Influences of humans and ENSO on fire history of *Austrocedrus chilensis* woodlands in northern Patagonia, Argentina

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**Abstract:** In northern Patagonia, Argentina, five areas near the ecotone of xeric woodlands and the steppe were sampled for fire history to assess spatial and temporal variations in fire regimes. A total of 214 fire-scar samples from the xeric conifer *Austrocedrus chilensis* (D. Don) Florin & Bout. yielded 430 cross-dated fire dates from AD 1439 to 1989. A regional trend of increasing fire frequency during the latter half of the 19th century coincides with increased native American occupation of the area. There is a marked decline in fire frequency following the demise of the native American population in the late 1800s and in association with increasingly effective fire suppression during the 20th century. Inter-site variations in the frequency of small fires appear to reflect intra-regional variations in human activities. In contrast, regional synchronicity of years of more widespread fires implies greater climatic control of major burning events. El Niño-Southern Oscillation (ENSO) events are an important factor in the subtropical anticyclone of the southeast Pacific that affects weather in northern Patagonia, and, at a time scale of fifty years, periods of widespread fire closely track increased ENSO events as determined from historical sources and tree-ring reconstructions. However, the multi-decadal relationship of increased frequency of years of widespread fire and increased ENSO activity could only be tentatively established due to the relatively small number of pre-1800 fire dates and the potentially confounding influence of variations in human activities. This tentative association of increased fire occurrence with greater climatic variability at a fifty-year time scale complements earlier research that relates more widespread to droughts preceded by years of above-average moisture availability at time scales of 1 to 4 years.

**Keywords:** Austrocedrus, dendroecology, fire history, Patagonia, climatic variation, land use.

**Résumé:** Dans le nord de la Patagonie (Argentine), cinq sites situés près de l'écotone entre la forêt xérophile et la steppe ont été échantillonnés pour reconstituer l'histoire et les variations spatiales et temporelles du régime des feux. Un total de 214 échantillons portant une ou plusieurs cicatrices de feu ont été prélevés sur les troncs du conifère *Austrocedrus chilensis* (D. Don) Florin & Bout. Ces cicatrices témoignent du passage de 430 feux entre 1439 et 1989 AD. On constate une augmentation régionale de la fréquence des feux au cours de la seconde moitié du 19e siècle. Cette augmentation coïncide avec l'occupation croissante de la région par les américains. On remarque également une forte diminution de la fréquence des feux dès la fin du 19e siècle à la suite du déclin des populations autochtones et en raison d'activités de suppression des feux de plus en plus efficaces au cours du 20e siècle. Les feux de petite surface ont une fréquence variable selon les sites. Cette variabilité reflète probablement un patron différentiel d'utilisation des sites par les humains. Par contre, le rapprochement régional des années avec feux de grande superficie suggère une influence climatique prépondérante. L'oscillation méridionale du El Niño a une grande influence sur les anticyclones subtropicaux du sud-est du Pacifique, elle affecte en conséquence les conditions climatiques du nord de la Patagonie. Au cours d'une période de 50 ans, les épisodes de feux de grande superficie sont étroitement associés aux années avec El Niño telles que reconstituées grâce aux sources historiques ou par dendrochronologie. Toutefois, la relation entre l'augmentation de la fréquence des feux de grande superficie et les El Niño ne peut être établie avec certitude en raison du nombre peu élevé de feux avant le 19e siècle et l'effet perturbateur des activités humaines. Cette association entre une fréquence des feux de plus élevé et une plus grande variabilité climatique (à une échelle d'une cinquantaine d'années) ajoute une perspective nouvelle aux travaux sur le régime des feux. Ces derniers ont montré qu'il existe une relation (à une échelle de 1 à 4 ans) entre des feux fréquents et des sècheresses précédées par des années avec précipitation au-dessus de la moyenne.

**Mots-clés:** Austrocedrus, dendroécologie, historique des feux, Patagonie, variations climatiques, utilisation des sites.

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**Introduction**

Regional climatic variation influences fire regimes through its influence on fuel conditions and lightning ignitions (Flannigan & Harrington, 1988; Flannigan & Wotton, 1991; Granström, 1993; Renkin & Despain, 1992). Reconstructions of fire regimes, based on stratigraphic charcoal and/or tree-ring records, have demonstrated strong correlations between fire occurrence and low- and high-frequency climatic variation (Clark, 1989; 1990; Baisan & Swetnam, 1990; Swetnam, 1990; 1993; Johnson & Larsen, 1991; Larsen, 1996). Although climatic variation is an important determinant of fire regimes, particularly through its influence on fire spread, many fire history studies also show at least some association of changes in fire regimes with variations in human activities (Kershaw, 1986; Johnson, Fryer & Heathcott, 1990; Savage & Swetnam, 1996).
In most landscapes, fire regimes are influenced by both climatic and anthropogenic factors, and neither source of variation can be ignored.

In *Austrocedrus chilensis* forests and woodlands in northern Patagonia, Argentina (ca 40° s latitude) there is evidence of a long history of fire including stratigraphic charcoal, fire-scarred trees, and an abundance of fire-adapted plants (Veblen & Markgraf, 1988; Veblen et al., 1995). Variability in fire regimes of the forest/steppe ecotone of northern Patagonia has been linked to both changes in human activities and climatic variation (Veblen & Lorenz, 1988; Veblen, Kitzberger & Lara, 1992; Kitzberger, Veblen & Villalba, 1997). Previous studies have shown that an abrupt rise in fire frequency in the mid-nineteenth century coincides with increased Native American use of the area. These studies also have related the abundance of ca 80- to 100-year-old tree cohorts to massive burning by European colonists in the late 1800s, and increases in woodland densities during the present century with a sharp decline in surface fires formerly set by Native American hunters (Veblen & Lorenz, 1987; Veblen & Markgraf, 1988; Veblen, Kitzberger & Lara, 1992; Kitzberger, Veblen & Villalba, 1997).

Recent research has demonstrated important influences of high-frequency (i.e., 1 to 4 years) climatic variability on fire regimes along the gradient from Andean rain forests to xeric *Austrocedrus* woodlands at the ecotone with the Patagonian steppe (1997). In the *Austrocedrus* woodlands, fire is promoted both by drought during the fire season and above-average moisture conditions during one or two growing seasons preceding the fire season. Greater moisture availability enhances fuel production which promotes fire occurrence, if followed by drought (Kitzberger, Veblen & Villalba, 1997). Thus, high-frequency variability in moisture availability is favorable for burning. These relationships are evident in the modern fire records of national parks and instrumental climate records which span ca 50 years, and in tree-ring records spanning several hundred years. For northern Patagonia, these high-frequency climatic influences are strongly associated with the intensity and latitudinal position of the southeast Pacific subtropical anticyclone, which is the major drought-producing mechanism of the region (Kitzberger, Veblen & Villalba, 1997). Variations in this circulation feature are strongly linked to the El Niño-Southern Oscillation (ENSO; Aceituno, 1988; Villalba, 1994).

To disentangle the effects of climatic variation and human activities on fire regimes requires: (i) extensive networks of precisely dated fire histories from areas of different timing and intensity of human occupation, and (ii) proxy records of climatic variation extending over periods of at least several centuries. Although tree-ring records of climatic variation in southern South America are becoming substantially more abundant (Boninsenga, 1992; Lara & Villalba, 1993; Villalba, 1994; Villalba et al., 1996), to our knowledge the only other published study of precisely dated fire histories for the temperate latitudes of South America is that of Kitzberger, Veblen & Villalba (1997). In this paper, we add to a network of fire histories in northern Patagonia, Argentina, by using cross-dated tree-ring samples to describe temporal and spatial variations in fire history over the past several centuries in five areas of *Austrocedrus* woodlands. Key issues are: (i) the regional extent of increased fire occurrence associated with increased Native American settlement in the latter half of the 19th century, and (ii) the influence of ENSO on fire regimes at multi-decadal scales.

**Material and methods**

**Study area**

The areas sampled for fire history are in or near southwestern Lanín and adjacent northwestern Nahuel Huapi National Parks. Physiographically, the area encompasses the eastern foothills of the Andes and the adjacent Patagonian plains at an elevation of ca 800 m. Soils are mainly derived from recent volcanic ash that overlay Pleistocene glacial topography. To the west, the Andean Cordillera reaches elevations of over 2000 m and has a pronounced rainshadow effect on moist Pacific air masses flowing from west to east. Mean annual precipitation declines from > 3000 mm near the continental divide to ca 800 mm in the eastern foothills (Barros et al., 1983), which is reflected in a steep vegetation gradient from temperate rainforest to the Patagonian steppe (Veblen, Kitzberger & Lara, 1992). Towards the west, the rainforests are dominated by 40- to 45-m tall evergreen *Nothofagus dombeyi* and have dense understoreys of the 3- to 6-m tall bamboos (*Chusquea culeou*). Towards the east, *Austrocedrus chilensis* and *N. dombeyi* form extensive codominated stands which gradually become pure stands of *Austrocedrus*. Bordering the steppe are open woodlands of *Austrocedrus* mixed with sedge-thick shrubs and small trees such as *Lomatia hirsuta*, *Maytenus boaria* and *Schinus patagonicus*. In the driest easternmost parts of Nahuel Huapi and Lanín National Parks, *Austrocedrus* is rare and steppe elements such as the spiny shrubs (e.g., *Mulinum spinosum, Discaria articulata* and *Berberis buxifolia*) and bunch grasses (e.g., *Stipa spp.*) become dominant.

Near the forest-steppe ecotone, mean annual temperature is approximately 8°C, and mean monthly temperatures vary from 2°C to 3°C during the winter months (June through August) to 12°C to 14°C during the summer months of December through March (data from the Bariloche Airport weather station). The distribution of precipitation is highly seasonal with approximately 60% falling during May through August. Thornthwaite’s (1948) water-balance index is negative during the months of October through March, creating dry conditions conducive to fire, and more than 90% of fires occur during these months (Kitzberger, Veblen & Villalba, 1997). Since the beginning of record-keeping by national park authorities, fires greater than 10 ha in extent have been recorded only for the months of October through April, and peak during January through March.

Seasonal and annual variations in precipitation in northern Patagonia (at ca 40° s) are strongly influenced by changes in the intensity and latitudinal positions of the southeast Pacific anticyclone, which affects the westerly storm tracks (Pitock, 1973; 1980). In winter, the subtropical anticyclone is located near 33° s off the coast of central
Chile, which steers cyclonic storms into northern Patagonia. During the spring and summer months (November–March) the subtropical anticyclone migrates southwards to ca 40°S where it blocks the westerly flow of moist air masses into northern Patagonia (Schwerdtfeger, 1976; Pittock, 1980). Annual variations of one to two degrees in the mean latitude of the anticyclone are accompanied by variations of 0.5°C in mean surface temperature and 10-20% in regional precipitation (Pittock, 1973).

The strength of the southeast Pacific subtropical anticyclone is closely related to the anomalous Pacific tropical convection associated with ENSO (Aceituno, 1988; Karoly, 1989). Coincident with El Niño events (the warm or negative phase of the Southern Oscillation), winter precipitation is abundant along the temperate latitudes of the Pacific coast of South America, particularly in central Chile. In northern Patagonia, summers following warm El Niño events are generally warmer than average (Kiladis & Diaz, 1989). Conversely, most cold events (La Niña) correspond to cooler summers. However, there are large variations in the effects of ENSO on the climate of northern Patagonia that are related to the timing, duration and amplitude of ENSO events (Villalba, 1994).

Although most modern fires are set by humans, lightning is an important source of ignition. For the period 1938-1989 in Lanín and Nahuel Huapi National Parks, lightning ignited 15% of all fires and accounted for 21% of the area burned (Bruno & Martin, 1982; Administración de Parques Nacionales, unpubl. data). Increased lightning ignitions are associated with warmer summer temperatures reflecting incursions of subtropical air masses from the northeast (Kitzberger, Veblen & Villalba, 1997). Prior to white settlement, the Native American population frequently set fires in the forest/steppe ecotone to drive guanaco (Lama guanicoe; an American camelid), which was their principal game animal (Veblen & Lorenz, 1988). Despite the fact that most fires are set by humans, previous research has shown that the occurrence of widespread fires is strongly conditioned by climatic conditions over periods of one to four years (Kitzberger, Veblen & Villalba, 1997).

**FIRE HISTORY CHRONOLOGIES**

Master fire chronologies were developed from five sample areas (Figure 1). The South Limay (SL), East Limay (EL), Caleufú (CA) and Rahue (RA) sample areas are each ca 2 km² in area and North Limay (NL) is ca 4 km² in area. All five areas are characterized by a similar range of elevations (ca 700 to 1100 m), a diversity of aspects, and similar mean annual precipitation of ca 1000 mm (Barros et al., 1983). Ring-width variations in *Austrocedrus chilensis* from sites spanning the five sample areas are highly and significantly (p < 0.05) inter-correlated over the common interval of 1775 to 1974, which implies a similar pattern of climatic variation (Villalba, 1995). The vegetation of each area consists of mostly open woodland of *Austrocedrus chilensis* in which trees are scattered and the surface vegetation is a mixture of low shrubs and bunch grasses. Dense stands of *Austrocedrus* occur as small patches where conditions are moister, such as in ravines and on south-facing aspects.

Given the locations of the five areas sampled, significant variation in their history of human use is likely. Areas SL and NL, to the southwest of the confluence of the Traful and Limay Rivers, are part of an important area of Native American travel, settlement and hunting activities during the past several centuries, as indicated by 16th to 19th century explorers (Cox, 1863; Fonck, 1900). In area CA, Native American settlement is also reported for the mid-19th century (Cox, 1863). Area EL, although adjacent to area SL, is to the east of the Rio Limay, which is a major barrier to human travel, even on horseback. Area RA is adjacent to an extensive region of *Araucaria araucana* forest, which was a major center of Native American settlement for at least the last several hundred years (Fuentesalba, 1977). Thus, all five areas should have experienced the same regional climate, but RA, NL and SL are areas of known formerly intensive Native American activities. EL is an area unlikely to have been much utilized by humans, and area CA is an area of some Native American settlement.

All sample areas were intensively searched for fire-scarred *Austrocedrus* trees and partial cross-sections were cut from live as well as dead trees (Arno & Sneck, 1977). The location of each fire-scarred tree was recorded in the field with a portable global positioning system and plotted on 1:100 000 scale topographic maps. Maximum height above the ground of each fire scar was estimated. In each sample area, we attempted a full census of all fire dates by sampling all fire-scarred trees. However, where scar depths were similar on nearby trees and preliminary ring counts indicated that the scars were from the same years, we did not take more than ca 3 samples. Samples were air dried and sanded to create polished surfaces on which annual rings were clearly visible under a stereo microscope. On samples from live trees, dates of rings containing fire scars were determined by counting backwards from the outermost.
ring and were verified by cross-dating against marker rings from a master tree-ring chronology from a nearby area (site CUY in Villalba, 1995). Fire scars from dead trees for which the year of the outermost ring was unknown and from trees with severely suppressed growth could not be visually cross-dated. Instead, they were cross-dated quantitatively by measuring ring widths on the partial cross sections and using the program COFECHA (Holmes, 1983) which statistically compares the measured ring-width series with a master tree-ring chronology from the nearby site. According to convention among dendrochronologists in the southern hemisphere calendar dates of annual rings are assigned to the year in which ring formation begins (Schulman, 1956). Thus, for Austracaceus, which forms annual rings from October through March, the calendar year of the ring is that of October through December. Fire scars that occur in the earlywood probably occurred between October and December, and fire scars in the latewood correspond to fires that probably occurred between January and March. Dormant season fires could occur in any month from April through September, but national park records indicate that most dormant season fires occur in April and May.

The computer program FHX2 (Grissino-Mayer, 1995), an integrated software package for analysis of fire history information from tree rings, was used to analyze fire-interval data. Point fire interval (PFI) refers to recurrence of fire for an individual tree. Composite fire intervals (CFI; sensu Dieterich, 1980) refer to fires affecting a group of trees or occurring within a specified area (i.e., either a single sample area or group of sample areas). CFIs are likely to be constrained by the time required for sufficient fuel to accumulate to permit consecutive fires at a single point, and are generally a much more conservative estimate of fire occurrence. CFIs include all fires within an area and some of these may burn areas that are not overlapping. Thus, CFIs are less likely to be sensitive to fuel accumulation and are more likely to be sensitive to changes in ignition frequencies. The tendency for CFIs to decrease as the size of the area sampled increases (Baker, 1992) must be considered in comparing CFIs of the three smaller areas to those from the larger area (NL).

Occurrence of larger percentages of trees with fire scars of the same date within a sample area indicate more widespread fires or larger relative areas burned during those years (Sweatman, 1990; Grissino-Mayer, 1995). Thus, in addition to analyzing fire intervals based on the occurrence of any fire in the area, we also analyzed fire intervals for fire-event years in which at least 10% of the recorder trees were scarred. Recorder trees, or “fire-scar susceptible trees” (sensu Omme, 1980), are the trees that have been scarred at least once prior to or during the fire year in question. Because of the small number of recorder trees during early parts of the fire history records, statistics were computed only for years during which ≥ 2 trees were scarred.

We computed mean fire intervals (MFI; sensu Romme, 1980), standard deviations and coefficients of variation and skewness for both CFIs and PFIs. Most fire interval distributions tend to be positively skewed (Baker, 1992) because there is no upper limit to the maximum interval between fires, whereas the lowest possible fire interval is one year. Consequently, we also utilized the Weibull Median Probability Interval (WMPI; Johnson & Van Wagner, 1985; Grissino-Mayer, 1995) as a measure of central tendency. Fire interval distributions were fit to the Weibull distribution from which the probability of fire intervals greater than a specified length can be estimated (i.e., the exceedance probability). Thus, the fire interval associated with the 50% exceedance probability is given by WMPI. Kolmogorov-Smirnov goodness-of-fit tests were used to evaluate the fits of fire interval distributions to normal and Weibull distributions (Grissino-Mayer, 1995).

To analyze temporal trends in fire intervals, no a priori periods of interest were defined. Instead, moving 49-year sums of the number of fire event years were computed. To differentiate years of widespread fire from years of less extensive fire, 49-year sums were computed separately for (i) years in which at least one fire scar was dated, and (ii) years during which ≥ 10% of recorder trees were scarred. Potential influences of multi-decadal climatic variation were examined by comparing 49-year fire sums with 49-year sums of ENSO events. The records of ENSO events consisted of Quinn & Neal’s (1992) record derived from textual historical sources, and reconstruction of ENSO events based on tree-ring variations in central Chile and northern Patagonia (Villalba, 1994), and northern Mexico and the southern Great Plains (Stahle & Cleaveland, 1993).

**Results**

**Fire regimes: spatial patterns**

In the five sample areas, a total of 214 fire-scarred were sampled and yielded 430 cross-dated fire dates over the period 1439 to 1989 (Table I). The percentage of multiple-scarred sections varies from 41% in area NL to 86% in area RA. Most of the multiple-scarred samples contained only two or three fire dates, and the maximum number of fire scars dated on a single sample was ten. To statistically compare the fire regimes of the five sample areas, we used the time period 1722 to 1922, which predates any effects of modern fire suppression and starts late enough so that each data set contains at least 3 fire-scarred trees at the outset. In all cases, composite fire inter-

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**Table I. Summary of information on fire history sample areas. Period is defined by the dates of the earliest to the most recent fire scars**

<table>
<thead>
<tr>
<th>Study area</th>
<th>Area (km²)</th>
<th>Number of dated series</th>
<th>Period</th>
<th>Number of fire dates</th>
<th>Number of multiple scars (%)</th>
<th>Number of years with scars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahue</td>
<td>2</td>
<td>29</td>
<td>1439-1901</td>
<td>38</td>
<td>25 (86%)</td>
<td>26</td>
</tr>
<tr>
<td>Calefú</td>
<td>2</td>
<td>29</td>
<td>1599-1897</td>
<td>45</td>
<td>21 (72%)</td>
<td>23</td>
</tr>
<tr>
<td>East Limay</td>
<td>2</td>
<td>21</td>
<td>1575-1950</td>
<td>45</td>
<td>15 (71%)</td>
<td>20</td>
</tr>
<tr>
<td>South Limay</td>
<td>2</td>
<td>42</td>
<td>1641-1989</td>
<td>81</td>
<td>23 (59%)</td>
<td>37</td>
</tr>
<tr>
<td>North Limay</td>
<td>4</td>
<td>96</td>
<td>1634-1980</td>
<td>161</td>
<td>39 (41%)</td>
<td>47</td>
</tr>
<tr>
<td>Total</td>
<td>214</td>
<td>214</td>
<td>1493-1989</td>
<td>430</td>
<td>123 (56%)</td>
<td>153</td>
</tr>
</tbody>
</table>
val distributions are described better by the Weibull distribution than by the normal distribution as determined by Kolmogorov-Smirnov goodness-of-fit tests. Consequently the WMPI is the preferred descriptor of central tendency, even though the composite fire interval distributions are significantly different from a normal distribution \((p < 0.05)\) in only 3 of the 10 cases tested (Table II). WMPI is generally less than MFI, but large differences between the two measures are rare and reflect interval distributions that are more positively skewed (Table II). The generally positive skewness coefficients for fire intervals reflect the abundance of short intervals and no constraint on the maximum interval. For the four 2 km² areas (RA, CA, SL, and EL), WMPIs for years with at least one fire scar vary from 5.3 to 18.9 years (Table II). As expected, WMPI is lower for the larger area NL (4.3), but only marginally so. WMPIs for all fire years for the adjacent areas SL and NL indicate 3 or 4-fold greater fire frequencies than at area EL on the eastern side of the large Limay River that serves both as a fire break and as an impediment to human travel. Similarly, WMPIs for years with \( \geq 10\% \) recorder trees scarred show that the frequency of fire in areas NL and SL is four to five times greater than in area EL, despite its location only 1 to 3 km from the former areas (Table II).

Table II. Composite fire interval statistics for the period 1722 to 1922 for years with at least one fire scar and years in which scars occurred on \( \geq 10\% \) of the recorder trees (minimum of 2 fire scars). Means and WMPIs marked by an asterisk indicate interval distributions that do not fit a normal or a Weibull distribution \((p < 0.05)\), respectively.

<table>
<thead>
<tr>
<th>Sample area</th>
<th>Mean</th>
<th>WMPI</th>
<th>Range</th>
<th>SD²</th>
<th>CV¹</th>
<th>Skewness²</th>
<th>N³</th>
</tr>
</thead>
</table>
| **YEARS WITH > 1 FIRE SCAR**
| Rahue | 13.9 | 13.1 | 3-29 | 7.3 | 0.5 | 0.4 | 12 |
| Calefú | 8.0 | 7.2 | 2-21 | 6.0 | 0.8 | 0.6 | 8 |
| East Limay | 20.7 | 18.9 | 6-45 | 13.9 | 0.7 | 0.6 | 8 |
| South Limay | 7.0 | 5.3 | 1-23 | 6.7 | 1.0 | 1.2 | 26 |
| North Limay | 6.7 | 4.3 | 1-36 | 9.6 | 1.4 | 2.1 | 29 |
| **YEARS WITH > 10% RECORDER TREES SCARRED**
| Rahue | 24.8 | 24.5 | 9-39 | 10.7 | 0.4 | -0.2 | 6 |
| Calefú | 41.2 | 35.9 | 15-107 | 43.9 | 1.0 | -1.0 | 4 |
| East Limay | 40.0 | 40.6 | 32-57 | 11.8 | 0.3 | 0.8 | 4 |
| South Limay | 12.5 | 9.8 | 1-35 | 10.3 | 0.8 | 0.9 | 10 |
| North Limay | 10.7 | 7.1 | 1-40 | 12.4 | 1.2 | 1.3 | 14 |

¹WMPI is the Weibull median probability interval.
²SD is the standard deviation of the mean fire interval.
³CV is the coefficient of variation of the mean fire interval.
⁴Skewness is the skewness coefficient of the fire interval distribution.
⁵N is the number of fire intervals.

The minimum composite fire intervals for years of any fire occurrence are similar for all groups (1 to 6 years), as are the maximum intervals (21-45 years; Table II). Such small minimum intervals between consecutive fires imply that most fires did not burn an entire sample area. For years with \( \geq 10\% \) recorder trees scarred, there is substantially greater variation in the ranges of intervals. Minimum intervals for these years of more extensive burning are a single year for areas SL and NL and 9 to 32 years for areas RA, CA and EL; maximum intervals are less variable, ranging from 35 to 107 years (Table II). Again, the small minimum intervals for areas SL and NL strongly imply that, even during years of widespread fire, the entire sample area did not burn.

Point fire interval (PFI) may be a better way to compare fire frequency in different areas because it is not influenced by the size of the area sampled (Table III). Again, WMPI is the preferred measure of central tendency because in each area the PFI distribution fits a Weibull distribution but does not fit a normal distribution in three areas (Kolmogorov-Smirnov goodness-of-fit test; \( p < 0.05 \); Table III). The generally larger minimum PFIs (3 to 15 years) compared to CFI (1 to 6 years) probably reflect time necessary for fuel accumulation before fire can recur at the same point in this environment. Again, the lower WMPIs for areas SL and NL indicate substantially higher fire recurrences to the same points in comparison with the other three sites.

Table III. Point fire interval statistics for the period 1722-1922. Means marked by an asterisk indicate interval distributions that do not fit a normal distribution \((p < 0.05)\).

<table>
<thead>
<tr>
<th>Sample area</th>
<th>Mean</th>
<th>WMPI</th>
<th>Range</th>
<th>SD²</th>
<th>CV¹</th>
<th>Skewness²</th>
<th>N³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahue</td>
<td>39.8</td>
<td>37.9</td>
<td>9-81</td>
<td>21.0</td>
<td>0.5</td>
<td>0.6</td>
<td>24</td>
</tr>
<tr>
<td>Calefú</td>
<td>42.3</td>
<td>38.3</td>
<td>15-122</td>
<td>30.0</td>
<td>0.7</td>
<td>1.5</td>
<td>26</td>
</tr>
<tr>
<td>East Limay</td>
<td>25.9</td>
<td>35.3</td>
<td>12-80</td>
<td>16.6</td>
<td>0.5</td>
<td>1.2</td>
<td>14</td>
</tr>
<tr>
<td>South Limay</td>
<td>30.2</td>
<td>26.5</td>
<td>4-107</td>
<td>24.1</td>
<td>0.8</td>
<td>1.9</td>
<td>35</td>
</tr>
<tr>
<td>North Limay</td>
<td>26.9</td>
<td>24.6</td>
<td>3-118</td>
<td>19.0</td>
<td>0.7</td>
<td>2.6</td>
<td>35</td>
</tr>
</tbody>
</table>

¹WMPI is the Weibull median probability interval.
²SD is the standard deviation of the mean fire interval.
³CV is the coefficient of variation of the mean fire interval.
⁴Skewness is the skewness coefficient of the fire interval distribution.
⁵N is the number of fire intervals.

**FIRE REGIMES: TEMPORAL PATTERNS**

Temporal patterns of fire occurrence exhibit regional consistencies as well as important inter-site differences. The most obvious regional trend is the relative scarcity of fires since the early 1900s (Figure 2). This is particularly the case for more widespread fires that scarred \( \geq 10\% \) of the recorder trees (Figure 3). All five sample areas show a period of relatively low occurrence of widespread fires in the late 1700s and early 1800s (Figures 3 and 4). For example, no years of widespread fire were recorded between 1795 and 1820 in any of the five areas (Figure 3). Strikingly, in all five areas the years with the maximum numbers of fire-scarred trees occur immediately or soon after this hiatus in widespread fires. For example, in area EL a fire in 1827 scarred 9 trees (69% of the recorder trees), in areas CA and NL a fire in 1854 left 18 scars (82%) and 9 scars (43%), respectively, in area SL a fire in 1859 scarred 16 trees (64%), and in area RA a fire in 1860 scarred 12 trees (43%; Figure 2). Moreover, maximum heights of scars in 1827, 1854, 1859, and 1860 are 0.33, 0.20, 0.40, and 0.35 standard deviations higher than the long-term mean, for each site burned in the respective year, which also implies greater fire intensity. These observations are consistent with greater fuel accumulation that would have occurred during the several decades lacking widespread fire in the late 19th and early 19th centuries. These years of more widespread
fire also coincide with periods of extreme drought as inferred from tree-ring records (Kitzberger, Veblen & Villalba, 1997). For years of more widespread fire (≥ 10% and minimum of 2 trees scarred), all four areas show an increase in fire events during 1840 to 1890 (Figure 3).

Despite the regional consistency of these trends in fire occurrence, major differences in temporal patterns of fire are also evident. Forty-nine-year moving sums of years recording any fires show strong peaks in 1850-1890 in areas RA, NL and SL, a minor peak in area CA, and no peak in
area EL (Figure 4). Given the fact that the number of recorder trees gradually increases towards the present, it is possible that the late nineteenth century increase in number of fire scars is an artifact of the changing sample depth. However, in areas RA, NL and SL, most trees that were established well before 1800 also show an increase in fire scars from 1850 to 1890 (Figure 2). Of the 32 trees in areas RA, NL and SL that had established prior to 1750 and recorded a fire scar by at least as early as 1820, twice as many fire years occurred between 1853 and 1903 as during the preceding fifty-year period (10 versus 5 years). Similarly, for the period 1842 to 1872 (just prior to white settlement) as compared with the preceding 30 years, three times as many fire years occurred (6 versus 2 years). The lack of increase in fire frequency in area EL is striking given its proximity to areas NL and SL. However, this pattern is consistent with a major increase in Native American use of areas RA, NL and SL beginning in the mid-nineteenth century, in contrast to less use of area EL, which is more difficult to access due to its location east of the Limay River.

When 49-year moving sums for years of widespread fires (i.e., > 10% scarred class) are considered, inter-site differences among all areas during the latter half of the 19th century are much less (Figure 4). Thus, the increases in fire frequency that occurred in areas RA, SL and NL during the latter part of the 19th century are mainly due to an increase in small, patchy fires. The increases in occurrence of small fires in these three areas probably reflect increased human-set fires more strongly than shifts in climatic conditions as discussed below.

**CLIMATIC INFLUENCES**

Periods of distinct levels of ENSO activity over the past 400 years are identified by 49-year moving sums of ENSO events from Quinn & Neal’s (1992) historical record, and from tree-ring records for southwestern South America (Villalba, 1994), and for northern Mexico and the southern Great Plains (Stable & Cleaveland, 1993; Figure 5). ENSO events are relatively frequent between ca 1650 and 1750, decline somewhat in the late 1700s and early 1800s, increase to a peak in the late 1800s, and decline during the 1900s.

For the five sample areas combined, the 49-year moving sum of years of widespread fire (≥ 10% of recorder trees scarred) generally track the variation in the running 49-year sums of ENSO events (Figure 5). For example, peaks in widespread fire that occur in the early 1700s and late-1800s are concurrent with more frequent ENSO events. This is evident when the temporal pattern of widespread fires is compared to written historical records of ENSO (Quinn & Neal, 1992) as well as to tree-ring proxy records of ENSO both from southwestern South America (Villalba, 1994) and from North America (Stable & Cleaveland, 1993). Given
All fire years

Years with ≥ 10% scarred trees

Moving 49-year sums of years with scars on > 1 tree (all fires) and > 10% of recorder trees. Study area codes are: RA = Rahue, CA = Calcufu, EL = East Limay, SL = South Limay, and NL = North Limay.
the relatively small numbers of fire scars for the pre-1800 period, however, the association of increased fire and ENSO over a fifty-year time-scale must be cautiously interpreted.

Possible mechanisms relating fire occurrence in Patagonia to ENSO activity were investigated by computing the mean Southern Oscillation Index (SOI) for periods associated with extensive fire versus absence or near absence of fire. Years of extensive fire include years during which more than 2000 ha burned in National Parks Los Alerces, Lago Puelo, Lanín and Nahuel Huapi, encompassing most of the Argentine Andes and adjacent plains from 39° to 43° S, during the period of park records (1938-1989), or years during which ≥ 10% of the fire-scar susceptible trees recorded fire scars in any of the five sample areas or six nearby sample areas (Kitzberger, Veblen & Villalba, 1997) from 1882 to 1989. Years of low fire incidence are years in which < 10 ha burned in 1938-1989 in the same four national parks, or years in which < 10% of the fire-scar susceptible trees recorded scars during the period 1882-1989. Mean SOI values were computed for 48-month periods centered on years of extensive versus years of low incidence of fire. Years of extensive fire (n = 22) are associated with above-average SOIs during the year prior to the fire season (particularly during winter-spring; Figure 6). Conversely, years of low incidence of fire (n = 53) occurrence are associated with below-average SOIs during the year prior to fire occurrence. As discussed below, this pattern indicates that years of extensive fires in Patagonia are associated with late stages of the positive phase of the SO (i.e., La Niña conditions).

Discussion

Based on five new fire history chronologies for northern Patagonia, we assessed the regional consistency of previously published temporal trends in fire regimes over the past 400 years and attempted to distinguish anthropogenic from climatic influences on these trends by comparing fire histories for areas of different histories of human use. These new data are consistent with previously established regional patterns of anthropogenic influences on fire regimes but also identify some important local variations. Examination of these intra-regional differences in temporal trends of fire history suggest important influences of low-frequency climatic variations on fire regimes.

All areas sampled in the Austrocedrus woodlands of northern Patagonia demonstrate that fire has been important in this environment since at least the beginning of these tree-ring records from the 1400s to the 1600s (Figure 2). Vigorous resprouting of nearly all the woody and most of the herbaceous plants of the foresi/steppe ecotone results in rapid rates of fuel accumulation which, in turn, permit moderately high fire frequencies. Over a 200-year comparison period (1722 to 1922) prior to effective fire suppression, at single points the WMPI ranges from 25 to 38 years, and over areas of 2 to 4 km² it ranges from 4 to 19 years. More widespread fire that scorched ≥ 10% of recorder trees have composite WMPI intervals that range from 7 to 41 years in sample areas of 2 to 4 km², which probably reflects the greater time required for accumulation of fuels to support extensive fire spread. The most extensive and intensive fires (as judged by the percentages of scorched recorder trees and heights of scars) occurred soon after a hiatus in widespread fires during the late 18th and early 19th centuries, which probably resulted in exceptional fuel accumulation.

Fire frequencies during the Native American period (i.e., prior to ca 1900) were moderately high, and given the relatively short intervals for fire recurrence at the same point, these are believed to have been mostly low intensity surface fires. Given the low modern frequency of lightning-ignited fires (Bruno & Martín, 1982) and 19th-century eyewitness accounts of Native Americans setting fires (Cox, 1863; Fonck, 1900), it is likely that the more frequent source of fire ignition has been humans during the past several hundred years.

In all five sample areas, fire frequency decreases from the 19th to 20th centuries, and the decline is particularly
striking for more widespread fires. This abrupt decline coincides with the demise of the Native American population that formerly set fires mainly for hunting purposes. It also coincides with the termination of the European settlement period (ca 1890 to 1920) during which fire was extensively used to clear forests, especially more mesic forest types to the west of the area sampled in the current study, to create pasture for livestock (Willis, 1914; Veblen & Lorenz, 1988). Since the 1930s, lack of intentional burning and suppression of natural fires have been relatively effective at maintaining low fire frequencies and limiting fire spread. Heavy grazing by livestock beginning about 1900 may also have contributed to a reduction in fuels and fire spread.

Although major changes in the frequency of small surface fires coincides strongly with the changes in human activities at the end of the 19th century, years of widespread fire are strongly conditioned by high frequency (1 to 4 years) climatic variation (Kitzberger, Veblen & Villalba, 1997). For example, data from park records of fire as well as tree-ring records of fire indicate that generally in northern Patagonia years of low fire incidence (i.e., years of few and clustered fire scars) are not significantly related to variation in moisture availability over periods of 1 to 4 years. In contrast, years of widespread fire (i.e., years of many and dispersed fire scars) are strongly related to high frequency climatic variation (Kitzberger, Veblen & Villalba, 1997). In the current study we tentatively demonstrate an association of years of widespread fire with climatic variation at a multi-decadal scale. By comparing temporal trends of years characterized by any fire (mostly small surface fires) with those characterized by widespread burning (i.e., > 10% of recorder trees scarred) it appears to be possible to at least partially distinguish between anthropogenic and climatic influences on fire regimes. Temporal trends for years of any fire occurrence strongly reflect changes in human activities. Even adjacent areas (SL and NL versus EL) had strikingly different temporal patterns, depending on their location on either side of a major river that acts as a barrier to both fire spread and human travel. Reports of abundant archeological remains in the area of SL and NL, in contrast to their absence in the area of EL, suggest that the river was a significant impediment to human occupation of area EL (Crivelli & Silva, 1983). For years of widespread fire, temporal patterns of years are more similar throughout the region and appear to reflect the controlling influence of climatic variation.
In the present study, we tentatively extended to a multi-decadal scale the association of widespread fire in northern Patagonia with variations in the strength and position of the southeast Pacific subtropical anticyclone that previously had been demonstrated for time scales of 1 to 4 years (Kitzberger, Veblen & Villalba, 1997). ENSO events are a major influence on the subtropical anticyclone, which in turn influence moisture availability and fire activity in northern Patagonia. We have preliminarily associated increased fire activity to increased frequency of ENSO events at a time scale of 50 years. Analogous relationships between fire occurrence and climatic variation associated with ENSO anomalies and other atmospheric teleconnections are reported for the southwestern United States (Swetnam & Betancourt, 1990; 1992) and the southern Canadian Rockies (Johnson & Wowchuk, 1993).

Years of extensive fires in northern Patagonia are associated with late stages of the positive phase of the SO (i.e., La Niña; Figure 6). This association is consistent with the association of low winter-spring rainfall with positive SOIs (i.e., cold phases) generally along the west coast of South America between latitudes 35° and 45°S (Aceituno, 1988). However, during the summer months there is a positive correlation of rainfall with the SOI. Similarly, spring temperatures in northern Patagonia show significant positive correlations with the SOI (i.e., association of warm spring temperatures and La Niña events), but during the summer this relationship becomes negative (i.e., cooler summer temperatures). The negative phase of the SO (i.e., El Niño) is associated with warmer summers in northern Patagonia (Villalba, 1994). This pattern of association of the SO, fire, and climatic conditions indicates that as La Niña phases change into El Niño conditions, prolonged droughts with hot summers promote extensive fires. Conversely, degenerating warm phases of the SO (El Niño) result in above-average winter-spring precipitation which is associated with a low incidence of fire. Thus, the alternation of strong cold-warm SO phases (La Niña-El Niño) promotes more widespread fire in northern Patagonia.

High-frequency variation in fire occurrence in northern Patagonia has previously been shown to be favored by climatic variability over time scales of 1 to 4 years, specifically the alternation of wet and dry years (Kitzberger, Veblen & Villalba, 1997). Interestingly, at much longer time-scales, comparison of sedimentary charcoal records with fossil pollen records from different environments in southern South America indicate increased fire occurrence during periods of greater climatic variability during the late Glacial and late Holocene periods (Heusser, 1987; Moreno, 1993; Markgraf & Anderson, 1994). It has been suggested that climatic variability regardless of the local precipitation regime during the late glacial may have contributed to increased fire (Markgraf & Anderson, 1994). Similarly, the late Holocene period of increased sedimentary charcoal approximately coincides with the onset of increased ENSO variability over the past ca 3000 years (McGloine, Kershaw & Markgraf, 1992). In the present study, periods of increased ENSO variability at time scales of 50 years are preliminarily shown to be periods of increased fire activity during the tree-ring record of fire over the past ca 400 years (Figure 5). However, this preliminary interpretation of an association of ENSO variability and fire occurrence at time scales of 50 years requires two important caveats. In our study, we have relatively few fire scar dates from earlier than ca 1800 AD, which prevents a robust statistical demonstration of temporal fire trends over a long period. Secondly, given the coincidence of the 1850 to 1900 period of increased ENSO activity with increased human activity in northern Patagonia, the distinction of climatic from anthropogenic influences on the fire regimes is difficult. Longer fire history reconstructions and reconstructions for sites exhibiting a greater range of intensity of human use are required to clarify climatic and anthropogenic influences on fire regimes in northern Patagonia.

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Literature cited


