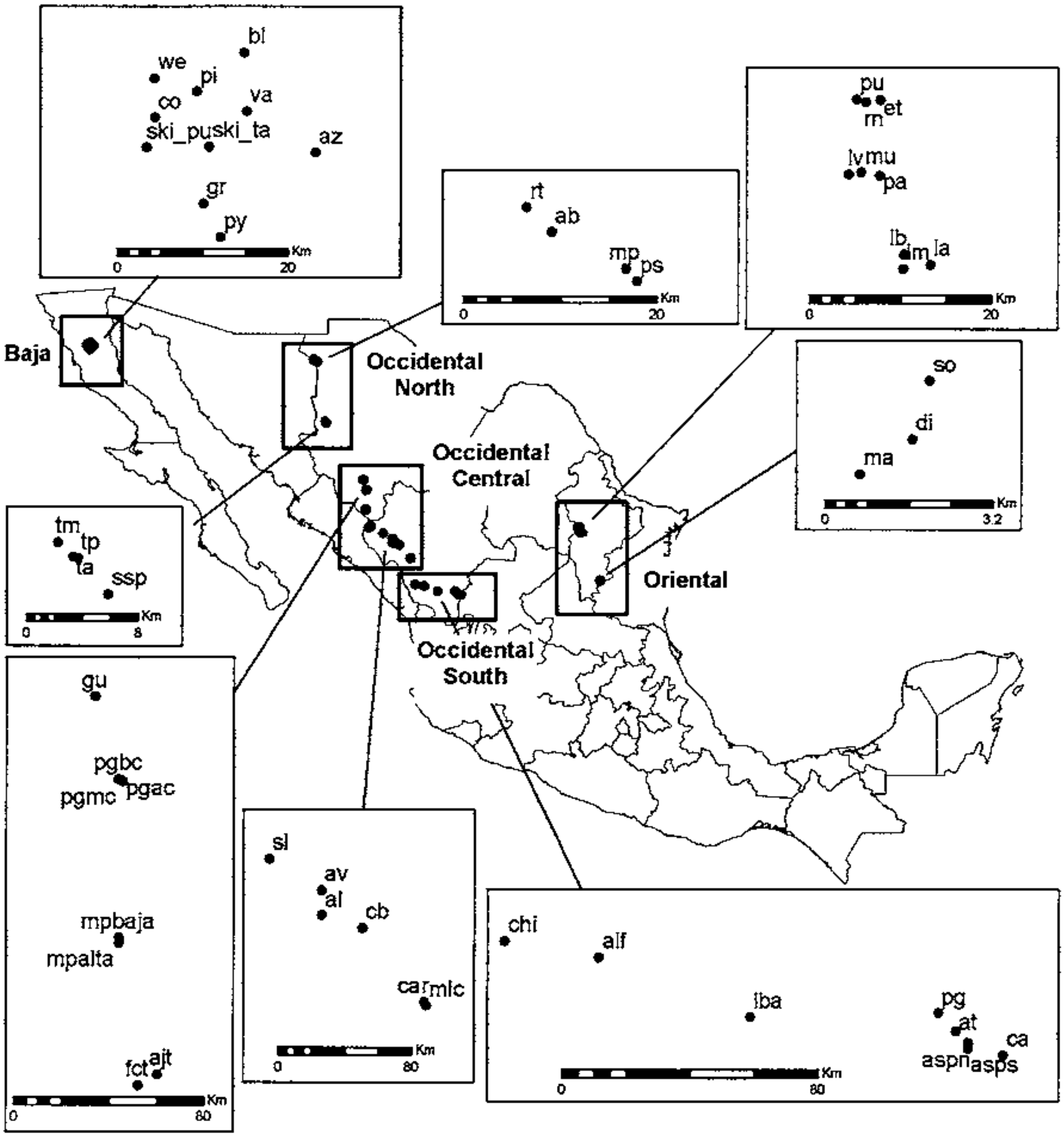

FIGURE 5.1. Map of 52 sites within 5 regions in Mexico, see Table 5.1 for individual site codes.

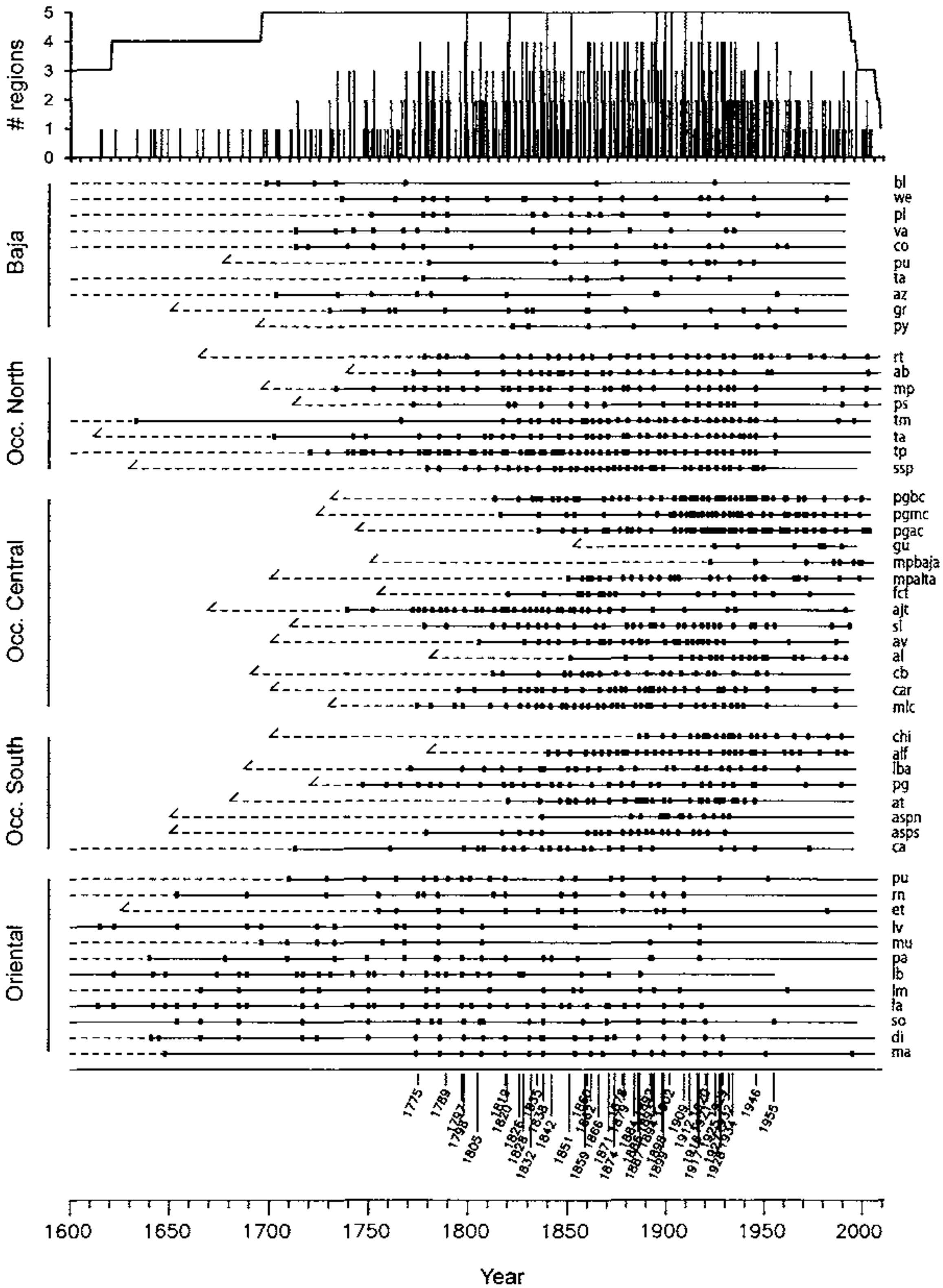

FIGURE 5.2. Fire history graph of 52 sites in 5 regions. Top: region recording depth (horizontal line) and regions recording fire (columns). Bottom: 45 years when 4+ regions recorded fire.

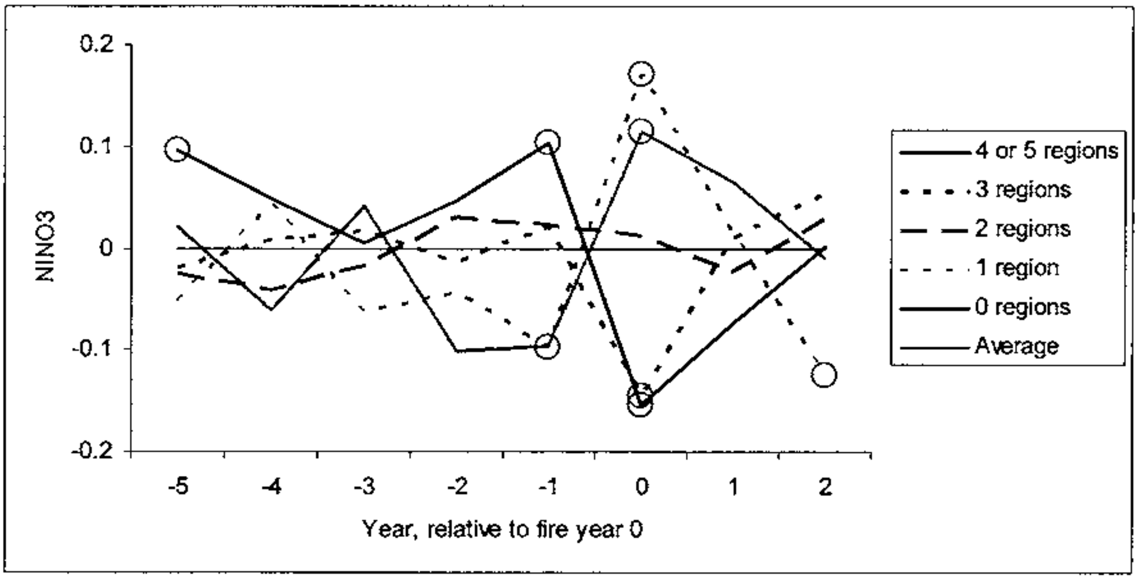

FIGURE 5.3. Superposed epoch analysis showing average departure from the mean value of NINO3 SST for years when 4+, 3, 2, 1, and 0 regions recorded fire. Fire years are indicated by 0, and values are also given for 5 years prior to fire years (negative values) and 2 years after fire years. Circles represent points that pass the 95% confidence interval.

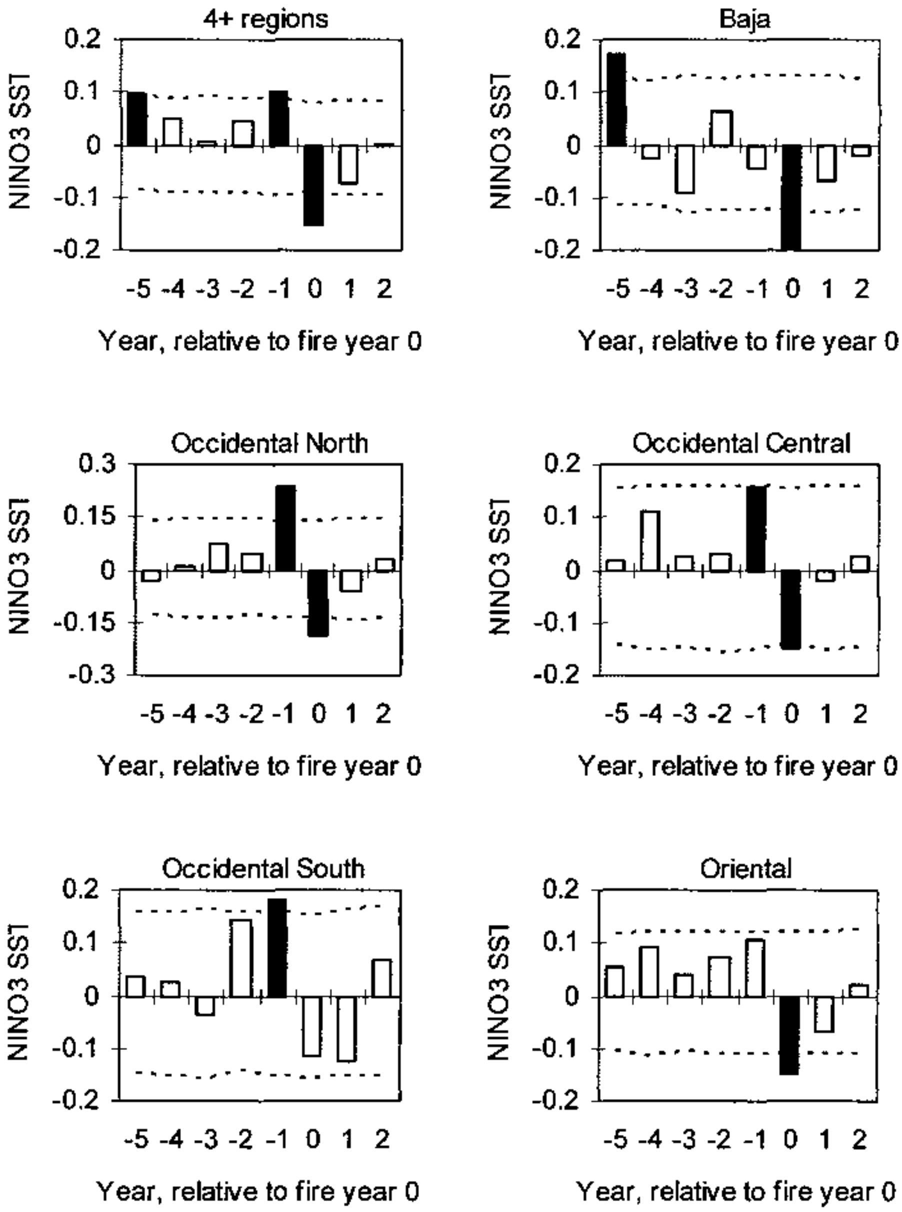

FIGURE 5.4. SEA analyses between NINO3 and across-region and within-region synchronous fire years, showing departure from the mean value of NINO3 SST (Cook 2000) in fire years (indicated by 0) and years before and after fire years. Black bars are those that pass the 95% confidence interval (dotted line).

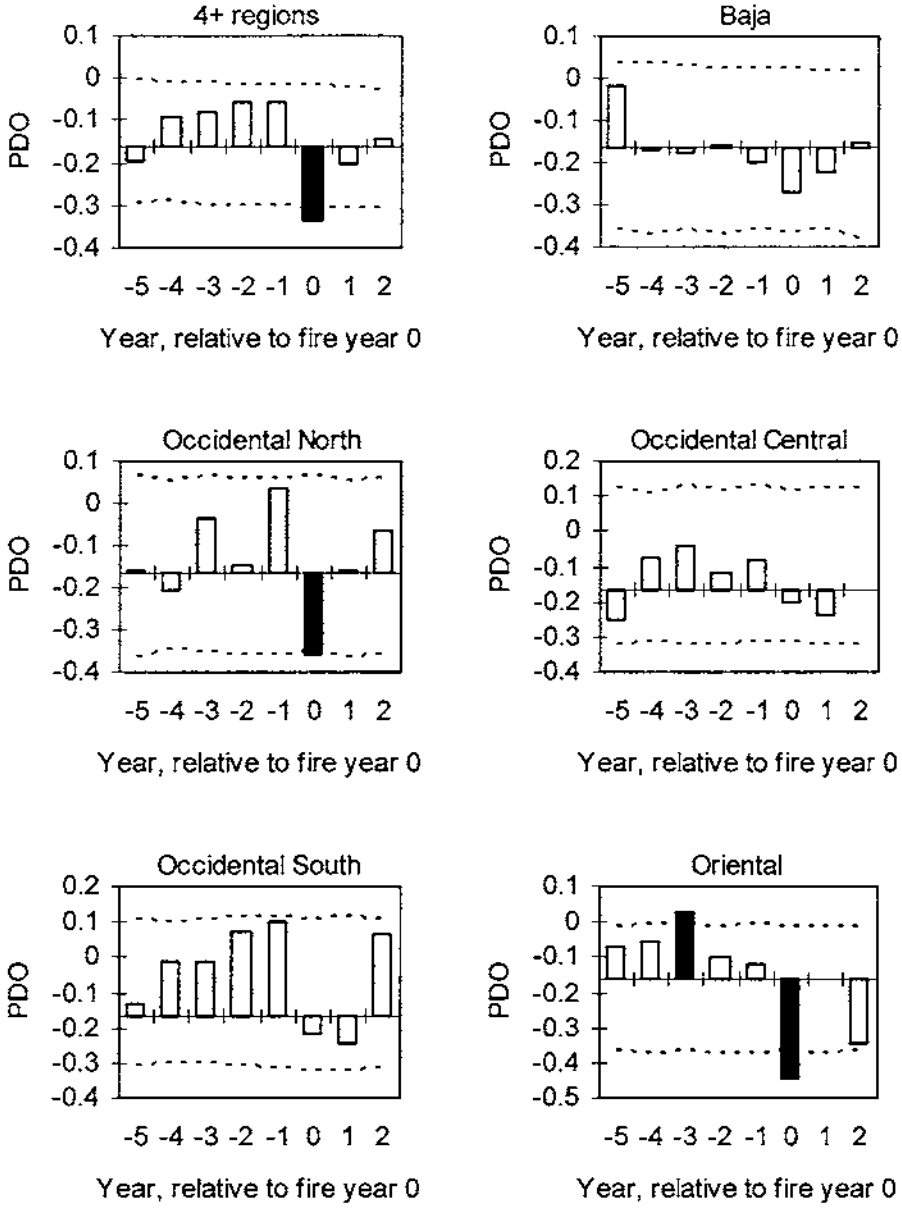

FIGURE 5.5. SEA analyses between PDO and across-region and within-region synchronous fire years, showing departure from the mean value of NINO3 SST (D'Arrigo et al. 2001) in fire years (indicated by 0) and years before and after fire years. Black bars are those that pass the 95% confidence interval (dotted line).

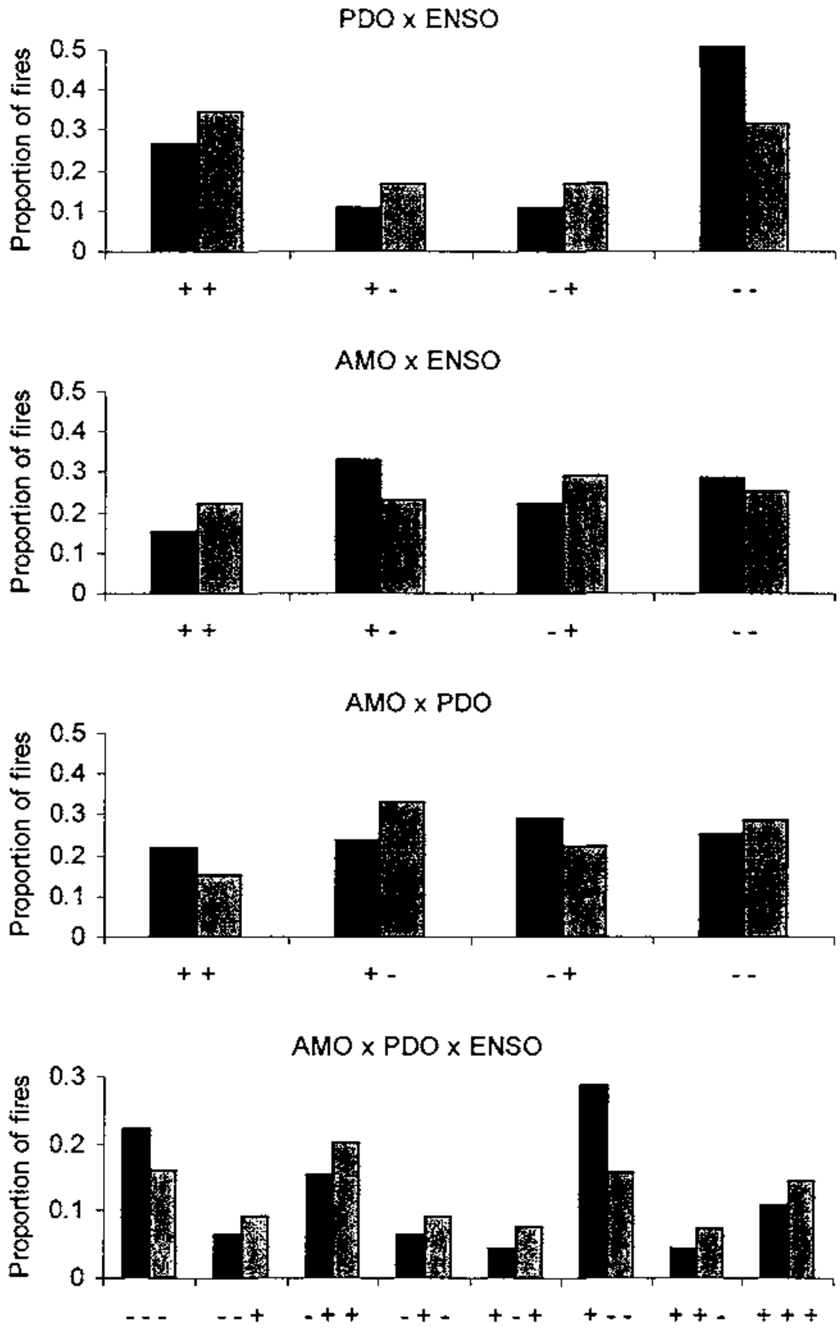

FIGURE 5.6. Expected and observed frequencies of fire in two-way and three-way combinations of AMO, PDO, and ENSO. Warm (positive) phases of these oscillations are represented by + symbols, and cool (negative) phases are represented by – symbols. Black bars represent observed fire occurrence; grey bars represent expected fire occurrence.

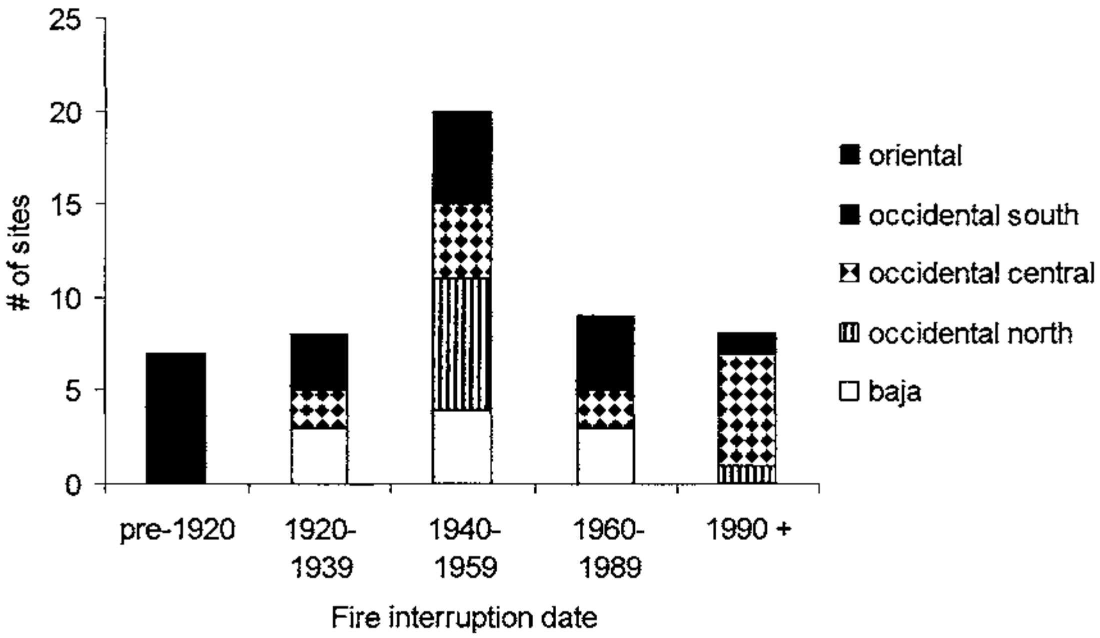

FIGURE 5.7. Number of sites in each region that experienced fire interruption or no fire interruption (1990+) in multi-decade categories.

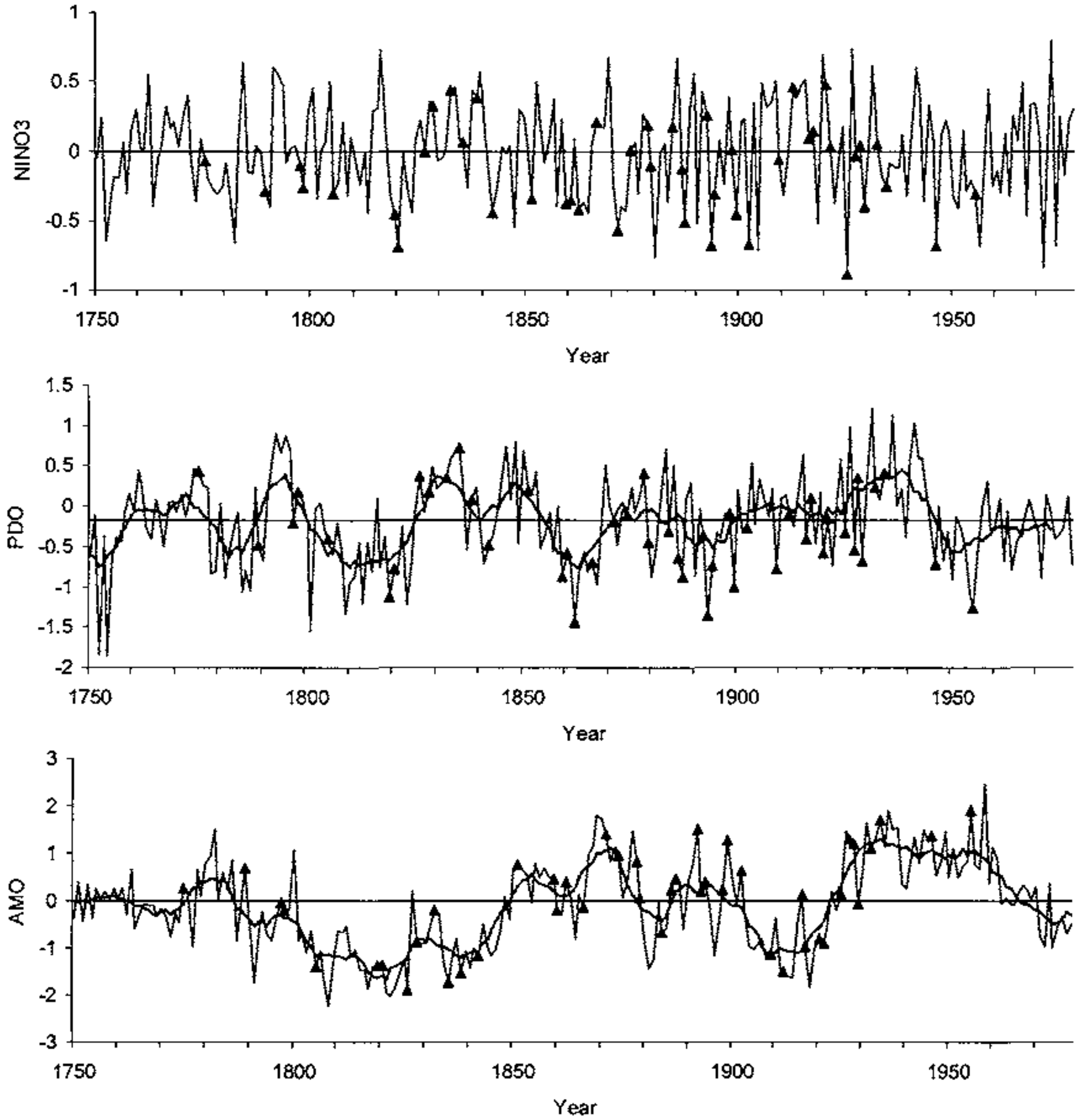

FIGURE 5.8. Annual climate indices during across-region synchronous fire years (triangles). Light black lines are tree-ring reconstructed climate and heavy grey lines are 10-year averages.

CHAPTER 6: CONCLUSION AND MANAGEMENT RECOMMENDATIONS

This dissertation has documented a range of influences on fire occurrence in eastern and northern Mexico. Climate is important over long time periods and broad scales, but it can also influence the probability of fire occurrence at individual sites. Fine-scale factors, including topography, elevation, aspect, slope, and forest species composition are important influences on fire regimes and can interrupt synchrony between closely spaced sites. Finally, humans are an important component when considering influences on fire in Mexico too; humans have been influential in causing fire exclusion and have also been an important ignition source of fires.

Currently, people account for the majority of fire starts (up to 90%) in Mexico, and the main reason fires are started is to improve agricultural and pasture areas (Rodríguez-Trejo 2008). People have used fire to meet various objectives in Mexico for millennia; it has been speculated that human-caused fires may even have played a role over evolutionary time in pine forests of Mexico (Rodríguez-Trejo and Fulé 2003).

Today there are three categories of pine forests in Mexico, according to Rodríguez-Trejo and Fulé (2003): 1) forests with 'excessive' human-caused fire which is contributing to deforestation and degradation, 2) forests maintained by natural or anthropogenic fires, with fire regimes similar to fire regimes of the past centuries, and 3) forests where fire exclusion has allowed fuel buildup to occur or successional change to take place, leading to high risk of severe wildfire.

In the three fire history chapters in this dissertation, there are examples of both the second and third category of forest described by Rodríguez-Trejo and Fulé (2003). At Peña Nevada, a severe wildfire deforested much of the peak in 1998; it is likely that a large amount of fuel buildup during fire exclusion since the 1920s, along with a severe climate event (the extreme 1998 El Niño), contributed to the severity of the fire. In our sites in the northern Sierra Madre Oriental, fire exclusion began as early as 1887; the forests in those sites are probably at high risk of a high-severity fire if a fire starts during extreme fire weather. Only at Pico de Orizaba did we find a forest that experienced many fires throughout the 20th century and has an open, low-density structure. However, in that location, in the 21st century fire frequency has slowed either due to fire suppression or lack of continued frequent human ignitions. We did not work in areas where excessive human-caused fire has degraded the forest or caused deforestation.

Rodríguez-Trejo has written that integrated fire management with the goal of maximizing positive impacts of fire and minimizing negative impacts of fire is necessary in Mexico (Rodríguez-Trejo 2008). Positive impacts of fire include maintenance of biological diversity, plant regeneration, tree growth, nutrient and organic matter recycling, maintenance of wildlife habitat, and improved pasture. Negative impacts include risk for firefighters, people, and property, deforestation, erosion, pollution, tree and wildlife mortality, catastrophic fire danger, extremely frequent fires, and economic impacts (Rodríguez-Trejo 2008).

In forests of Peña Nevada, the northern Sierra Madre Oriental, and Pico de Orizaba, where fires were historically frequent and the forests are fire-adapted, a policy of strict fire suppression is unwise and instead I recommend integrated fire management, as described by Rodríguez-Trejo. Although negative risks to property, safety, and natural resources must be considered, reintroducing fire at Peña Nevada and the northern Sierra Madre Oriental, and allowing frequent fire to continue at Pico de Orizaba are management options that should be considered. The lessons learned in the American Southwest, where billions of dollars are needed to restore forests altered by more than a century of fire exclusion, should be applied where fire exclusion has taken place in fire-adapted forests. Mexico is seeing a slow rise in the use of prescribed fire in appropriate situations (Rodríguez-Trejo and Fulé 2003), and hopefully this trend will continue where appropriate.

This dissertation documented the importance of climate as an influence on fire over the past several centuries. Given that climate variability affected fire occurrence in the past, future climate change could also affect fire occurrence. As our climate change projections improve and our understanding of how climate change will impact global climate oscillations develops, explorations of historical climate-fire relationships may be useful in providing insight into how fire occurrence will change in the future.

Literature Cited

Rodríguez-Trejo, D. A. 2008. Fire regimes, fire ecology, and fire management in Mexico. Ambio **37**:548-556.

Rodríguez-Trejo, D. A. and P. Z. Fulé. 2003. Fire ecology of Mexican pines and a fire management proposal. International Journal of Wildland Fire **12**:23-37.