Dendroecological testing of the pyroclimatic hypothesis in the central Great Basin, Nevada, USA

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Abstract. In the Great Basin region of western North America, records of past climate and wildfire variability are needed not only for fire use, but also for understanding the mechanisms behind the century-long expansion of piñon-juniper woodlands. The Mt. Irish area (Lincoln County, south-eastern Nevada) is a remote mountain ecosystem on the hydrographic boundary between the Great Basin and the Colorado River Basin. Non-scarred ponderosa pines (Pinus ponderosa C. Lawson var. scopulorum Engelm.) and single-needle pinyons (Pinus monophylla Torr. & Frém.) were used to develop a tree-ring reconstruction of drought (mean PDSI for May–July from NV Climate Division 3) from 1396 to 2003. A hypothetical fire regime was obtained from the PDSI reconstruction and from explicitly assumed relationships between climate and wildfire occurrence. A census of fire-scarred trees was then sampled at the study area, and crossdated fire-scar records were used to generate the fire history, independently of the pre-existing pyroclimatic model. Out of 250 collected fire-scar wood sections, 197 could be crossdated (about 89% from ponderosa pines), covered the period from 1146 to 2006, and contained 485 fire scars, 390 of which could be dated to a single year. Numerical summaries were computed for the period 1550–2006, when recorder trees ranged from 16 to 169, using a total of 360 fire scars on 176 sections. Up to 1860, the time of Euro-American settlement, fires that scarred at least two trees were very frequent (minimum fire interval: 1 year, mean: 4, median: 2, Weibull median: 3, maximum: 19), while fires that scarred at least 10% of the recorder trees were relatively rare (minimum fire interval: 40 years, mean: 66, median: 50, Weibull median: 63, maximum: 123). Fire frequency remained high during the 1780–1840 period, when fire was reduced or absent in other areas of the western United States. Both the “expected” and the “observed” fire history showed lower fire frequency after Euro-American settlement, which most likely displaced Native people and any deliberate use of fire, but did not introduce publicly organized suppression in the area. Therefore, less favorable climatic conditions, not post-settlement fire management, were responsible for reduced wildfire occurrence in the modern era.

Key words: dendroecology; fire history; Great Basin; mixed-conifer woodlands; Mt. Irish; Pinus monophylla; Pinus ponderosa; ponderosa pine; single-leaf pinyon; tree rings; wildfire records.

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INTRODUCTION

Fire history studies play an important role in understanding how various factors, from natural (such as climate) to human (such as land-use patterns), can affect wildfires, which are a major disturbance process in terrestrial ecosystems of western North America (Veblen et al. 2003). In
forest environments that are characterized by low-intensity fire events, the primary source of information on long-term dynamics are fire-scarred trees, whose xylem ring patterns can provide seasonal to annual, spatially explicit records for long (>300 years) time periods (Veblen et al. 2003). This has allowed quantitative analyses of changes in wildfire regime before and after Euro-American settlement (Fule´ et al. 1997), together with the development of hypotheses on how such changes are influenced by large-scale climatic patterns, especially dry and wet periods linked to oceanic interannual to interdecadal variability (Swetnam 1993, Kitzberger et al. 2007). The temporal accuracy provided by tree-ring records over the past several centuries has also been combined with catchment-scale information over the past several millennia obtained from charcoal and pollen deposition in sedimentary systems (Whitlock et al. 2004), which also points to climatically-driven changes in vegetation, wildfire regime, and their interaction (Whitlock et al. 2003).

In the Great Basin of North America, relatively little information exists on ecosystem dynamics related to wildfire prior to Euro-American settlement, although this factor has been linked to the century-long expansion of pinyon-juniper woodlands (Baker and Shinneman 2004). Human influences besides fire suppression, such as grazing (Burkhardt and Tisdale 1976) and introduction of invasive species (Mensing et al. 2006), have impacted the frequency, intensity, and distribution of wildfires in many Great Basin areas, where pinyon-juniper woodlands occupy more than 7 million hectares at elevations ranging between 1200 and 2800 m (Tueller et al. 1979). The increase in distribution and density of pinyon-juniper populations has been attributed to livestock grazing, a climatic shift toward warmer and wetter conditions, reduced fire frequency, increases in atmospheric CO\textsubscript{2}, and recovery from prior disturbance, such as logging related to mining activities (Miller and Wigand 1994, Romme et al. 2009). However, woodland expansion has also occurred in areas that have not been influenced by livestock grazing (Soule and Knapp 1999), it does not occur over all areas where climate change should lead to tree establishment, and overall there is insufficient evidence that reduced fire frequency has been responsible for tree invasion (Baker and Shinneman 2004). Few studies have attempted to disentangle the causal factors, and quantify their interactions, behind woodland expansion. For instance, there is still ample debate on the relative importance that changes in climate vs. human land use, such as the transition from Native American burning to Euro-American extinguishing, have had on the generally observed reduction of fire frequency in modern times (Betancourt et al. 1993).

One of the most common methods to identify fire-climate relationships has been to use superposed epoch analysis, or SEA (Prager and Hoenig 1989), a nonparametric technique used to test for statistical associations between irregularly spaced events (e.g., fire) and an autocorrelated time series (e.g., drought index). Using this approach, it has been found that climate in prior years usually does not affect fire extent in the interior Pacific northwest region (Heyerdahl et al. 2002, Hessl et al. 2004), whereas large fire years tend to be preceded by wet conditions in the American southwest (Baisan and Swetnam 1990) and in relatively dry forests of the Colorado Front Range (Veblen et al. 2000), with smaller regional fires in both the southwest and the Sierra Nevada regions normally associated with a prior dry year (Swetnam and Baisan 2003). A controversial issue in studies of past environmental changes is that records derived from paleoarchives lack explicit expectations, making most analyses ad hoc and a posteriori. In other words, there is no true hypothesis-testing approach (sensu Platt 1964), and in most cases examination of the data through sophisticated correlation studies results in the selection of a seemingly significant “response” or “effect” (see for instance Wilmking et al. 2004). In an attempt to address this issue, we propose a different approach, where a priori assumptions on the occurrence of past wildfires are used in combination with a long climatic record to derive an “expected” fire regime, and then this “pyroclimatic hypothesis” is tested by using fire-scar records. A case study is presented for a remote mountain area on the hydrographic boundary between the Great Basin Interior Drainage and the Colorado River basin, but well within the physiographic Great Basin Section of the Basin and Range Province (Grayson 1993).
**Materials and Methods**

**Study area**

Our study site, centered at 37°38′41″ N, 115°24′04″ W, occupies the upper portion of the Mount Irish Range located within Lincoln County, in south-eastern Nevada (Fig. 1). The site perimeter is mostly defined by steep, rocky cliffs, encircling an area of about 1.6 km² in horizontal surface, with elevation ranging from 2400 to 2650 m. Substrate is part of the carbonate eastern assemblage that includes limestone, dolomite, shale, and quartzite (Stewart and Carlson 1978). Vegetation can be described as a mixed conifer woodland, which is often found on isolated high ranges in the southern Great Basin Desert, and in this case is not far from the floristic boundary with the northern Mojave Desert (Osmond et al. 1990). Dominant tree species include ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.), single-leaf pinyon (*Pinus monophylla* Torr. & Frém.), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), Utah juniper (*Juniperus osteosperma* (Torr.) Little), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.). Mountain mahogany (*Cercocarpus* sp.), bitterbrush (*Purshia* sp.), and sagebrush (*Artemisia* sp.) are the dominant shrub species. Tree species are mixed together (Fig. 2), and woody cover is patchy, with total basal area of 12.2 m²/ha, of which about 50% is single-needle pinyon pine, about 22% ponderosa pine, 18% juniper, and 10% white fir (Bradley 2009). While ponderosa pine and white fir are restricted to the study area, pinyon and juniper also occur at lower elevations all around the mountain.

Climate data for the site were obtained from the PRISM (Parameter-elevation Regressions on Independent Slopes Model; Daly et al. 1994) dataset at 2.5 arc-minute resolution over the 1895–2006 period. Monthly data averaged over two PRISM grid cells that include the study area show that the annual average total precipitation is 288 mm, of which 33% on average falls in the three wettest months, i.e., January (30 mm), February (34 mm), and March (30 mm). The driest month is June (12 mm), which is followed by summer rains in July (27 mm) and August (30 mm). The warmest month on average is July (20.7°C), followed by August (19.5°C), while the coldest months are January (−1.5°C) and December (−0.7°C). Average annual mean temperature is 8.6°C. The time-series patterns of PRISM data were compared to those of Nevada Climate Division 3 (Guttman and Quayle 1996), which includes the study area and spans all of south-central Nevada, from the California border to the Utah one. Over the 112-year period of overlap, linear correlation by month ranged from 0.69 to 0.88 for monthly total precipitation, and from 0.69 to 0.92 for monthly mean temperature.

Archival records and field reconnaissance suggest human impact has been minimal at the study area. Its remote location and ruggedness makes access difficult, and only by foot or horse back. The lack of any permanent surface water would discourage grazing (even by sheep and goats). Lithic scatter (Sullivan III 1983) on the mountain as well as petroglyphs not far from its base are evidence of Native American presence. The “Mount Irish Archeological Site”, where rock art is present, is approximately 5 km southeast of the study site. In the 1860s a small mining community, Logan City, was established at the base of Mount Irish, and the town population increased after the Ely and Sanderson silver lode was discovered, reaching approximately 300 people by 1867 (Hulse 1971). According to Miller (1979), Native Americans (Southern Paiutes) occupied the base of Mount Irish and were unhappy with Euro-American settlement. Several smaller mining camps sprang up in the area, but the lode ran dry by 1869, and the town withered away, with most of its inhabitants moving to nearby Pioche (Miller 1979). Scars that were caused by ax cuts, still visible on the lower bole of trees at the time of our field work, as well as five, deeply eroded, high-cut tree stumps, and a mining pit, are evidence of Euro-American presence on the mountain in the late 1800s.

**Dendroclimatic methods**

Wood increment cores were collected in May 2004 from dominant ponderosa pines and single-needle pinyons (Table 1) that were in good health and showed evidence of relatively old age (such as large branches). All sampled ponderosas, and about half of the pinyons, were inside the study area (Fig. 1); the other half of the sampled pinyons was located on the steep rocky slopes that form the southern boundary of the site, on
the way from Logan Pass to Mount Irish. Two 4.3-mm wide cores were taken from each tree, on opposite sides of the lower stem, approximately 1–1.5 m from the ground, and along the slope contours (Grissino-Mayer 2003). Cores were stored and dried inside paper straws in the field,
then transported to the laboratory, where they were glued to grooved wood mounts, progressively sanded (first mechanically, then by hand) until individual cells were clearly visible under a binocular stereo-zoom microscope with 10–50× magnification. Crossdating (Stokes and Smiley 1996) was performed visually (Fig. 3), then ring-width was measured using a Velmex sliding stage with 1-μm resolution. On ponderosa pine samples, earlywood and latewood were measured separately, using as boundary the relatively abrupt change in color (Fig. 3, upper portion). After measuring, crossdating was numerically checked using the COFECHA software (Holmes 1983, Grissino-Mayer 2001a).

Master chronologies were computed by species according to the following formula:

$$I_t = \sum_{i=1}^{n_t} (w^{0.5} - y)_i / n_t + c_i$$

Table 1. Summary of increment core collections from non-fire-scarred trees† at the study area.

<table>
<thead>
<tr>
<th>Site Name (ID)</th>
<th>Longitude (°W)</th>
<th>Latitude (°N)</th>
<th>Elevation (m)</th>
<th>Species</th>
<th>Trees</th>
<th>Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Irish, NV (MTI)</td>
<td>115.40–115.41</td>
<td>37.63–37.64</td>
<td>2255–2590</td>
<td>PIMO</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Mt. Irish, NV (MIR)</td>
<td>115.40–115.41</td>
<td>37.63–37.64</td>
<td>2255–2590</td>
<td>PIPO</td>
<td>13</td>
<td>25</td>
</tr>
</tbody>
</table>

† PIMO = *Pinus monophylla*; PIPO = *Pinus ponderosa*
with \( n_t \) = number of samples in year \( t \), with \( n_t \geq 3 \); \( w = \) crossdated ring width (mm, with 1000th digit resolution) of sample \( i \) in year \( t \); \( y = \) value of sample \( i \) in year \( t \) computed by fitting a modified negative exponential with asymptote \( \geq 0 \) or a straight line with slope \( \leq 0 \) to ring width series \( i \); \( (w^{0.5} - y)_{it} = \) index value of sample \( i \) in year \( t \); \( c_t = \) constant added to sample \( i \) in year \( t \) so that the chronology has mean equal to 1. The square-root transformation was selected among other potential choices of power transformations, such as the logarithmic and inverse ones, using the Box-Cox test (Sokal and Rohlf 1981). Calculations were performed using a combination of the standalone ARSTAN software (Cook and Holmes 1986) and the dplR library (Bunn 2008) for the R numerical computing package (R Development Core Team 2010).

Local dendroclimatic signals were determined by bootstrapped correlation and response functions (Biondi and Waikul 2004) between the master tree-ring chronologies and monthly mean temperature and total precipitation from the PRISM dataset using a 12-month window, from the previous October to the current September. At the regional level, correlation maps were drawn between each Mt. Irish chronology and all publicly available tree-ring chronologies (Grissino-Mayer and Fritts 1997) for the western USA. Since fire occurrence is linked to dry and wet periods (Westerling et al. 2003), the Palmer Drought Severity Index (PDSI; Guttman 1998) from Nevada Climate Division 3 was targeted for reconstruction using the Mt. Irish tree-ring

Fig. 3. Cross-dating occurred not just between samples of the same species, but also between samples of different species. The two cores shown here are from a ponderosa pine (MIR-02A) and a single-needle pinyon (MTI-14B), and some of the marker years are identified by white arrows. Notice the black pencil dots used by the operator to mark rings whose date is a multiple of 10 (single dot) or 50 (two dots).
chronologies, which included separate earlywood and latewood width chronologies for ponderosa pine samples. Multivariate linear regression methods were used for the reconstruction, whose performance was evaluated using calibration/validation statistics (Fritts 1976, National Research Council 2006) that resemble quantitative criteria used for hydrological model assessment (Krause et al. 2005). For instance, reduction of error (RE; Fritts 1976, p. 333) is equivalent to the Nash-Sutcliffe efficiency (E; Nash and Sutcliffe 1970). Since regression was performed on time series data, an additional evaluation measure, based on the first-order autocorrelation of model residuals, was the Durbin-Watson statistic (SAS Institute Inc. 2004).

Two hypothetical fire regimes were derived from PDSI using a set of predetermined rules, mostly derived from published correlations between PDSI and total area burned in different ecoregions of the western USA (Westerling et al. 2003). One algorithm emphasized the role of drying fuels during the current and preceding years, while another assumed that fire still occurred during a dry year, but had to be preceded by a relatively wet period to allow for enough fuel build-up. The “dry” hypothesis identified as fire years those when (1) current year PDSI was < −3, or (2) current year PDSI was < 0 and prior year PDSI was < −3, or (3) current year PDSI and prior year PDSI were < 0, and PDSI two years before was < −3 (no fire could occur if it had already happened the year before). The “wet” hypothesis assumed that fire occurred when (1) current year PDSI was < 0 and prior year PDSI was > 2, or (2) current year PDSI was < 0, prior year PDSI was > 0, and PDSI two years before was > 2 (no fire could occur if it had happened the year before).

**Fire history methods**

Fire scar samples were obtained during 2007, two years after the completion (Biondi and Strachan 2005) and presentation (Biondi et al. 2006) of the PDSI reconstruction and hypothetical fire history for the site. Partial cross sections were taken using standard methods (Arno and Sneck 1977) from almost all fire-scarred trees, either alive or dead, found at the site. Some fire scars (less than 5% of total) were not sampled because either the wood was too rotten or because sampling posed danger to the chainsaw operator. Some trees were sampled more than once either because they had very large fire scars or because the first wedge sample was not considered of good enough quality. A few wedge samples were also collected from ax scars, which were easily recognized in the field because of their location—on the lower bole but without any connection to the ground—and of their shape—oval or square rather than triangular. A number of site and tree location parameters (geographical coordinates, elevation, aspect, slope, species, diameter, height, sociological status, scar height and azimuth), including digital photographs, were recorded in the field.

In the laboratory, wedge samples were surfaced using a belt sander, with increasingly finer grit sand paper until the wood cell structure was clearly visible under a binocular microscope with 10–50× magnification. Wedges that were either broken into multiple pieces or too thin or too rotten to be sanded properly were mounted on plywood backing prior to surfacing. Visual crossdating was attempted for each sample against the Mount Irish master tree-ring chronologies. Samples that were difficult to date, and had not been mounted on plywood, were flipped and surfaced on the opposite side as a way to increase the likelihood of crossdating. Ring width was measured on wedge samples as it was done for the increment cores, and crossdating quality control was done similarly as well. Fire years were only included in the analysis if charred wood was clearly visible on the wedge sample. When scars occurred at the boundary between two rings, rather than using information from nearby trees, we considered fire sightings records from public agencies for all of Lincoln County (Fire Science Library 1998, Hall 2006) and lightning strike data representative of a 6.5 km squared area around Mount Irish (Vaisala Global Atmospherics Inc. 2007). The vast majority of recorded fires (91.4% out of 3151) and lightning strikes (91.3% out of 2255) occurred from June to September, making it very unlikely that scarring could have occurred before that year’s growing season. Therefore, ring boundary fires were assigned to the inner, i.e., older, year, whose growth ring was either completed or partially formed when scarring took place.

In a few cases, due mostly to insect galleries
that obliterated ring structure and/or to very narrow rings boundaries that could not be distinguished from one another, a range of years was given to a fire scar. These scar intervals provide a general idea of the fire occurrence, but could not be included in the usual numerical summaries of fire history. Fire dates were never cross-dated with one another to allow for the possibility that fires occurred in adjacent years and scarred nearby trees. To avoid personal bias, all dates were checked by at least two members of the DendroLab, both of them unaware of the theoretical fire history that had been developed earlier from the PDSI reconstruction. Numerical and graphical analysis of fire regime, before and after Euro-American settlement, was based on FHX2 software (Grissino-Mayer 2001) to compute the mean fire return interval (MFRI), or the mean of all fire-free intervals, as it is the best measure of central tendency for cross-study comparisons (Baker and Ehle 2001). In order to downplay single-tree fires, intervals were assessed only for fire dates recorded by two or more trees. Larger fires were evaluated by focusing on years when at least 5% or 10% of the recorder trees were scarred. It should be noted that these thresholds are arbitrary, despite being commonly employed in the literature to derive relationships with climate using superposed epoch analysis (Swetnam and Baisan 2003).

**Results**

**Pyroclimatic hypothesis results**

Crossdating was possible within a species and between species (Fig. 3). Both chronologies were longer than 640 years, with the pinyon one reaching as far back as AD 1301, and the ponderosa one being slightly shorter, back to AD 1363 (Table 2). As mentioned below, older ponderosas were sampled for fire history, and crossdated wedges included xylem growth rings back to AD 1146. Mean segment length (Table 2) was longer than 400 years, which allowed for reconstruction of decadal to centennial patterns (Cook et al. 1995). Ring widths were very small, as shown by a mean of 0.6 mm for ponderosa pine samples, and 0.4 mm for single-needle pinyon samples. Locally absent rings (2% for ponderosa, 4% for pinyon; Table 2), and high inter-series correlation (signal-to-noise ratio greater than seven), indicated climate-limited growth conditions. Earlywood width of ponderosa pine cores accounted on average for 88% of the annual ring size, and was therefore much more variable than latewood width, as also reflected by the standard deviation and Gini coefficient of the tree-ring chronologies (Table 2). The signal strength (SS) of all reference chronologies reached high (>0.7) values with little replication, which indicated coherence of radial growth variability among samples. Inter-species crossdating was confirmed by the high linear correlation (0.7 for the 1396–2003 period of overlap) between the ponderosa and pinyon chronologies (Fig. 4). The ponderosa earlywood chronology was more similar to the whole-ring chronology (r=0.97) than the latewood chronology (r=0.83 with the whole-ring chronology, and r=0.77 with the earlywood one). Correlation maps (Fig. 5) with hundreds of other tree-ring chronologies (Grissino-Mayer and Fritts 1997) for western North America revealed that both the pinyon and the whole-ring ponderosa chronologies resembled overall tree-ring patterns from the

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**Table 2. Summary of reference tree-ring chronologies**† (see Table 1), with both dating‡ and chronology§ information.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>First Year</th>
<th>Last Year</th>
<th>Length (yrs)</th>
<th>Dated Trees/Cores</th>
<th>MSL (yrs)</th>
<th>Dated LAR/Total</th>
<th>G</th>
<th>St. Dev.</th>
<th>A1</th>
<th>Period with N ≥ 3</th>
<th>Period with SS ≥ 0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTI</td>
<td>1301</td>
<td>2003</td>
<td>703</td>
<td>11/18</td>
<td>439</td>
<td>279/7906</td>
<td>0.074</td>
<td>0.138</td>
<td>0.258</td>
<td>1373–2003</td>
<td>1373–2003</td>
</tr>
<tr>
<td>MIR</td>
<td>1363</td>
<td>2003</td>
<td>641</td>
<td>11/21</td>
<td>457</td>
<td>155/9596</td>
<td>0.073</td>
<td>0.134</td>
<td>0.323</td>
<td>1396–2003</td>
<td>1396–2003</td>
</tr>
<tr>
<td>MIRew</td>
<td>1363</td>
<td>2003</td>
<td>641</td>
<td>11/21</td>
<td>457</td>
<td>155/9596</td>
<td>0.071</td>
<td>0.130</td>
<td>0.326</td>
<td>1396–2003</td>
<td>1396–2003</td>
</tr>
<tr>
<td>MIRlw</td>
<td>1363</td>
<td>2003</td>
<td>641</td>
<td>11/21</td>
<td>457</td>
<td>155/9596</td>
<td>0.028</td>
<td>0.053</td>
<td>0.272</td>
<td>1396–2003</td>
<td>1481–2003</td>
</tr>
</tbody>
</table>

† MIRew = PIPO earlywood widths (µm); MIRlw = PIPO latewood widths (µm)
‡ Statistics independent of the standardization formula: MSL = mean segment length (yrs); LAR/Total = number of Locally Absent Rings/number of rings measured; N = number of measured samples per year
§ Statistics that depend on the standardization formula: G = Gini coefficient (Biondi and Qeadan 2008a); St. Dev. = standard deviation; A1 = first-order autocorrelation; SS = signal strength (Holmes 2001).
southern Great Basin and American Southwest regions.

Dendroclimatic signals were relatively stable, according to moving correlation functions (Fig. 6). The main positive response was with winter and early spring (January–March) precipitation, which is the wettest period of the year on average. The main negative response was with spring-summer (May and July) temperature. The pinyon chronology also showed a positive response to precipitation during the growing season (especially May) and a negative relationship with March–April temperature. The ponderosa chronology was negatively influenced by warm temperature earlier in the year as well, indicated by negative correlations with February–March and the previous October–November. Overall, these signals pointed to a drought response, as would be expected in these environments, given that moisture supply, concentrated in winter and early spring, is depleted by evapotranspiration demands that peak in late spring and summer. In fact, correlations with monthly PDSI for Nevada Climate Division 3 were generally high, and the reconstruction focused on the May–July period, as summer PDSI has normally been the target of tree-ring reconstructions (e.g., Cook et al. 1999). The best combination of predictors, according to Mallow’s $C_p$ criterion (SAS Institute Inc. 2004), was given by the master chronologies for pinyon ring width and ponderosa latewood width, which together explained 41% of the mean May–July PDSI from 1930 to 2003 (Table 3). PDSI values for the western USA in the early 1900s are considered unreliable because of very sparse instrumental records (Guttman and Quayle 1996). All calibration and verification statistics (Table 3) were statistically significant (Holmes 1999), reduction of error and coefficient of efficiency were greater than zero, indicating reconstruction skill, and the Durbin-Watson statistic was close to two, suggesting uncorrelated residuals. The reconstruction also matched well-known climatic episodes in the western USA (Fye et al. 2003), such as the early 1900s pluvial, the droughts of the 1930s, 1950s, and early 2000s, and the wet spells associated with the 1982–83 and 1997–98 El Niño events (Fig. 7).

After applying the pyroclimatic hypotheses to the 608-year PDSI reconstruction, the “dry” set of assumptions resulted in 37 fire years, while the “wet” ones resulted in 29 fire years (Fig. 7). Since only 9 years were common to the two pyroclimatic regimes, 76% of the “dry” fire events and 69% of the “wet” ones were unique. In the “dry” scenario, fire years were much less common since the mid-1800s: using 150-year intervals, there

![Graph of mean index over time](image-url)
were 4 fires from 1851 to 2000, 10 from 1701 to 1850, 8 from 1551 to 1700, and 14 from 1401 to 1550. There were four fire years in the most recent 150-year period also according to the “wet” hypothesis, but fire events were more equally distributed in the previous 150-year segments, with 8 from 1701 to 1850, 9 from 1551 to 1700, and 8 from 1401 to 1550. The mean fire return interval (MFRI) was 17 years for the “dry” fire-climate regime (minimum of 3, mode of 5, median of 11, and maximum of 51), and 20 years for the “wet” one (minimum of 3, mode of 11, median of 16, and maximum of 59). As indicated by comparing mean, median, and mode, the distribution of “dry” fire year intervals was less symmetric around the mean than for the “wet” ones.

**Fire history results**

A total of 250 fire-scarred trees were sampled in the field, and 197 wedge samples could be crossdated (Table 4). Given the very thin xylem layers formed in these environments, scarring could obliterate the ring structure, therefore dating was impossible in some cases. Even when dates could be assigned to fire scars, the season of occurrence could usually not be resolved. Ring widths measured on 147 wedge samples had the same average as the increment core samples (0.6 mm for ponderosa pine, 0.4 mm for pinyon pine). Crossdated samples spanned 860 years, from 1146 to 2006, and contained 485 fire scars, of
which 390 could be dated to a single year, from 1246 to 1977. A total of 88 scars were found inside a growth ring, making their date relatively easy to identify (Fig. 8, upper panel). Many more fire scars (302) spanned the boundary between two rings (Fig. 8, lower panel), and their date was assigned to the inner, older ring, as described above in the methods. Several fire scars could only be dated within a window of three or more years (50 scars) or were unusable due to insect damage or unusual ring-width patterns (45 other scars). Most of the crossdated samples were from ponderosa pines (89%); the rest was essentially white fir (11%), since only one other sample (single-needle pinyon) could be crossdated. About 95% of the crossdated fire-scar wedges were from live trees. Fire history summaries were derived from 360 fire scars on a total of 176 sections in the period 1550–2006, when sampled trees ranged from 47 to 172, and “recorder” trees, i.e., sampled trees that had been scarred by fire once already, ranged from 16 to 169 (Fig. 9).

<table>
<thead>
<tr>
<th>Model type</th>
<th>Years</th>
<th>Intercept MTI</th>
<th>MTI</th>
<th>MIRlw</th>
<th>R²</th>
<th>SP</th>
<th>RMSE</th>
<th>DW</th>
<th>RE</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction</td>
<td>1930–2003</td>
<td>−29.3 (0.002)</td>
<td>10.2 (0.0001)</td>
<td>19.2 (0.069)</td>
<td>0.41</td>
<td>16</td>
<td>2.12</td>
<td>1.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>1930–1966</td>
<td>−35.8 (0.003)</td>
<td>6.1 (0.054)</td>
<td>29.1 (0.021)</td>
<td>0.34</td>
<td>9</td>
<td>1.89</td>
<td>2.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verification</td>
<td>1967–2003</td>
<td>−35.3</td>
<td>6.1</td>
<td>29.1</td>
<td>0.40</td>
<td>4</td>
<td>0.38</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>1967–2003</td>
<td>−25.5 (0.132)</td>
<td>10.5 (0.033)</td>
<td>15.7 (0.448)</td>
<td>0.41</td>
<td>8</td>
<td>2.24</td>
<td>1.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verification</td>
<td>1930–1966</td>
<td>−25.5</td>
<td>10.5</td>
<td>15.7</td>
<td>0.31</td>
<td>7</td>
<td>0.43</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† All values of SP, DW, RE, and CE were significant at the 0.05 level. Abbreviations are: SP = sign-products; RMSE = root mean square error; DW = Durbin-Watson statistic; RE = reduction of error; CE = coefficient of efficiency.
Fire activity was high until about 1860, the time of Euro-American settlement near the study area; wildfire frequency decreased dramatically after that (Fig. 10). Between 1550 and 1860, the mean fire return interval (MFRI) was 4 years, the median was 2 years, and the Weibull median probability interval (WMPI) was 3 years, with a minimum and maximum fire interval of 1 and 19 years, respectively. There were 73 fire events that scarred at least two trees, and 39 that scarred 5% or more of recorder trees. These less localized fires took place in consecutive years more frequently in the 1600s (1618–1619, 1623–1624, 1649–1650) than in any other century (1713–1714).

Table 4. Summary of wedge samples collected from scarred trees of different species on Mt. Irish, Nevada (PIPO = *Pinus ponderosa*, PIMO = *Pinus monophylla*, JUsp = *juniperus* species, ABCO = *Abies concolor*).

<table>
<thead>
<tr>
<th>Number</th>
<th>PIPO</th>
<th>PIMO</th>
<th>JUsp</th>
<th>ABCO</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampled trees with fire scars</td>
<td>216</td>
<td>8</td>
<td>3</td>
<td>23</td>
<td>250</td>
</tr>
<tr>
<td>Sampled trees with ax cuts</td>
<td>6†</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Crossdated samples</td>
<td>171</td>
<td>4</td>
<td>0</td>
<td>22</td>
<td>197</td>
</tr>
<tr>
<td>Undated samples</td>
<td>45</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>53</td>
</tr>
<tr>
<td>Measured samples</td>
<td>129</td>
<td>3</td>
<td>0</td>
<td>15</td>
<td>147</td>
</tr>
<tr>
<td>Crossdated samples not measured</td>
<td>87</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>103</td>
</tr>
<tr>
<td>Fire scars‡</td>
<td>432</td>
<td>10</td>
<td>0</td>
<td>43</td>
<td>485</td>
</tr>
<tr>
<td>Fire scars dated to a single year§</td>
<td>359</td>
<td>7</td>
<td>0</td>
<td>24</td>
<td>390</td>
</tr>
<tr>
<td>Fire scars with uncertain date¶</td>
<td>45</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>Unusable fire scars</td>
<td>28</td>
<td>1</td>
<td>0</td>
<td>16</td>
<td>45</td>
</tr>
</tbody>
</table>

† Three of these six trees also had a fire scar, and were counted in the previous category as well
‡ A wedge sample could contain more than one fire scar
§ Of these scars, 302 were found on the boundary between two rings, and were assigned to the inner, older ring because wildfires and lightning strikes occur mostly in the summer, after the start of the growing season (see text for details)
¶ These scars had a fire-date window of 3 or more years
One of these consecutive fire events, 1824–1825, coincides with consecutive fire events in Zion National Park, Utah (Madany et al. 1982). Widespread fire events (10% or more of recorder trees scarred) happened in 1573, 1630, 1673, 1713, and 1836, giving a MFRI of 66 years, a WMPI of 63 years, and a fire interval range between 40 and 123 years. Results were essentially independent of white fir and single-leaf pinyon samples, as would be expected considering their small number. For instance, MFRI and WMPI for at least two trees scarred in 1550–1860 using only ponderosa pine samples were essentially the same (after rounding to the nearest integer) as for the three species combined.

Fire return interval statistics for the period 1861–2006 could not be estimated because of only 20 scars and two fires (1883 and 1916) that scarred two trees or more. However, this result was partially due to the fact that, of the 95 scars that could not be crossdated to a calendar year, about 20 occurred in the post-settlement period (Fig. 11), most likely because the outside portion (older biological age) of sampled trees is where rings become smaller, less easily datable, and more likely to be eroded away by insect galleries and weathering processes.

Given that the ‘dry’ and ‘wet’ scenarios identified climatically-driven fire events, the most appropriate comparison between the expected (Fig. 7) and observed (Fig. 9) fire regimes involved years when a substantial proportion of sampled trees recorded a fire. Initially we used as threshold either 5 or 10% of the recorder trees, but we then added the 7% threshold because it provided a better match between the ‘hypothetical’ and ‘actual’ fire regimes. Prior to 1860, and going back in time as far as the reconstructed PDSI, the observed MFRI using this 7% cutoff was 13 years (minimum of 1, mode of 1, median

Fig. 8. Examples of fire scars on ponderosa pine wedge samples. Relatively few scars (88 out of 485) were found inside a growth ring, such as the 1788 one (upper panel). Many more fire scars (302) spanned the boundary between two rings, such as the 1717–1718 ones (lower panel). Because wildfires and lightning strikes occur mostly in the summer, after the start of the growing season, all ring boundary fires were assigned to the older ring, i.e., 1717 in this example. Notice the pencil marks (a dot in the lower panel, lines in the upper panel) made by the operator for dating and measuring purposes.
of 10, and maximum of 42) and the predicted MFRI for the dry regime was 14 years (minimum of 3, mode of 5, median of 10, and maximum of 43), while it was 18 years for the wet regime (minimum of 3, mode of 11, median of 15, and maximum of 59).

**DISCUSSION**

The area we investigated is representative of several other mountain-top ecosystems in the Great Basin, where ponderosa pine is found in complex mixtures with elements of the more typical pinyon-juniper woodlands (Charlet 1996). These communities occur near transition zones, such as that between the Great Basin and Mojave Desert vegetation, whose horizontal boundary is strongly modified by a topographically complex terrain, and fluctuates over time depending on climatic forcing, disturbance regimes, and species migrations (Grayson 1993). The presence of pinyon pines roughly as old as the ponderosa pines is a clear indication that both species have been present in the stand for at least the past 700 years. While the ecological, aesthetic, and recreational value of these ponderosa pine populations has recently been recognized with the creation of many new protected areas (receiving “wilderness” status in 2004 [United States Senate 2004]), dendroecological studies of fire regime in Nevada’s Great Basin have focused mainly on pure pinyon-juniper woodlands (Py et al. 2006, Bauer and Weisberg 2009). In Arizona and New Mexico, wildfires recorded by ponderosa pine fire scars did not generally spread to adjacent pinyon-juniper woodlands (Huffman et al. 2008), but at Mt. Irish the two species are effectively mixed together, hence the forest type and associated fuel characteristics would not be different enough to alter stand-wide fire regime.
between areas with or without ponderosa pines.

The fire-climate connection presented by the pyroclimatic ‘dry’ and ‘wet’ scenarios was developed prior to, and independently of, the fire history reconstruction. Therefore, it represents a true a priori hypothesis, rather than a relationship established by applying a posteriori techniques—including superposed epoch analysis—to establish relationships with a climate record selected after the development of the fire history. While our predictive models were inaccurate for identifying individual fire years recorded in at least two trees, one would not expect climate-driven fire occurrence to be reflected in such small-scale fires. In fact, the 5%, 10%, and 25% filters that are commonly used to define large, climatically-driven wildfires (Swetnam and Baisan 2003) are arbitrary, and the relatively good agreement we obtained between “expected” and “observed” fire regimes using a 7% threshold for the latter suggests that such filters may depend on the type of ecosystem under consideration. The reduced frequency of wildfires after the mid-1800s derived from the two fire-climate scenarios, and especially from the “dry” one, was clearly confirmed by the analysis of fire scar records.

Our novel approach to identifying fire-climate relationships has the potential advantage of reducing investigator’s bias, but its results still depend on the choices made at multiple stages during the investigation. In fact, it should be noted that such an issue affects any retrospective study, although it has recently been emphasized.
for air temperature reconstructions (e.g., Bürger et al. 2006). For instance, in our own study, the standardization method used to produce master tree-ring chronologies may not be the most appropriate one, because the “conservative” curve-fitting option that was applied here to remove the biological trend from ring-width series is affected by numerical and conceptual drawbacks (Biondi and Qeadan 2008b). Similarly, the PDSI reconstruction could have been developed using different choices, such as the inclusion of prior-year PDSI as a lagged variable in an iterative loop to create a time-dependent model (e.g., Balestra and Nerlove 1966) or by adding other tree-ring chronologies within or near Nevada Climate Division 3 as predictors. Finally, the choices used to identify fire events could have been slightly different, either in terms of PDSI value used as cutoffs or with regard to the number of prior years considered by the dry and wet algorithms. Further developments should aim at producing software tools that reduce the effort required for producing multiple reconstructions using a number of different choices, in order to produce an assessment of model sensitivity to the investigator’s assumptions.

The natural range of variability of fire occurrence at Mount Irish, compared to results obtained for all of the western USA, was similar to that found in the American Southwest (Baker and Ehle 2001), with relatively frequent, patchy fires, but much less frequent, larger fires. The
lack of agreement between the ‘dry’ and ‘wet’ predictive models of fire occurrence may have implications for understanding fire-climate relationships in the study area. Both models were developed based on fire-climate relationships that have been reported in forest ecosystems throughout western North America, but the actual fire history record suggests that long-term fire-climate relationships in these mixed conifer woodlands of the south-central Great Basin may be unlike other regions. The predominantly arid climate of the Great Basin precludes the need for extended drought conditions to desiccate fuels as a condition for fire. Similarly, short periods of hot dry weather would not be critical for fire. It is also possible that occasional years of increased fuels interact with the random nature of natural ignitions to drive fire occurrence. At Mt. Irish at least one tree was scarred by fire on average every two years between 1550 and 1860, which points to low fire severity in general. While a relatively fire-free period occurred in 1783–1794 throughout the Southwest (Grissino-Mayer and Swetnam 2000) and in 1783–1850 for the Colorado Rockies (Sibold et al. 2006), this phenomenon has not been observed in the Great Basin (Bauer and Weisberg 2009). It is therefore likely that a pyroclimatic model would be even more accurate in systems where climate patterns are more strongly associated with fire occurrence.

Impacts of land use changes, such as introduction of sheep and cattle after Euro-American settlement, must have been limited at Mt. Irish because of the lack of surface water. While it is impossible to quantify the potential bias associated with using only crossdated fire events in numerical summaries (thereby excluding undated fires, which may be more likely to occur in recent times, when trees are older), our results do not suggest that the extent of this bias would negate a greatly reduced fire frequency after the mid-1800s. No evidence for extensive logging or fire suppression efforts could be seen at the site during field reconnaissance or from additional studies of the stand population structure (Bradley 2009). In fact, the Bureau of Land Management has had no incentive to extinguish fires at this site, given its remoteness, difficulty of access, and absence of threats to human life or property, and officially stopped suppressing wildfires in this area of Lincoln County in 1995 (Bureau of Land Management 2000).

Fire regime changes after the mid-1800s may have been favored by displacement of Native American tribes. Paiutes in southern Nevada and Shoshones in eastern Nevada used fire to drive game animals for hunting, to improve wild-food crops, to increase growth of wild seeds and wild tobacco (Stewart 1980), as well as to guide people to gathering points after a hunt (Wheat 1967). Native Americans made at least one attempt to drive settlers out of the Mount Irish area (Miller 1979), but were defeated and eventually driven away. Wildfire has not returned to the area during the 20th Century, when neither settlers nor tribes lived nearby. In a modeling study based on fire atlas reports (Dilts et al. 2009), spatial patterns of lightning strike density in the region were related to spatial patterns of wildfires from 1994 to 2005. Mt. Irish was identified as having a lower probability of fire occurrence based on low lightning strike densities. Because modern fire regime in this region has been affected by natural ignition frequency (i.e., lightning strikes during relatively dry thunderstorms), which increases going from west to east because of increased summertime convective activity (Dilts et al. 2009), shifts in warm-season circulation patterns could also have played a role in shaping pre-settlement wildfire regime.

In conclusion, the comparison between our pyroclimatic hypothesis and the reconstructed fire history points to an intriguing fire-climate relationship in the context of other ponderosa pine ecosystems in western North America, given that we identified a mainly climatic explanation for the reduced fire frequency that has been observed at Mt. Irish in the last century or so. When compared with the influences of livestock grazing and fire suppression, it appears that the recent period of decreased fire at the site is driven by an interaction of factors that differs from those used to guide ecosystem management in other western regions. Plans to ameliorate the impacts of climate change on wildfire regime that were developed for ponderosa pine ecosystems in other areas are therefore not applicable to Mt. Irish and the surrounding mixed conifer woodlands of the southern Great Basin.
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