EXAMINING HISTORICAL FIRE REGIMES AND FIRE SYNCHRONY AT MULTIPLE SCALES ACROSS NORTHERN ARIZONA

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ABSTRACT

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EVE FISCHER

Wildfire is a fundamental ecological process in many forests in western North America, long supported by abundant ignitions from lightning and Indigenous cultural burning practices. However, land use and fire suppression policies brought to the western U.S. via settler colonialism have effectively excluded fire from the landscape for more than a century. This lack of fire has led to a buildup of dense fuels, creating the conditions for more intense fires when these forests do burn, ultimately impacting ecological function and public safety. As climate change has progressed, drought has become much more common and severe in the West. In fact, many view the current drought period in the region as a 'mega drought,' ongoing since approximately 2000. Drought takes the moisture out of these dense fuel buildups, increasing the risk of severe wildfires. Today, fires in the West are much more extreme than they were even two decades ago.

A key aspect of addressing the current wildfire crisis and enacting thinning and prescribed burning projects aimed at restoring forest structure and function is understanding the historical fire regimes of these forests. Dendrochronology, the science of tree-ring dating, specifically its subfield, dendropyrochronology, the study of fire scars in the tree-ring record, is a primary tool in researching fire regimes of the past. This project utilizes these methods in order to assess historical patterns of fire in northern Arizona.

To add to the rich record of fire history studies in the area, we analyzed a total of 35 fire-scarred tree-ring samples to form a fire chronology for a site near Williams, Arizona, referred to as the Williams site. Similar to other ponderosa pine forests in the Southwest, we found that fires were frequent at the Williams site (mean fire interval = 3.45 years) and regulated by climate, finding that fires were most likely to occur in drier-than-average years that directly followed wetter-than-average years.

Next, we combined this new tree-ring fire-scar record with sixteen published tree-ring fire-scar chronologies from across the greater northern Arizona region and compared fire synchrony across the landscape for the years 1700-1900. We found that climate influenced fire at regional scales and fire synchrony tended to be greater among geographically closer subregions.

These results indicate that climate plays a strong role in the historical fire regimes of northern Arizona, in addition to local factors such as topography and land use. Climate is a key driver of fire in the Southwest, and as climate change progresses, fire regimes will also continue to shift. Anticipating this next era of fire behavior and climate interactions is a vital goal for contemporary fire ecology research.

Key Words: wildfire, fire synchrony, dendrochronology, tree rings, fire scars, climate change, fire-climate relationship, northern Arizona, forest management

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

The sections in the main text of this thesis are formatted with the intention to publish them as a manuscript in a journal. I also use “we” instead of “I” because co-authors will be included in the publishable version of the manuscript

CHAPTER 1: INTRODUCTION

Fire is a foundational part of the human story, and its deep connection to culture, society, and ecology is exemplified in the southwestern U.S. (Pausas & Keeley, 2023). Wildfire continues to take on a more prominent role in public perception of the impacts from climate change, with 52% of Americans thinking global warming is making wildfires in the western U.S. worse as of 2017 (Leiserowitz et al., 2017). There is also clear scientific evidence that this association is accurate, and that increasing temperatures and drought conditions are closely correlated with increasing wildfire severity (Mueller et al., 2020). Researching fire prediction and management is now more pressing than ever. Dry conifer forests in the southwestern U.S. are adapted to frequent, low severity fires, and in some instances rely on them (Abella, 2009; Fulé et al., 1997). These fire regimes, which can be defined as 'the spatial and temporal pattern of fires and their effects in a given area and over a given time period' (Oddi, 2018), have two broad categories of drivers: top-down factors (such as climate) and bottom-up factors (such as local topography and human influences) (Yocom Kent et al., 2017). Until the late 1800s, frequent, low severity fire regimes were supported in the dry conifer forests of western North America by lightning and cultural burning practiced by Indigenous peoples (Allen, 2002; Roos et al., 2023). This fire regime was interrupted by the large-scale livestock grazing and fire suppression regimes brought about by European colonization (Whitehair et al., 2018). Bringing together the seemingly disparate realities of fire's irreplaceable role in southwestern ecosystems with the real threat to human life and livelihood posed by the worsening wildfire crisis is a key dynamic for policy makers and resource managers to take on today.

One solution to counterbalance this vicious cycle of fire suppression and severe wildfire is thinning and prescribed burning treatments. These kinds of forest treatments aim to reduce fuel loads to lessen the risk of fire and move forest ecosystems closer to their historical states, following the precedent of the Indigenous cultural burning practices of the region. Indigenous cultural burning, along with abundant lightning ignitions, formed the backbone of high-frequency, low-severity fire regimes in the Southwest until the onset of the fire suppression period (Roos et al., 2023). Reintroducing fire to the landscape in the modern era can aid in reinstating historical fire regimes, reducing the risk of severe wildfire, and making southwestern ponderosa pine forests more resilient in the long term (Stan et al., 2022).

Dendrochronology, the science of tree-ring dating, was formally developed by A. E. Douglass in the early 20th century (Speer, 2010). His early work on the subject investigated the question of researching past climate conditions by examining tree-ring growth patterns (Douglass, 1919). In 1937, Douglass founded the Laboratory of Tree-Ring Research, which has worked to further research over the past century and aid in founding other dendrochronology labs around the world (Laboratory of Tree-Ring Research, 2025). Since then, the discipline has been used in a wide array of applications, including for fire history analysis. The field of dendrochronology brings into focus what the environmental conditions in these forests were like in the past, including how often they burned and how far fires spread (Speer, 2010).

Since its founding as a scientific discipline, dendrochronology has established itself as a foundational approach for developing paleoecological climate proxies and records of fire history. Seminal work in the field included early climate-focused tree-ring studies conducted by Douglass and his student, Dr. E. Schulman, who worked to confirm and analyze the link between climate and tree-ring growth, the basis of dendrochronology (Stokes & Dieterich, 1980). Interactions between fire events and tree rings were being investigated and written about as early as 1927 (Craighead, 1927), but the methodology of using dendrochronology to chronicle specific fire histories became more widespread and well documented several decades later (Arno & Sneck, 1977). A key part of fire history research is determining historic fire return intervals for particular areas in order to properly inform forest management (Grissino-Mayer et al., 1995). Fire return intervals in dry southwestern forests have been found to range roughly from 2-20 years (Dieterich, 1980; Swetnam & Baisan, 1996). Fire-scar sample collection involves systematically searching a site for visibly fire-scarred trees, rather than a more random sampling method, and requires that results be interpolated across a larger area (Arno & Sneck, 1977). However, inferences made based on these methods have been shown to accurately depict historic fire regimes across larger scales (Farris et al., 2010, 2013). Extensive tree-ring based fire chronology research has been developed using these methods and provides detailed information about historical fire regimes and forest conditions across North America and worldwide.

The fire history-related subfield of dendrochronology, sometimes referred to as dendropyrochronology, has continued to grow in recent years, following the development of new fire history analysis software and the innovative connections being made between multiple fire history studies (Brewer et al., 2016; Malevich et al., 2018; Margolis et al., 2022). Networks of tree-ring based fire histories are growing, such as the North American Tree-Ring Fire-Scar Network (NAFSN) and the International Multiproxy Paleofire Database (IMPD) which links together published tree-ring based fire chronologies from across the continent and around the world, respectively, allowing for more in-depth analyses of fire and its synchrony across broad spatial scales (Margolis et al., 2022; NOAA, 2020). These deeper analyses serve in part to help develop the body of evidence that supports forest management practices such as thinning and prescribed burning, which in turn helps put fire back on the landscape at a large scale.

Ultimately, these networks have the potential to greatly benefit both fire-adapted ecosystems and human communities alike in the long run.

In this study, we sought to develop a previously unpublished fire chronology for a site in northern Arizona, as well as to conduct a combined analysis of studies from across the northern Arizona region. Our aim was to provide a new medium-scale analysis of fire synchrony for this geographic area that describes its overall historical fire regime, as well as investigate the strength and role of the fire-climate relationship among these sites.

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CHAPTER 2: EXAMINING HISTORICAL FIRE REGIMES AND FIRE SYNCHRONY AT MULTIPLE SCALES ACROSS NORTHERN ARIZONA

ABSTRACT

Wildfire is a key disturbance in southwestern ecosystems, and fire regimes vary by scale as well as other factors. Fire regimes are affected by 'top-down' factors, such as climate, as well as 'bottom-up' factors, such as topography. These differential influences cause a mosaic of patterns in fire history across the landscape, as well as certain consistencies between the fire histories of various sites. Examining synchrony between fire regimes at different sites aids in identifying the overarching regional pattern of fire, and predicting the level of influence top-down factors will have on it moving forward. We conducted a dendrochronological analysis of the fire history of a site near Williams, Arizona, referred to as the Williams Site, using 35 tree-ring samples. The mean fire interval for this site was 3.45 years overall and the Weibull Median Probability Interval was 3.21 years overall. Additionally, we compared our site with sixteen published fire chronologies from across the greater northern Arizona region for fire synchrony for the years 1700-1900. We found that fire chronologies tended to be more similar among geographically closer subregions, but that chronologies were still unique at the individual level. We also conducted a Superposed Epoch Analysis (SEA) of the Williams Site, finding that fires were most likely in drier-than-average years that directly followed wetter-than-average years. These results indicate that climate plays a strong role in fire regimes in northern Arizona, and that the fire chronology of the Williams Site fits in well with trends in fire history across the broader landscape.

INTRODUCTION

Wildfire is a key disturbance in southwestern ecosystems, and fire regimes vary by scale as well as other factors. Particularly, fire regimes are affected by 'top-down' factors as well as 'bottom-up' factors (Swetnam & Betancourt, 1998). Top-down factors refer to forces that impact fire regimes at the macro level across a large area. For instance, climate is a major top-down factor that has global influence on fire regimes. Another example of a top-down factor would be fire suppression, which has heavily impacted fire regimes across the western US for more than a century (Whitehair et al., 2018). These differential influences cause a mosaic of patterns in fire history across the landscape, as well as certain consistencies among the fire histories of various sites. Examining synchrony among fire regimes aids in identifying the overarching regional pattern of fire as well as predicting the level of influence top-down factors will have on it moving forward. Of key importance to anticipating change in fire regimes is a foundational understanding of the links between fire regimes at multiple scales, and environmental factors influencing them. The similarities between fire chronologies can inform the level to which climate drives fire patterns, both as opposed to and in conjunction with local landscape and land-use factors. Fire synchrony is an aspect of fire history research that has been gaining traction in the literature. Foundational research on the relationship between major fire years and climate variables was conducted in high-elevation mixed-conifer forests in southern Arizona in 1990 (Baisan & Swetnam, 1990). More recently, fire synchrony has been examined at broader scales. For example, a 2017 study compiled 67 fire chronology sites from across northern Mexico and assessed synchrony at the regional level, finding both a strong overall influence from climate, as well as notable variability dependent on local, bottom-up factors (Yocom Kent et al., 2017). Another example is a recent study that increased the spatial scope of fire synchrony analysis to the entire North American continent, linking different fire regimes, ecosystems, and interactions with climate (Margolis et al., 2025).

The fire regimes of individual sites can vary greatly due to the influence of local factors, also referred to as bottom-up controls (Ireland et al., 2012). These factors can include natural fire barriers created by a site's topography, variations in slope and aspect, vegetation community type and abundance, elevation, and microclimate (Beaty & Taylor, 2008; Heyerdahl et al., 2001; Taylor & Skinner, 2003). Bottom-up controls that alter fire regimes can also include anthropogenic factors such as Indigenous cultural burning and land-use types (Grissino-Mayer et al., 1995; Huffman, 2013). These factors can interact with each other and with top-down factors to create complex mosaics of fire regimes across a given region (Falk et al., 2007; Whitehair et al., 2018).

Historical fire regimes in the Southwest have a strong relationship with climate, particularly driven by annual-scale variability in wet and dry conditions linked to the El Niño Southern Oscillation (ENSO) (Swetnam & Betancourt, 1998). Severe droughts, a phenomenon that has been increasing in the Southwest over the past two decades, are also closely correlated with significant fire years (Swetnam & Baisan, 1996; Williams et al., 2020).

The correlation between fire years and interannual climate oscillations typically follows a consistent pattern. ENSO switches phase from El Niño to La Niña on a 3-7 year basis, which in the Southwest translates to higher amounts of precipitation during El Niño years, and drier climatic conditions during La Niña years (Swetnam & Betancourt, 1998). The conditions created by ENSO in the Southwest strike a balance between periods of moisture and ecosystem productivity and drier periods that allow for combustion to take place, which is an important ingredient for frequent fire to occur (Pausas & Ribeiro, 2013). During wetter El Niño years, herbaceous vegetation has the chance to grow quickly, increasing fuel loads and continuity on the landscape. Then, when the switch to La Niña brings about more arid conditions, that surplus of vegetation dries out, meaning that lightning or human induced ignitions are more likely to lead to wildfire (Swetnam & Betancourt, 1998). Greater amounts of fuel that are more available to burn also contribute to these fires being more severe (Parks et al., 2023).

These large-scale climate patterns create the overall conditions for fire regimes to persist in the ways they typically do. The fire-climate relationship in the western U.S. is predicted to shift due to climate change, leading to more frequent severe wildfire events, risking the loss and type conversion of vulnerable ecosystems (Guiterman et al., 2022; Wasserman & Mueller, 2023). This anticipated change, combined with the high level of influence climate has on fire in this region, points to the urgency and importance of preparing western forests for the future.

Already, significant changes are underway in the modern fire regimes of the western U.S.. Wildfires in this region are more extreme in terms of large areas of severe fire than they were twenty years ago (Iglesias et al., 2022). Additionally, many view the current drought period in the broader region as a 'mega drought,' ongoing since approximately 2000 (Williams et al., 2020). Continual droughts, coupled with predictions of increasing temperatures across the West over the next several decades, stand to cause more frequent and intense wildfires, which may then become more limited if fuel production is unable to keep up (Rocca et al., 2014). It is predicted that these more severe fires will cause higher rates of tree mortality than historic, low severity fires, potentially leading to type conversions and the loss of large swaths of ponderosa pine forests (Guiterman et al., 2022; Savage & Mast, 2005).

To address this crisis, understanding past fire regimes is vital. Ponderosa pine forests in the Southwest are adapted to frequent, low severity fires (Fulé et al., 1997). This historic fire regime would have kept fuel loads at a sustainable level, maintaining healthy stands of adult trees. Understanding the specific bottom-up influences that contributed to these fire regimes, in addition to climate factors, helps us anticipate how best to reinstate similar patterns of fire in the modern era, thereby increasing the resilience of these forests.

Southwestern North America has been an epicenter for this kind of research, but more remains to be uncovered as we try to understand spatial and temporal links in the synchrony of fires. Therefore, we selected a study site in northern Arizona, nested among previously studied areas to address the following research questions:

1. At the site scale (700 ha), what were the temporal and spatial patterns of fire over the past several centuries, and what drove this historical fire regime?
2. At the regional scale, how synchronous were historical fires (1700-1900) among sites across northern Arizona?
3. Did historical fire synchrony vary spatially and/or temporally across sites in northern Arizona?

METHODS

Fire History: Williams, AZ

Study Area

We developed a site-specific tree-ring fire-scar chronology from samples collected throughout an approximately 700 ha site near Williams, AZ (Figure 1), referred to henceforth as the 'Williams site' (Figure 1). The site is in the Kaibab National Forest (112.0071531°W, 35.2215674°N) and is dominated by ponderosa pine (*Pinus ponderosa*), with Gambel oak (*Quercus gambelii Nutt.*), alligator juniper (*Juniperus deppeana* Steud.), Utah juniper (*Juniperus osteosperma* (Torr.) Little) and New Mexico locust (*Robinia neomexicana* Gray) also present (Honig and Fulé, 2012). Elevation within the site ranges from 2067 to 2184m, with an average slope of 7.5%. Mean annual precipitation at the site is 539mm from a combination of winter snow and summer convective storms (monsoons). Mean monthly temperatures range from 0.17°C in December to 20.22°C in July (1991-2020 Normals, PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, accessed March 2025) .

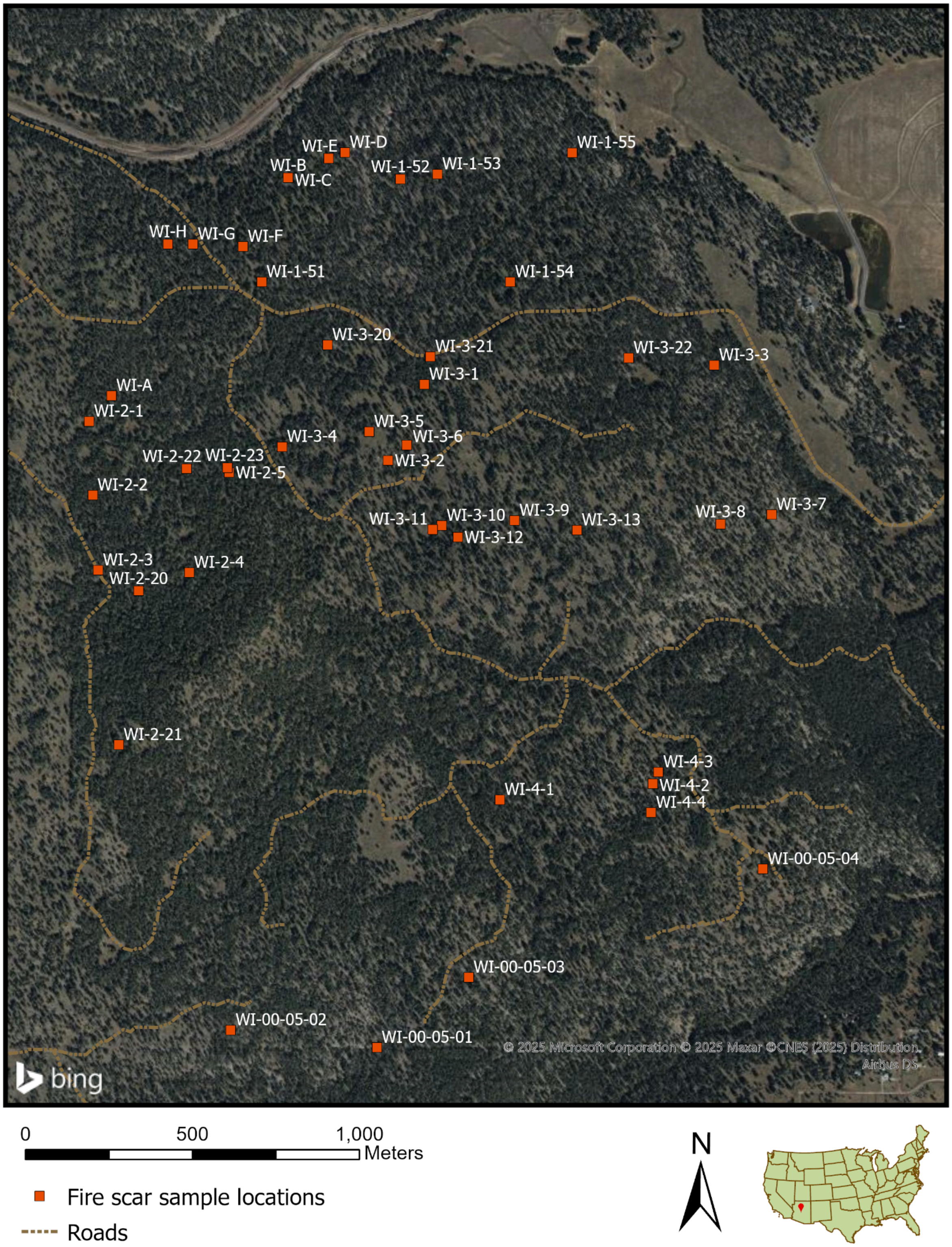

Figure 1: Williams Site map showing locations of sampled fire-scarred trees.

Sample collection, preparation, and crossdating

Samples from fire-scarred trees were collected by T. Heinlein, P.Z. Fulé and colleagues from the Williams site between 1997 and 2001 as part of a U.S. Forest Service-sponsored project (Heinlein et al., 2001; Figure 1). Samples were collected by systematically searching the site for visibly fire-scarred trees, logs, snags, and stumps, and removed as partial cross sections using a chainsaw. In total, 52 cross-section samples were collected in the field. The samples were first mounted on wood panel backings and then sanded down to a smooth surface to prepare them for analysis. In a companion study, a grid of plots was installed on the same study site and used to assess potential fire behavior under alternative climate and forest structure scenarios (Honig and Fulé 2012).

To ensure accurate dating of the tree rings in these samples, we visually crossdated them with the aid of the AZ521 chronology from the G.A. Pearson Natural Area (Graybill, 2002; accessed September 2023 via the International Tree-Ring Databank, https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring) located 25 km from the site. Samples that were difficult to date due to complacent or suppressed ring patterns, were scanned and their tree rings measured using the program CooRecorder (Maxwell and Larsson, 2021). We then used the program Cofecha (Holmes, 1983) to assist with the crossdating of these samples by searching for possible dating placements against the chronology from Graybill (2002). Samples whose tree rings could not be crossdated were removed from further analysis. Based on the calendar years assigned to each tree ring through the crossdating process, we determined the year of each fire scar in every accurately dated sample. We assigned each fire scar a growth season (Dormant (D), Early Earlywood (EE), Middle Earlywood (EE), Late Earlywood (LE), Latewood

(L), or Undetermined (U)) depending on their position within the tree ring (Dieterich & Swetnam, 1984).

Data analysis

We analyzed the fire history for the site using the program FHAES (Fire History Analysis and Exploration System) (Brewer et al., 2016). Using FHAES, we calculated composite fire interval statistics for the site using (1) all fire years, using a minimum of two samples containing fire scars as a threshold, and (2) years in which a minimum of two trees and ≥25% of the recording trees were scarred (i.e. 'widespread' fire years). Similar thresholds for composite fire chronologies have been used in other fire history reconstructions (Swetnam and Baisan, 2003) and using this filtering approach here makes our research comparable with the existing literature. Fires scarring 25% or more of the samples were considered to represent 'widespread' fire years, since fires that scar a larger portion of the total samples tend to have been wider in extent (Farris et al., 2010). We estimated the mean fire interval (MFI) and Weibull median probability interval (WMPI) for both the unfiltered and filtered data. Mean fire interval is a commonly used metric to assess the overall frequency of fire in a site, based on observed fire-scar data. A Weibull distribution is frequently used to represent the skewed distribution of fire interval data, and has been shown to model historical fire chronologies in the Southwest well (Grissino-Mayer, 1999). This flexible distribution provides a statistical bracket for historical fire interval variability, as well as a standard metric for fire chronology analysis. We focused on the WMPI, which represents the fire interval at the 50th percentile of the Weibull distribution, which is a measure of central tendency. WMPI can be more resistant to large interval values in the dataset as compared to exclusively data-based statistics like MFI. We used Kolmogorov–Smirnov goodness-of-fit tests to check if a normal or a Weibull distribution adequately modelled the data. Additionally, we summarized the data on ring position of fire scars to examine fire seasonality. These analyses constitute our site-level fire chronology development and lead into a larger-scale fire synchrony study focused on the northern Arizona region.

Climate analysis

To determine the influence of climate on the fire regime of the Williams Site, we compared our chronology results with tree-ring based reconstructions of El Niño Southern Oscillation (ENSO) (Cook et al., 2008) and the Palmer Drought Severity Index (PDSI) (Cook et al., 1999). We selected these climate variables since they have been seen to have a more significant effect on fire regimes in the Southwest, as compared to longer-term climate oscillations such as the Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) (Rother & Grissino-Mayer, 2014).

To make this climate comparison, we conducted a Superposed Epoch Analysis (SEA) in the burnr package in R (Malevich et al., 2018). We extended the analysis from six years prior to a fire year to four years after a fire year to indicate patterns in climate variability and drought both leading up to and following fires. We conducted this analysis at the whole site level, for all fire years (with a two sample minimum), and for widespread fire years only. To determine the significance of our SEA results, we included 95% and 99% confidence intervals calculated via bootstrapping.

Fire synchrony: northern Arizona

Data sourcing

We included the fire chronologies from sixteen other studies conducted across northern Arizona in our fire synchrony study in addition to our own chronology for the Williams site (Table 1, Figure 2). We sourced these chronologies from the International Multiproxy Paleofire Database (IMPD) (NOAA, 2020), the North American Tree-Ring Fire-Scar Network (Margolis et al., 2022), or directly from the study authors as necessary. In some cases, the studies we sourced contained a single fire-scar chronology. Other studies consisted of multiple sites or subregions, each having their own associated fire-scar chronology data (Guiterman et al., 2019; Ireland et al., 2012; Stan et al., 2014). In these instances, we followed the groupings made by the authors of each study, to stay in line with the intention of their research. For example, for the Chuska Mountains study area (Guiterman et al., 2019), we took 10 published sites and combined them into two groups, based on geographic location and human use history, as designated in that publication.

Table 1: Studies included in our the fire synchrony analysis (continued on next page).

Name	Site Code	Citation	Subregion	Lat	Long	Elevation (m)	Sample #	Species	Area (ha)
Peaks East	SFPE	Heinlein et al. 2005	Mogollon Rim	35.317	-111.608	2500	18	Mixed conifer	160
Peaks West	SFPW	Heinlein et al. 2005	Mogollon Rim	35.308	-111.717	2500	16	Mixed conifer	160
Camp Navajo	CN	Fulé et al. 1997	Mogollon Rim	35.25	-111.867	2134	52	PIPO	700
Walnut Canyon	WAC	Swetnam et al. 1990	Mogollon Rim	35.169	-111.517	2030-2070	18	PIPO	Not listed
Chimney Springs	CHS	Dieterich 1980	Mogollon Rim	35.266	-111.688	2260-2290	8	PIPO	Not listed
Hualapai	-	Stan et al. 2014	Western GC	35.833	-113.133	1940-2220	114	PIPO and Gambel oak	125
Chuska Mountains	-	Guiterman et al. 2019	Chuska Mountains	35.932	-109.016	2712	194	Mixed conifer	227
Lukachukai	LUKA	Whitehair et al. 2018	Chuska Mountains	36.468	-109.155	2340-2851	203	PIPO, PSME	5000
Little Park	LP	Fulé et al. 2003	Central Grand Canyon	36.333	-112.126	2794	132	Mixed conifer, Aspen	4400
Galahad Point	GPT	Fulé et al. 2003	Central Grand Canyon	36.271	-112.233	2350	31	PIPO	410

Name	Site Code	Citation	Subregion	Lat	Long	Elevation (m)	Sample #	Species	Area (ha)
San Francisco Peaks	LOW	Fulé et al. 2023	Mogollon Rim	35.299	-111.669	2400-3600	102	PIPO	1920
Black Mesa	BM	Huffman et al. 2015	Mogollon Rim	34.378	-111.003	2313-2405	133	Mixed conifer	1135
Williams	WI	Fischer et al. 2025	Mogollon Rim	35.222	-112.007	2067-2184	34	PIPO	700
Mt. Dellenbaugh	MD	Ireland et al 2012	Western GC	36.117	-113.517	1330-2153	134	PIPO	400
Powell Plateau	PP	Fulé et al. 2003	Central Grand Canyon	36.298	-112.394	2256-2336	46	PIPO	315
Fire Point	FP	Fulé et al. 2003	Central Grand Canyon	36.356	-112.361	2308-2368	39	PIPO	135
Rainbow Plateau	RP	Fulé et al. 2003	Central Grand Canyon	36.311	-112.318	2305-2335	34	PIPO	225
Grandview	GV	Fulé et al. 2003	Central Grand Canyon	35.996	-111.985	2244-2284	44	PIPO	810

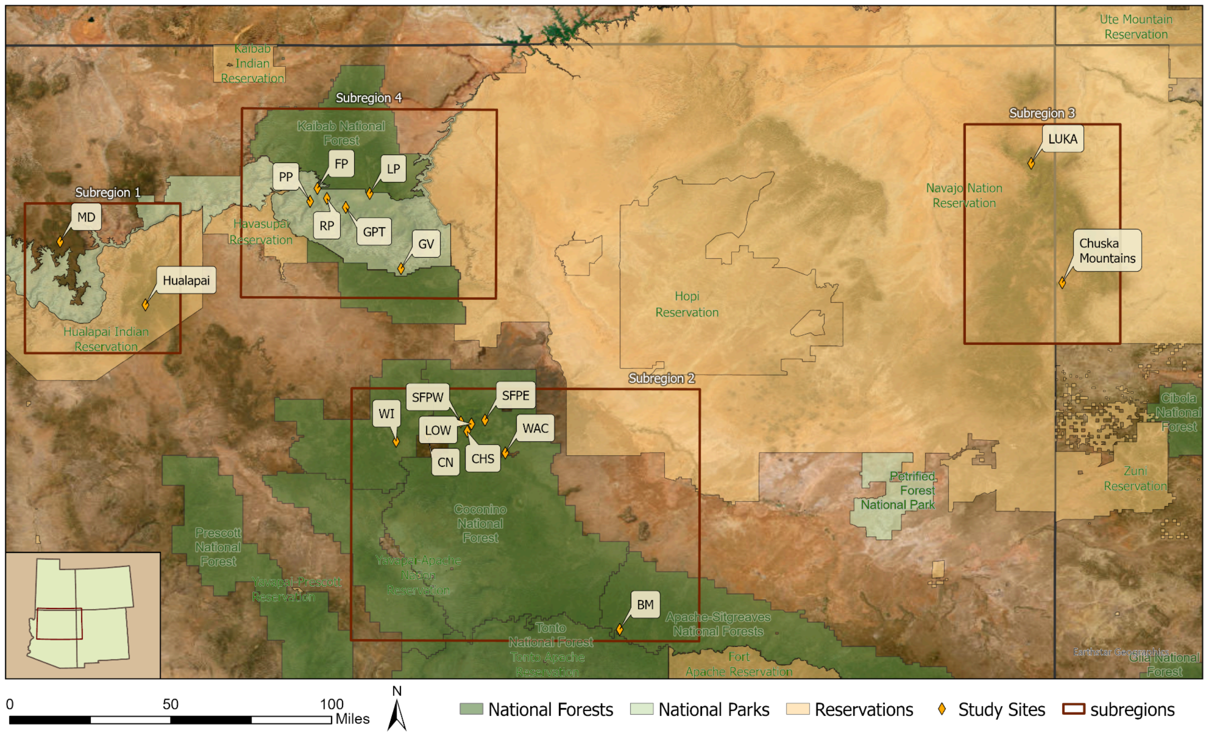

Figure 2: Locations of the studies used in our fire synchrony analysis, listed by site code/site name and grouped by subregion. Subregion 1: Western Grand Canyon, Subregion 2: Mogollon Rim, Subregion 3: Chuska Mountains, Subregion 4: Central Grand Canyon

Data analysis

To analyze the degree of overlap between these fire chronologies, we conducted a pairwise comparison of the chronologies using a Jaccard similarity analysis using FHAES (Brewer et al., 2016; Yocom Kent et al., 2017). The Jaccard Similarity Index is a measure of overlap between two sets of values. It calculates the total number of shared values between the two sets, divided by the total number of unique values across both sets to get a similarity score between 0-1 (Kannan et al., 2016).

We curtailed our analysis to the years 1700-1900 for a more consistent sample depth and comparability between chronologies. Based on geographic proximity, we considered two categories of factors in fire synchrony: bottom-up factors such as fire spread via continuous fuel, and top-down climate factors leading to multiple ignitions across the region within the same year.

First, we assessed fire years common across all sites to assess broad levels of synchrony. We conducted this analysis using two filtering approaches: all years when a minimum of 2 sites burned, to assess major fire years common between multiple sites. Second, to assess the level of influence of geographic proximity on fire synchrony, we grouped the study sites into four subregions (Table 1). We then averaged the Jaccard Index results across all sites and by subregion, to determine whether closer sites tended to have higher similarities between them. Our Jaccard analysis was given a two-sample-minimum threshold across all sites to rule out individual-tree fire scars and other injuries.

We also used the Jaccard Index to assess temporal changes in levels of synchrony. To do this, we calculated pairwise Jaccard Similarity Indices for 50 year increments across the study time period, from 1700-1900. We took the averages for each increment both across all sites and by subregion.

RESULTS

Williams Site

We successfully crossdated 34 of our original 52 samples for the Williams site (Figure 3). Within these samples, we dated a total of 457 fire scars, ranging from 1665 to 1879, for a site chronology spanning 224 years (Figure 3). Our chronology contained a total of 63 fire years when at least two samples recorded fire. Our chronology for widespread fires, containing years when at least 25% of all samples were scarred, contained 45 fire years. The MFI for the site was 3.45 years overall and 4.86 years for widespread fires, and the WMPI was 3.21 years overall and 4.53 years for widespread fires (Table 2). The closeness in metrics of all fire years and widespread fire years indicates that widespread fire years were very common across the Williams site during the study period. We were able to assess the seasonality of 237 of our total fire scars (52%) (Figure 4). The majority of season-identified fires occurred in the Middle Earlywood season (55%), which would have fallen in June-July (Baisan & Swetnam, 1990). The latest widespread fire scar was in 1879, marking the fire suppression onset date of our site chronology (Figure 3).

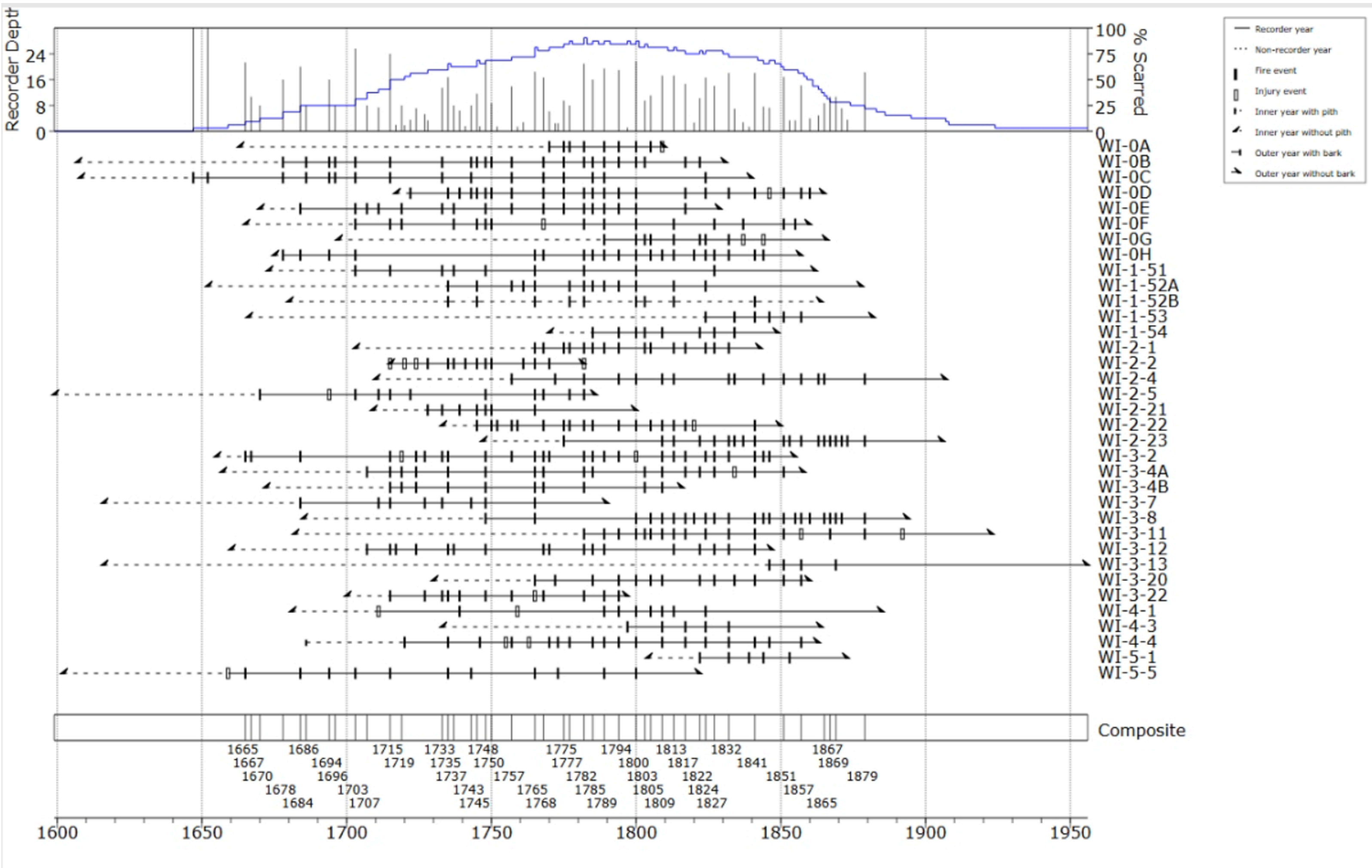

Figure 3: Williams Site fire chronology chart, including individual sample chronologies as well as a composite chronology (25% threshold) and sample depth chart. Samples are listed in order by location in the site from north to south.

Table 2: Williams site fire interval statistics

Parameters	2 sample minimum	25% Threshold
Total intervals	62	44
Mean fire interval	3.45	4.86
Minimum fire interval	1	2
Maximum fire interval	13	14
Weibull median probability interval	3.21	4.53

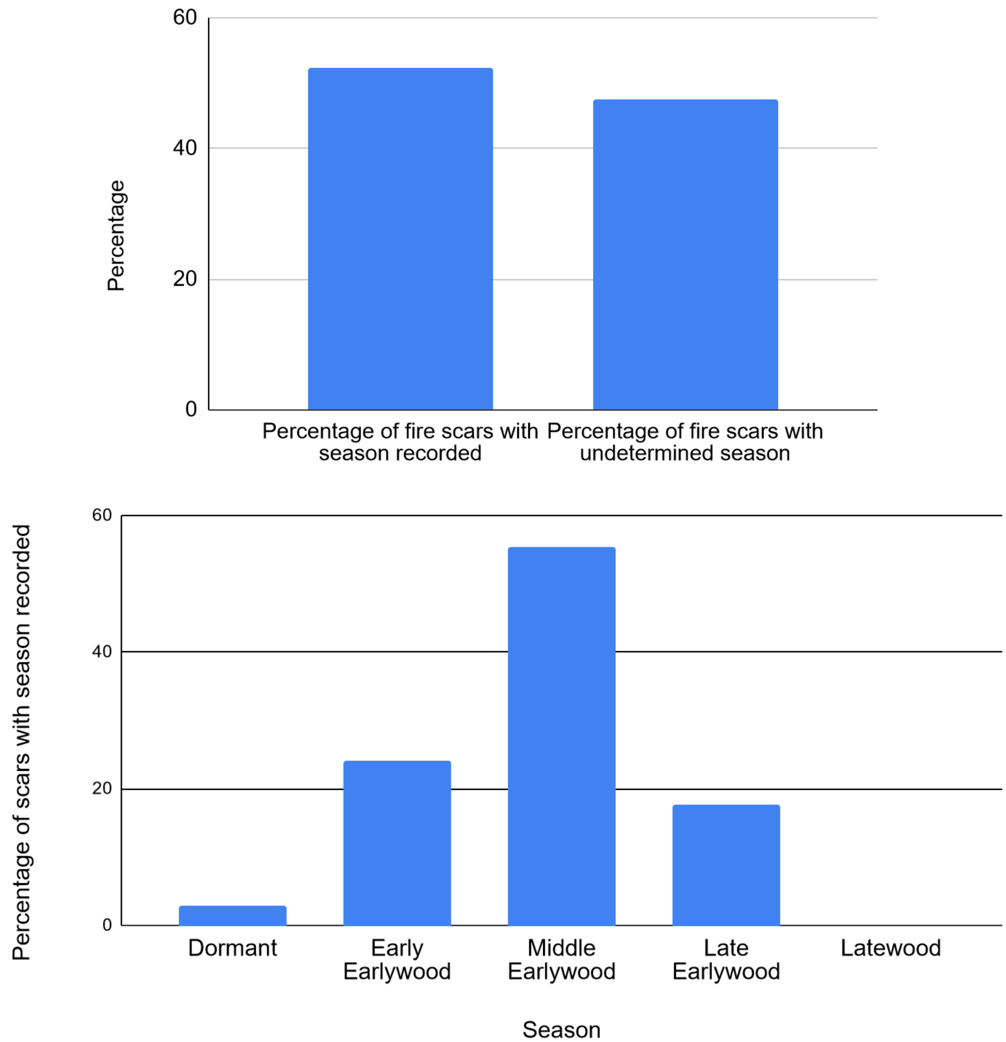

Figure 4: Williams site fire-scar seasonality statistics

Superposed Epoch Analysis

Our Superposed Epoch Analysis produced consistent results between both ENSO and PDSI comparisons. Each analysis showed a trend of wetter-than-average climatic conditions in the year before a fire, and a drier climate in the year fires occurred (Figure 4). While consistent, this observed trend was only statistically significant in one instance: widespread fires (25% threshold) occurring during years with a negative ENSO anomaly.

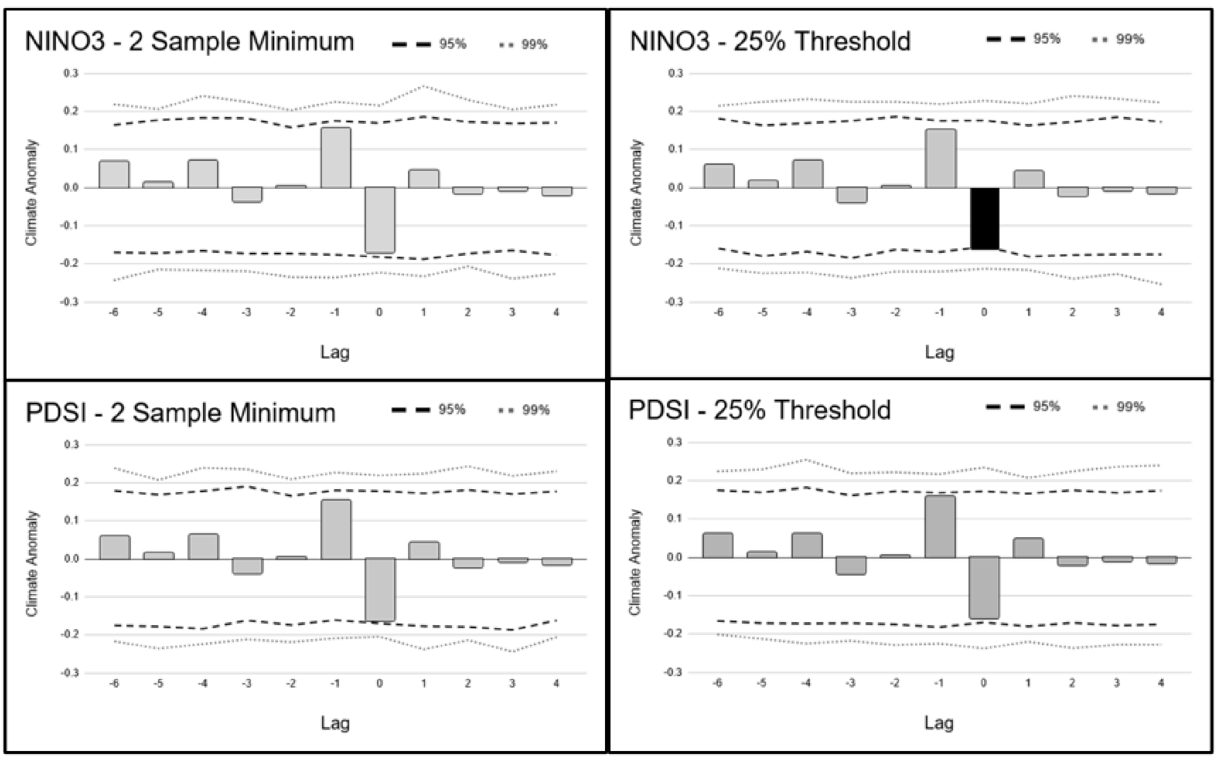

Figure 5: Superposed Epoch Analysis (SEA) graphs comparing the Williams Site chronology with ENSO (Cook et al., 2008) and PDSI (Cook et al., 1999) at two different thresholds: a two sample minimum, and a 25% of all samples in the chronology threshold. Fire years are indicated as 0 on the x-axis. The black bar indicates a statistically significant pattern in climate variability concurrent with fire years.

Fire synchrony: northern Arizona

Between 1700 and 1900, there were 45 years when all four subregions experienced fire: 1702, 1703, 1714, 1722, 1727, 1733, 1735, 1739, 1748, 1760, 1761, 1762, 1763, 1765, 1768, 1772, 1773, 1777, 1778, 1780, 1782, 1785, 1789, 1798, 1800, 1806, 1810, 1813, 1817, 1818, 1820, 1827, 1829, 1832, 1834, 1836, 1841, 1851, 1854, 1855, 1857, 1861, 1868, 1871, and 1879 (Appendix C). Additionally, there were another 47 years where three of the subregions burned, 28 years when two subregions burned, 51 years when only one subregion burned, and 20 years across the study time period in which none of the subregions recorded any fires.

We also narrowed down this analysis to include only widespread fires across sites, using a 25% threshold. With this parameter in place, we found 8 years in which all four subregions recorded widespread fire: 1702, 1714, 1727, 1748, 1772, 1778, 1818, and 1851 (Appendix D). There were also 37 years in which 3 regions had widespread fire, 43 years when two regions had widespread fire, 53 years when one region had widespread fire, and 60 years in which no widespread fire was recorded.

Looking across the region more broadly, there was a clear pattern of highly synchronous fire years shared by many sites (Figure 6; Figure7). Overall, the most synchronous fire year was 1748, which is well documented as a major fire year and exceptionally dry year in the Southwest (Swetnam & Baisan, 1996). This strong pattern of shared fire years across northern Arizona is indicative of the fire-climate relationship and influence of top-down factors on fire regimes in this region (Swetnam et al., 2016).

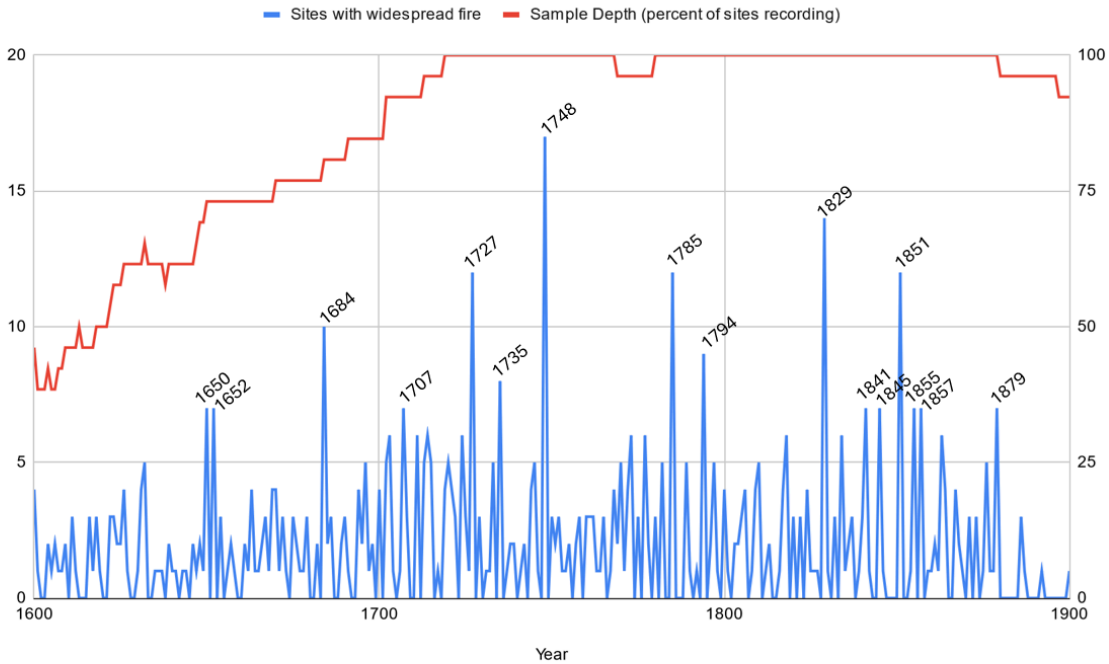

Figure 6: Widespread major fire years across all sites in the synchrony analysis. The number of sites burning in a given year, with a threshold of 25% of samples in each site, is represented in blue, associated with the left y-axis. The percent of all sites that are recording, or have an established fire scar record during a given year, is represented in red and by the right y-axis. The 16 most synchronous fire years are labeled.

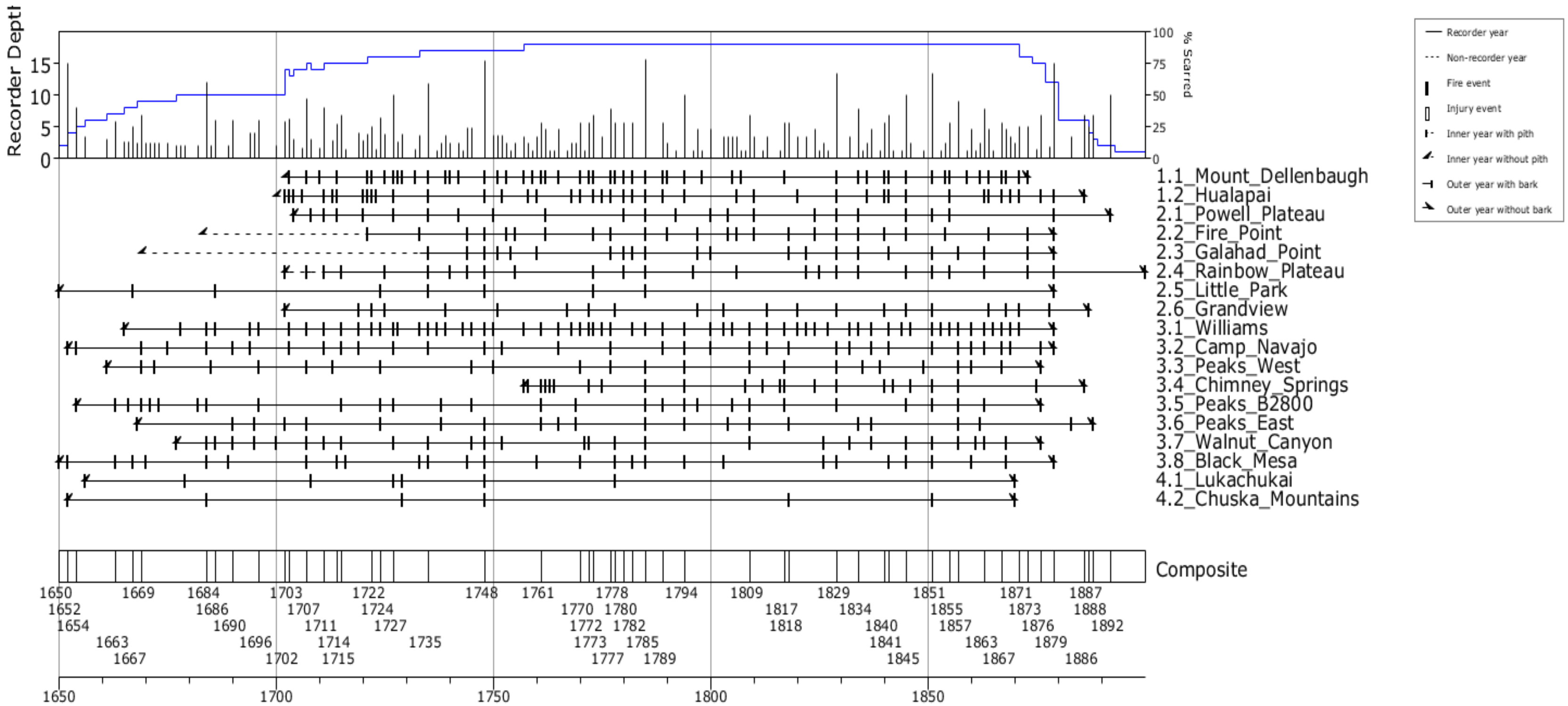

Figure 7: Composite chronology chart for all fire-scar studies in the synchrony analysis, listed in order by geographic location, west to east. All composite files are at a 25% threshold, and the overall composite chart (bottom of figure) contains fire scars that occurred in at least 25% of all composites.

The average Jaccard Similarity Index between all sites was 0.202, at a 2 sample minimum threshold, on a scale from 0 to 1 (Table 3; Figure 2). The Chuska Mountains subregion had the highest average similarity across the sites within it (0.392). The subregion with the lowest average similarity index between its sites was the Western Grand Canyon subregion (0.17). All subregion average Jaccard similarity indices, except for those for the Western Grand Canyon subregion, were higher than the general average score among all sites, indicating that fire synchrony tended to increase with geographic proximity.

By 50 year increment, the highest overall level of synchrony was between the years 1800-1850. Overall synchrony was the lowest between 1700-1750 (Table 4). So overall, we saw higher levels of synchrony in the 1800s than in the 1700s. We observed that there were some chronologies that had very few fires in certain time periods, chronologies that did not begin until the second time increment, or those that ended before the last one. Therefore, when broken down to smaller time periods, it was more common for chronologies to lack substantial overlap than when the entire study period was considered, meaning that synchrony appeared to be lower at this smaller temporal scale.

Table 3: Average Jaccard Similarity Indices by subregion and overall.

Subregion	Average Jaccard Similarity Index (2 sample minimum)
Western Grand Canyon	0.170
Mogollon Rim	0.292
Chuska Mountains	0.392
Central Grand Canyon	0.275
Overall	0.202

Table 4: Average Jaccard Similarity Indices by 50 year time increment

Time period	Jaccard Similarity Index
1700-1750	0.163
1751-1800	0.199
1800-1850	0.227
1851-1900	0.216

DISCUSSION

Through this project, we sought to answer the following research questions: 1. At the site scale (700 ha), what were the temporal and spatial patterns of fire over the past several centuries, and what drove this historical fire regime?, 2. At the regional scale, how synchronous were historical fires among sites across northern Arizona?, and 3. Did fire synchrony vary spatially and/or temporally across sites in northern Arizona? The following discussion is organized around these research questions.

Our analysis revealed that historical fires at the Williams site were fairly frequent, and commonly widespread across the site. The similarity between our overall and widespread fire chronologies indicates that recording trees at this site tended to burn together in larger fires as compared to separately in a series of less widespread fires. The site's MFIs, for both filtering approaches, are closely in line with historical fire intervals for Southwestern forests, which typically range from 2-17 years in ponderosa pine forests in Arizona and New Mexico (Swetnam & Baisan, 1996; Van Horne & Fulé, 2006).

Out of all fire scars we were able to assign seasons to, the majority were placed in the Middle Earlywood growth season (Figure 4). It has been observed that fire in the middle and late growing season was more prevalent historically, and early-season fires became increasingly common leading up to the twentieth century (Grissino Mayer & Swetnam, 2000). This is at least partially attributed to shifts in ENSO patterns during this time. Additionally, it is likely that many Indigenous cultural burnings were often conducted in the autumn, falling in the later growing or dormant season for ponderosa pines (Greenler et al., 2024). This kind of ignition timing has been seen to have beneficial effects on ponderosa pine regeneration, where trees treated with prescribed fire in the fall produced more seeds than those treated in the spring, or not treated at all (Peters & Sala, 2008).

The latest widespread fire in our composite chronology was in 1879, which is also in line with the regional onset of fire cessation and suppression, typically placed in the late 1800s (Marlon et al., 2012; Van Horne & Fulé, 2006). Being due west of the Camp Navajo site, also on the railroad, where the last fire was in 1883 (Fulé et al. 1997), it is likely that the Williams site was subjected to the effects of logging, grazing, and non-Indigenous land-use practices , similar to other forests across the West (Heyerdahl et al., 2001; National Park Service, 2022; Swetnam et al., 2016). These factors essentially heralded an end to historic fire regimes across the western U.S., ushering in the fire suppression era (Marlon et al., 2012). This period of fire exclusion has lasted through the present in most places, except in certain tribal reservation communities (Stan et al., 2014) or remote conservation areas (Stephens & Fulé, 2005). Currently, more prescribed fire is being used in forests across northern Arizona than in prior decades, such as through the Four Forest Restoration Initiative (4FRI), which includes goals of implementing prescribed fire in the Apache-Sitgreaves, Coconino, Kaibab, and Tonto National Forests over the course of the next twenty years (U.S. Forest Service, 2021). This initiative is part of the U.S. Forest Service's 10-year plan to address the national wildfire crisis, which was released in 2022 (U.S. Forest Service, 2022). As these kinds of plans are implemented and more fire is put back on the landscape, forested areas such as the Williams site may be able to return to similar conditions to those brought about by their historical fire regimes, making them less vulnerable to severe wildfire going forward (Stan et al., 2022).

Our Superposed Epoch Analysis revealed a correlation between fire years and climate oscillations, with wetter years directly preceding a particularly dry year with more fire activity.

This pattern is consistent with similar comparisons made in the Southwest, and is typically attributed to the higher vegetation growth and fuel buildup associated with wetter years that is rapidly desiccated in dry fire years, allowing for more fires to ignite and spread (Swetnam & Baisan, 1996). This pattern arises from the influence of El Niño Southern Oscillation (ENSO), which follows a 3-7 year cycle between El Niño and La Niña conditions (Swetnam & Betancourt, 1998). Vegetation grows more rapidly during El Niño years, aided by the abundant moisture present in the Southwest in those times, and dries out quickly in the extreme dry conditions that come about during the transition to La Niña years, setting the stage for frequent, cyclical fire. These climatic conditions were clearly an element in the historic fire regime of the Williams site, indicating the consistency in the fire-climate relationship commonly observed in the Southwest. This climate pattern also followed for the Palmer Drought Severity Index (PDSI), which is a measure of drought intensity. This metric showed very similar patterns in the fire-climate relationship as we saw with ENSO, although they were of a slightly lower magnitude and did not reach the level of statistical significance.

At the regional scale, we observed both synchrony and asynchrony between the studies in our analysis. Our widespread fire analysis revealed that there was significant synchrony across the region resulting in a defined set of major fire years. Many of the major fire years observed in our study are consistent with the findings in similar analyses in the literature (Swetnam et al., 2016). This correlation demonstrates the consistency and strength of the fire-climate relationship across the Southwest.

Our synchrony analysis using the Jaccard Index showed that, on average, sites in a closer geographic subregion had higher levels of synchrony compared to sites further apart.The average Jaccard Similarity Index of 0.202 (Table 3) indicates that synchrony was somewhat low overall, but patterns of synchrony between certain sites do indicate a more nuanced spatial factor at play. Low overall synchrony points in part to the high level of ecological variation across sites in the northern Arizona region, such as local factors like topography and fuels influencing fire regimes(Iniguez et al., 2008). Additionally, the spatial pattern of Indigenous burning (Roos et al., 2022; Sullivan & Forste, 2014) may have had a greater influence here than what would have occurred in a more homogenous landscape.

In general, the Jaccard similarities we calculated were seemingly low, with more than half our similarities being less than 0.2 on a 0-1 scale. However, some pairwise comparisons resulted in much higher similarities, such as the 0.738 similarity index between the Williams site and Black Mesa. The variability in the number of samples and fire years per site, as well as differential amounts of overlap between site-level chronology timelines, even when narrowed to a well-recorded time period, may have contributed to these seemingly overall low similarities between what, on the whole, may be similar fire regimes. However, the similarities between the sites in our study are comparable with the values produced in a similar regional fire synchrony study that used the Jaccard Index (Yocom Kent et al., 2017), and therefore may be a good indicator of synchrony regardless.

The Chuska Mountains subregion (Subregion 3) of our synchrony analysis had the highest intra-subregion average Jaccard Similarity Index (Table 3). These sites would have had a high degree of historical fuel connectivity, sitting on the same mountain range, and also had the fewest number of chronologies, with only three total in the subregion. This relatively high degree of connectivity could have allowed historical fires to spread across the entire subregion without interruption, therefore creating a higher level of synchrony between chronologies. This bottom-up explanation of synchrony and asynchrony also follows for the subregion with the lowest average overall Jaccard Similarity Index, the Western Grand Canyon subregion (Subregion 1). This subregion consisted of two studies, one with four site chronologies on the northern side of the Grand Canyon (Ireland et al., 2012), and the other with five chronologies located to the south of the Canyon (Stan et al., 2014). The significant natural barrier of the Grand Canyon provided a historical fuel break, keeping large fires from spreading between the two study areas. Asynchrony between sites was also a major finding of the publication located at Mount Dellenbaugh, which would also have contributed to these results (Ireland et al., 2012).

Sites included in this study were from a wide variety of landscapes with differing topographic features. Some sites were in mountainous areas, and had different vegetation communities than sites in flatter terrain. These differences in local factors could have contributed to the levels of relative asynchrony we observed across the region overall. Although the fire-climate relationship is a vital feature of historic fire regimes in the Southwest, the influence of bottom-up controls should not be underestimated. Local factors such as topography and human land use have been continually seen to have high levels of impact on fire regimes (Bowman et al., 2011; McKenzie et al., 2006). Some scholars argue that essentially all fire regimes in the modern era are driven by human activities (Scheller et al., 2019).

While the amount of synchrony we found in this study does indicate the influence of top-down factors on historical fire regimes in northern Arizona, we also saw the significance of local, bottom-up factors in these fire regimes. Accounting for the ways in which local geographic nuances and histories play into long-term fire regimes and fire regime change is a necessary part of forest management considerations. Prescribed fire has been seen to be more effective at achieving restoration and density goals in ponderosa pine forests when it is implemented continually, rather than only in one or two instances (Waring et al., 2016). Therefore, considering the specific fire frequency of historical fire regimes is paramount to enacting effective forest treatments.

CONCLUSION

Northern Arizona is an ecologically diverse place, with significant variability in elevation, plant communities, and topography even between sites of the same forest type. Frequent historical fire regimes in dry coniferous forests, however, are one consistency across the region. Though the timing of historic fire has been influenced by local factors to produce differences across distance, the strong correlation between fire regimes and climate oscillations points to the strength of the fire-climate relationship in this area. This link between climate and fire histories is vital to take into account as we approach the future of forest management and move away from the past century of fire suppression, while simultaneously stepping into a time of undeniably altered fire regimes and a changing global climate.

We observed this significant fire-climate relationship both at the individual site level and between sites across northern Arizona, giving credence to the vital role of top-down influences in shaping southwestern fire regimes. Additionally, we saw notable variability among subsets of this region, indicating the impact of bottom-up influences as well. We emphasize that multiscaled approaches are vital to a holistic understanding of southwestern fire regimes and ecosystems, and that both top-down and bottom-up factors are influential and necessary to take into account.

The field of dendropyrochronology has great potential to improve our understanding of fire regimes in the past and thereby to influence future practices. The ability of dendrochronology to provide detailed information about past climatic conditions is one of its major strengths, and harnessing the record of the past that is stored in tree rings can make the decisions we make about these resilient ecosystems more informed and effective. This kind of research is key to placing wildfire in a historical context, highlighting both the predictable and unprecedented aspects of fire behavior today.

This study is intended to deepen the knowledge in the literature on fire history, and to knit together fire histories from around northern Arizona. We believe that it is important to take into account the nuances that local fire regimes can have while also keeping the big picture of the fireclimate relationship in clear view as we progress the future of forest management.

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CHAPTER 3: CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The purpose of this project was to contribute to the fire history record for northern Arizona, and North America more broadly, as well as to analyze fire chronologies across the region. We intended to fill a physical gap in the literature by generating the fire chronology for the Williams site, as well as providing a medium-scale regional analysis of fire synchrony. The increasing presence of fire synchrony in the literature, in conjunction with the development of larger fire history databases like the North American Tree-Ring Fire-Scar Network (Margolis et al., 2022) and the International Multiproxy Paleofire Database (NOAA, 2020a) indicate a move in the field towards large scale, complex analyses that speak not only to webs of local fire regime influences, but also towards understanding global patterns and drivers of fire. These databases create new potential for the analysis of fire history and the fire climate relationship, broadening the field as a whole.

More than a century of strict fire suppression has left southwestern forests in a completely altered state compared to the way they were for millennia before colonization. Returning these ecosystems to a closer approximation of their historic state is an incredibly significant task, but is also an incredibly important one. Wildfires are predicted to continue to increase in this region, following climate change trends that support fire propagation and severity (Mueller et al., 2020), as well as extensive accumulation of dead and live fuels (Westerling et al., 2006). The pressing nature of the wildfire crisis and tensions surrounding fire and forest management at the present moment make fire history research all the more important. As we move forward, a deep understanding of past fire regimes will be key to developing and implementing the forest management of the future.

We recommend that future research continue to explore broader, interconnected analyses of fire history and fire synchrony, especially in the following ways:

- Include multiple scales of analysis that capture the differing effects of bottom-up and top-down factors on fire regimes.
- Address and evolve with current management contexts to work in conjunction with resource managers to achieve forest restoration goals.
- Make use of the expansive and growing networks of fire history data to widen analyses and better understand fire regime interactions at large scales.
- Assess modern fire regime change and the influence of climate change and impacts of thinning and prescribed burning projects as they continue to be implemented.
- Involve Tribes and Indigenous researchers to improve understanding of Traditional Fire Knowledge (Lake et al., 2017) and support Indigenous-led efforts to restore cultural burning (Hankins, 2024).

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APPENDICES

APPENDIX A: Table of sites in synchrony study

Name	Site Code	Citation	Latitude	Longitude	Number of sites in study	Elevation (m)	Sample depth	Species	Area sampled (ha)
Peaks East	SFPE	Heinlein et al. 2005	35.316667	-111.608333	1	2500	18	Mixed conifer	160
Peaks West	SFPW	Heinlein et al. 2005	35.308333	-111.716667	1	2500	16	Mixed conifer	160
Camp Navajo	CN	Fulé et al. 1997	35.25	-111.866667	1	2134	52	PIPO	700
Walnut Canyon	WC	Swetnam et al. 1990	35.16925	-111.517	1	2030-2070	18	PIPO	not listed
Chimney Springs	CHS	Dieterich 1980	35.266449	-111.68813	1	2260-2290	8	PIPO	not listed
Hualapai (centroid)	-	Stan et al. 2014	35.833333	-113.133333	5	1940-2220	114	PIPO and Gambel oak	125
Manzanita High	MH	Stan et al. 2014	35.85	-113.166667	1	-	30	PIPO and Gambel oak	25
Manzanita Low	ML	Stan et al. 2014	35.833333	-113.133333	1	-	20	PIPO and Gambel oak	25
Turkey Tank	TT	Stan et al. 2014	35.933333	-113.083333	1	-	18	PIPO and Gambel oak	25
Twenty Pines	TP	Stan et al. 2014	35.716667	-113.116667	1	-	29	PIPO and Gambel oak	25
Youth Camp	YC	Stan et al. 2014	35.866667	-113.083333	1	-	16	PIPO and Gambel oak	25
Lukachukai	LUKA	Whitehair et al. 2018	36.468006	-109.154961	1	2340-2851	203	PIPO, PSME	250
Galahad Point	GP	Fulé et al. 2003	36.27074	-112.23344	1	2350	31	PIPO	410
Little Park	LP	Fulé et al. 2003	36.333	-112.126	1	2794	132	Mixed conifer, Aspen	4400
Grandview	GV	Fulé et al. 2003	35.996111	-111.985278	1	2244-2284	44	PIPO	810
Fire Point	FP	Fulé et al. 2003	36.355833	-112.360833	1	2308-2368	39	PIPO	135

Name	Site Code	Citation	Latitude	Longitude	Number of sites in study	Elevation (m)	Sample depth	Species	Area sampled (ha)
Powell Plateau	PP	Fulé et al. 2003	36.2975	-112.393611	1	2256-2336	46	PIPO	315
Rainbow Plateau	RP	Fulé et al. 2003	36.311111	-112.318333	1	2305-2335	34	PIPO	225
San Francisco Peaks	LOW	Fulé et al.2023	35.29932	-111.6692	1	2400-3600	102	PIPO	1920
Black Mesa	BM	Huffman et al. 2015	34.37777	-111.003091	1	2313-2405	133	Mixed conifer	1135
Williams	WI	Fischer et al. 2025	35.366667	-112	1	2067-2184	34	PIPO	700
Chuska Mountains (centroid)	-	Guiterman et al. 2019	35.9326	-109.0155	12 (9 included)	2210-2779	146	Mixed conifer	216.9
Chuska East	CE	Guiterman et al. 2019	36.07672	-108.849	1	2712	8	Mixed conifer	1
Squirrel Springs North	SQN	Guiterman et al. 2019	35.9175	-108.884	1	2455	18	Mixed conifer	11
Piney Hill	PNH	Guiterman et al. 2019	35.7512	-109.179	1	2433	22	PIPO	67
Natural Bridges Canyon	NBC	Guiterman et al. 2019	35.7106	-109.149	1	2307	9	PIPO	1.3
Monument Canyon Upper	MCU	Guiterman et al. 2019	35.99692	-109.283	1	2210	5	PIPO	1
Kailcheebito Spring	KCS	Guiterman et al. 2019	35.9326	-109.147	1	2392	13	PIPO	4.3
Falling Irons	FFe	Guiterman et al. 2019	36.17914	-109.032	1	2779	38	Mixed conifer	78
Duck Lake	DKL	Guiterman et al. 2019	36.12386	-108.906	1	2747	12	PIPO	35.3
Scattered Willow Wash	SWW	Guiterman et al. 2019	35.79067	-109.225	1	2391	21	PIPO	18
Mt. Dellenbaugh (centroid)	MD	Ireland et al 2012	36.116667	-113.516667	16	1330-2153	134	PIPO	400
East	-	Ireland et al 2012	36.116667	-113.45	3		30	PIPO	75

Name	Site Code	Citation	Latitude	Longitude	Number of sites in study	Elevation (m)	Sample depth	Species	Area sampled (ha)
West	-	Ireland et al 2012	36.15	-113.6	5		25	PIPO	125
Central	-	Ireland et al 2012	36.15	-113.533333	3		17	PIPO	75
East Rim	-	Ireland et al 2012	36.1	-113.466667	5		55	PIPO	125

APPENDIX B: Jaccard Similarity results table

Subregion 1:

Site Name	1Stan_MH	1Stan_ML	1Stan_TT	1Stan_TW	1Stan_YC	1mdCentral	1mdEast	1mdEastrim	1mdWest
1Stan_MH	1	0.548	0.206	0.174	0.227	0.2	0.149	0.259	0.265
1Stan_ML	0.548	1	0.185	0.103	0.229	0.143	0.167	0.196	0.222
1Stan_TT	0.206	0.185	1	0.121	0.156	0.19	0.088	0.098	0.04
1Stan_TW	0.174	0.103	0.121	1	0.19	0.188	0.111	0.169	0.114
1Stan_YC	0.227	0.229	0.156	0.19	1	0.152	0.163	0.169	0.054
1mdCentral2008	0.2	0.143	0.19	0.188	0.152	1	0.056	0.14	0.08
1mdEast2008	0.149	0.167	0.088	0.111	0.163	0.056	1	0.302	0.114
1mdEastrim2008	0.259	0.196	0.098	0.169	0.169	0.14	0.302	1	0.16
1mdWest2008	0.265	0.222	0.04	0.114	0.054	0.08	0.114	0.16	1
2BlackMesa	0.268	0.187	0.104	0.19	0.214	0.103	0.214	0.34	0.113
2CampNavajo	0.262	0.204	0.111	0.159	0.281	0.07	0.304	0.26	0.17
2ChimneySprings	0.15	0.129	0.036	0.05	0.05	0.034	0.167	0.13	0.148
2Williams	0.276	0.189	0.103	0.259	0.259	0.14	0.276	0.345	0.175
2PeaksEast	0.132	0.091	0.103	0.057	0.098	0.073	0.143	0.154	0.098
2PeaksWest	0.304	0.171	0.103	0.143	0.167	0.128	0.217	0.21	0.216
2Peaks_B2800	0.262	0.204	0.091	0.141	0.217	0.13	0.217	0.26	0.127
2WalnutCanyon	0.228	0.208	0.152	0.138	0.158	0.102	0.32	0.25	0.146
3ChuskaHighComp	0.178	0.127	0.072	0.146	0.121	0.111	0.186	0.222	0.071
3ChuskaLowComp	0.221	0.141	0.069	0.111	0.154	0.099	0.184	0.267	0.082
3LakachukaiWhitehair	0.21	0.122	0.08	0.19	0.16	0.095	0.205	0.242	0.051
4GalahadPoint	0.267	0.146	0.083	0.104	0.25	0.051	0.156	0.241	0.079
4LittlePark	0.203	0.167	0.065	0.197	0.215	0.117	0.162	0.273	0.097

Site Name	1Stan_MH	1Stan_ML	1Stan_TT	1Stan_TW	1Stan_YC	1mdCentral	1mdEast	1mdEastrim	1mdWest
1Stan_MH	1	0.548	0.206	0.174	0.227	0.2	0.149	0.259	0.265
1Stan_ML	0.548	1	0.185	0.103	0.229	0.143	0.167	0.196	0.222
1Stan_TT	0.206	0.185	1	0.121	0.156	0.19	0.088	0.098	0.04
1Stan_TW	0.174	0.103	0.121	1	0.19	0.188	0.111	0.169	0.114
1Stan_YC	0.227	0.229	0.156	0.19	1	0.152	0.163	0.169	0.054
1mdCentral2008	0.2	0.143	0.19	0.188	0.152	1	0.056	0.14	0.08
1mdEast2008	0.149	0.167	0.088	0.111	0.163	0.056	1	0.302	0.114
1mdEastrim2008	0.259	0.196	0.098	0.169	0.169	0.14	0.302	1	0.16
1mdWest2008	0.265	0.222	0.04	0.114	0.054	0.08	0.114	0.16	1
4firepoint	0.224	0.136	0.103	0.167	0.178	0.098	0.122	0.293	0.098
4grandview	0.149	0.132	0.088	0.087	0.042	0.118	0.19	0.211	0.114
4powellplateau	0.176	0.133	0.068	0.152	0.206	0.067	0.169	0.267	0.083
4rainbowplateau	0.245	0.19	0.1	0.163	0.239	0.1	0.14	0.246	0.095

Subregion 2:

Site Name	2Black Mesa	2Camp Navajo	2Chimney Springs	2Williams	2PeaksEast	2PeaksWest	2Peaks_ B2800	2Walnut Canyon
1Stan_MH	0.268	0.262	0.15	0.276	0.132	0.304	0.262	0.228
1Stan_ML	0.187	0.204	0.129	0.189	0.091	0.171	0.204	0.208
1Stan_TT	0.104	0.111	0.036	0.103	0.103	0.103	0.091	0.152
1Stan_TW	0.19	0.159	0.05	0.259	0.057	0.143	0.141	0.138
1Stan_YC	0.214	0.281	0.05	0.259	0.098	0.167	0.217	0.158
1mdCentral2008	0.103	0.07	0.034	0.14	0.073	0.128	0.13	0.102
1mdEast2008	0.214	0.304	0.167	0.276	0.143	0.217	0.217	0.32
1mdEastrim2008	0.34	0.26	0.13	0.345	0.154	0.21	0.26	0.25
1mdWest2008	0.113	0.17	0.148	0.175	0.098	0.216	0.127	0.146
2BlackMesa	1	0.379	0.11	0.738	0.168	0.214	0.327	0.286
2CampNavajo	0.379	1	0.102	0.617	0.274	0.339	0.412	0.391
2ChimneySprings	0.11	0.102	1	0.158	0.143	0.143	0.161	0.094
2Williams	0.738	0.617	0.158	1	0.281	0.373	0.525	0.39
2PeaksEast	0.168	0.274	0.143	0.281	1	0.192	0.234	0.241
2PeaksWest	0.214	0.339	0.143	0.373	0.192	1	0.436	0.2
2Peaks_B2800	0.327	0.412	0.161	0.525	0.234	0.436	1	0.254
2WalnutCanyon	0.286	0.391	0.094	0.39	0.241	0.2	0.254	1
3ChuskaHighComp	0.379	0.302	0.119	0.557	0.161	0.213	0.263	0.229
3ChuskaLowComp	0.395	0.345	0.123	0.484	0.171	0.171	0.345	0.218
3Lakachukai Whitehair	0.393	0.315	0.132	0.517	0.176	0.22	0.286	0.236

4GalahadPoint	0.269	0.404	0.154	0.286	0.191	0.261	0.357	0.179
4LittlePark	0.396	0.36	0.109	0.452	0.133	0.232	0.308	0.159
4firepoint	0.266	0.206	0.114	0.196	0.224	0.173	0.215	0.211
4grandview	0.178	0.159	0.105	0.169	0.098	0.143	0.159	0.158
4powellplateau	0.33	0.286	0.133	0.371	0.155	0.188	0.253	0.227
4rainbowplateau	0.214	0.311	0.089	0.288	0.235	0.212	0.29	0.2

Subregion 3:

Site Name	3ChuskaHighComp	3ChuskaLowComp	3Lakachukai Whitehair
1Stan_MH	0.178	0.221	0.21
1Stan_ML	0.127	0.141	0.122
1Stan_TT	0.072	0.069	0.08
1Stan_TW	0.146	0.111	0.19
1Stan_YC	0.121	0.154	0.16
1mdCentral2008	0.111	0.099	0.095
1mdEast2008	0.186	0.184	0.205
1mdEastrim2008	0.222	0.267	0.242
1mdWest2008	0.071	0.082	0.051
2BlackMesa	0.379	0.395	0.393
2CampNavajo	0.302	0.345	0.315
2ChimneySprings	0.119	0.123	0.132
2Williams	0.557	0.484	0.517
2PeaksEast	0.161	0.171	0.176
2PeaksWest	0.213	0.171	0.22
2Peaks_B2800	0.263	0.345	0.286
2WalnutCanyon	0.229	0.218	0.236
3ChuskaHighComp	1	0.392	0.404
3ChuskaLowComp	0.392	1	0.381
3LakachukaiWhitehair	0.404	0.381	1
4GalahadPoint	0.181	0.243	0.234
4LittlePark	0.365	0.322	0.337

4firepoint	0.165	0.189	0.181
4grandview	0.146	0.2	0.16
4powellplateau	0.219	0.234	0.29
4rainbowplateau	0.149	0.247	0.176

Subregion 4:

Site Name	4Galahad Point	4LittlePark	4firepoint	4grandview	4powell plateau	4rainbow plateau
1Stan_MH	0.267	0.203	0.224	0.149	0.176	0.245
1Stan_ML	0.146	0.167	0.136	0.132	0.133	0.19
1Stan_TT	0.083	0.065	0.103	0.088	0.068	0.1
1Stan_TW	0.104	0.197	0.167	0.087	0.152	0.163
1Stan_YC	0.25	0.215	0.178	0.042	0.206	0.239
1mdCentral 2008	0.051	0.117	0.098	0.118	0.067	0.1
1mdEast2008	0.156	0.162	0.122	0.19	0.169	0.14
1mdEastrim 2008	0.241	0.273	0.293	0.211	0.267	0.246
1mdWest2008	0.079	0.097	0.098	0.114	0.083	0.095
2BlackMesa	0.269	0.396	0.266	0.178	0.33	0.214
2Camp Navajo	0.404	0.36	0.206	0.159	0.286	0.311
2Chimney Springs	0.154	0.109	0.114	0.105	0.133	0.089
2Williams	0.286	0.452	0.196	0.169	0.371	0.288
2PeaksEast	0.191	0.133	0.224	0.098	0.155	0.235
2PeaksWest	0.261	0.232	0.173	0.143	0.188	0.212
2Peaks_B2800	0.357	0.308	0.215	0.159	0.253	0.29
2Walnut Canyon	0.179	0.159	0.211	0.158	0.227	0.2
3Chuska HighComp	0.181	0.365	0.165	0.146	0.219	0.149
3Chuska LowComp	0.243	0.322	0.189	0.2	0.234	0.247

3Lakachukai Whitehair	0.234	0.337	0.181	0.16	0.29	0.176
4Galahad Point	1	0.328	0.364	0.182	0.295	0.415
4LittlePark	0.328	1	0.25	0.215	0.28	0.246
4firepoint	0.364	0.25	1	0.167	0.323	0.409
4grandview	0.182	0.215	0.167	1	0.152	0.188
4powell plateau	0.295	0.28	0.323	0.152	1	0.317
4rainbow plateau	0.415	0.246	0.409	0.188	0.317	1

APPENDIX C: Major fire years analysis

Year	Number of Subregions with fire
1700	2
1701	0
1702	4
1703	4
1704	2
1705	1
1706	1
1707	3
1708	1
1709	1
1710	0
1711	3
1712	1
1713	3
1714	4
1715	2
1716	2
1717	0
1718	0
1719	1
1720	3
1721	1
1722	4
1723	1
1724	3
1725	2
1726	1
1727	4
1728	2
1729	3
1730	0
1731	1
1732	0
1733	4
1734	1
1735	4
1736	0
1737	3
1738	1
1739	4
1740	3
1741	1
1742	2
1743	1
1744	2
1745	3
1746	3
1747	0
1748	4
1749	1
1750	3
1751	3
1752	3
1753	2
1754	3
1755	2
1756	1
1757	2
1758	2
1759	3
1760	4
1761	4
1762	4
1763	4
1764	1
1765	4
1766	0
1767	2
1768	4
1769	2
1770	3
1771	2
1772	4
1773	4
1774	2
1775	3
1776	0
1777	4
1778	4
1779	3
1780	4
1781	2
1782	4
1783	0
1784	1
1785	4
1786	1
1787	1
1788	1
1789	4

1790	3	1825	2	1860	3
1791	1	1826	2	1861	4
1792	3	1827	4	1862	3
1793	3	1828	1	1863	3
1794	3	1829	4	1864	3
1795	3	1830	3	1865	1
1796	3	1831	2	1866	1
1797	3	1832	4	1867	2
1798	4	1833	1	1868	4
1799	2	1834	4	1869	3
1800	4	1835	1	1870	3
1801	3	1836	4	1871	4
1802	1	1837	2	1872	2
1803	3	1838	2	1873	3
1804	2	1839	2	1874	1
1805	3	1840	3	1875	1
1806	4	1841	4	1876	2
1807	2	1842	3	1877	3
1808	2	1843	2	1878	1
1809	3	1844	1	1879	4
1810	4	1845	3	1880	1
1811	1	1846	1	1881	1
1812	3	1847	3	1882	0
1813	4	1848	2	1883	1
1814	0	1849	1	1884	1
1815	1	1850	2	1885	0
1816	1	1851	4	1886	3
1817	4	1852	1	1887	2
1818	4	1853	1	1888	1
1819	2	1854	4	1889	0
1820	4	1855	4	1890	0
1821	2	1856	2	1891	0
1822	3	1857	4	1892	1
1823	2	1858	1	1893	0
1824	3	1859	3	1894	1

1895	1
1896	1
1897	0

1898	0
1899	1
1900	1

Totals:

Number of subregions	Total number of years
4	45
3	47
2	28
1	51
0	20

APPENDIX D: MAJOR WIDESPREAD FIRE YEARS ANALYSIS

Year	Number of subregions with widespread fire
1700	3
1701	0
1702	4
1703	3
1704	2
1705	0
1706	1
1707	3
1708	3
1709	0
1710	1
1711	3
1712	0
1713	3
1714	4
1715	2
1716	1
1717	1
1718	0
1719	2
1720	3
1721	3
1722	3
1723	1
1724	2
1725	2
1726	0
1727	4
1728	2
1729	2
1730	0
1731	1
1732	1
1733	3
1734	0
1735	3
1736	0
1737	1
1738	1
1739	3
1740	2
1741	1
1742	2
1743	1
1744	2
1745	2
1746	1
1747	0
1748	4
1749	0
1750	2
1751	2
1752	3
1753	2
1754	1
1755	1
1756	0
1757	2
1758	2
1759	2
1760	3
1761	2
1762	3
1763	2
1764	1
1765	3
1766	0
1767	1
1768	2
1769	1
1770	2
1771	1
1772	4
1773	3
1774	0
1775	2
1776	0
1777	3
1778	4
1779	0
1780	2
1781	0
1782	3
1783	0
1784	0
1785	3
1786	0
1787	0
1788	0
1789	3
1790	2
1791	0
1792	1
1793	0
1794	3
1795	0

1796	2
1797	2
1798	1
1799	0
1800	3
1801	1
1802	0
1803	2
1804	2
1805	3
1806	2
1807	1
1808	1
1809	1
1810	3
1811	0
1812	1
1813	2
1814	0
1815	0
1816	1
1817	2
1818	4
1819	0
1820	3
1821	0
1822	2
1823	0
1824	2
1825	1
1826	1
1827	1
1828	0
1829	3
1830	1

1831	0
1832	1
1833	0
1834	3
1835	1
1836	1
1837	1
1838	0
1839	1
1840	3
1841	3
1842	1
1843	0
1844	1
1845	3
1846	1
1847	0
1848	0
1849	1
1850	0
1851	4
1852	0
1853	1
1854	2
1855	3
1856	0
1857	2
1858	0
1859	1
1860	2
1861	2
1862	2
1863	3
1864	2
1865	1

1866	0
1867	2
1868	3
1869	2
1870	1
1871	3
1872	1
1873	3
1874	0
1875	1
1876	2
1877	1
1878	1
1879	3
1880	0
1881	0
1882	0
1883	1
1884	0
1885	0
1886	2
1887	1
1888	1
1889	0
1890	0
1891	0
1892	1
1893	0
1894	0
1895	0
1896	1
1897	0
1898	0
1899	0
1900	1

Totals:

Number of sites recording widespread fire	Total number of years
0	60
1	53
2	43
3	37
4	8