Climatic influences on fire regimes along a rain forest-to-xeric woodland gradient in northern Patagonia, Argentina

THOMAS KITZBERGER, THOMAS T. VEBLEN and RICARDO VILLALBA
Department of Geography, University of Colorado, Campus Box 260 Boulder, Colorado 80309, U.S.A.

Abstract. Influences of annual climatic variation on fire occurrence were examined along a rainfall gradient from temperate rainforest to xeric woodlands in northern Patagonia, Argentina. Fire chronologies were derived from fire scars on trees and related to tree-ring proxy records of climate over the period 1820–1974. Similarly, fire records of four Patagonian national parks for the period 1940–1988 were compared to instrumental weather data. Finally, the influences of broad-scale synoptic weather patterns on fire occurrence in northern Patagonia were explored.

Fire in *Nothofagus* rainforests is highly dependent on drought during the spring and summer of the same year in which fires occur and is less strongly favoured by drought during the spring of the previous year. The occurrence of fire in dry vegetation types near the steppe ecotone is less dependent on drought because even during years of normal weather fuels are thoroughly desiccated during the dry summer. In xeric *Austrocedrus* woodlands, fire occurrence and spread are promoted by droughts during the fire season and also appear to be favoured by above-average moisture conditions during the preceding 1 to 2 growing seasons which enhances fuel production. Thus, in the xeric woodlands fire is not simply dependent on drought but is favoured by greater climatic variability over time scales of several years.

Fire activity in northern Patagonia is greatly influenced by the intensity and latitudinal position of the subtropical high pressure cell of the southeast Pacific. Greater fire activity is associated with a more intense and more southerly located high pressure cell which blocks the influx of Pacific moisture into the continent. Although long-term changes in fire occurrence along the rainforest-to-xeric woodland gradient have been greatly influenced by human activities, annual variation in fire frequency and extent is also strongly influenced by annual climatic variation.


INTRODUCTION

Fire frequency in any ecosystem is a consequence of interactions among fuel accumulations, fuel moisture content and ignition sources. Except for the human component of ignition sources, all these factors are directly or indirectly influenced by climate (Chandler et al., 1983). Climatic variation influences fire regimes across a broad range of temporal scales. For example: long-term climate determines fuel types and accumulation rates; annual to seasonal variation largely determines flammability of live vegetation and coarse dead fuels; weekly to daily variation controls the desiccation of fine fuels; and daily to hourly variation influences fire behaviour (Rothermel, 1983).

The effects of weather at hourly to daily time scales on fire behavior have been effectively modelled (Rothermel, 1972; Albini, 1984). Similarly, long-term changes in fire regimes have been associated with century-scale climatic fluctuations (Clark, 1990; Johnson & Larsen, 1991).

Variation in fire occurrence has also been related to annual climatic variation (Clark, 1989; Baisan & Swetnam, 1990; Swetnam & Betancourt, 1990; Johnson & Wowchuk, 1993; Swetnam, 1993). Analysis of fire regime responses to monthly to annual climatic variation is important for separating the effects of seasonal and annual climatic variations on fuel desiccation and ignition frequencies from longer-term climatic influences on fuel types and loads.

Furthermore, to better predict consequences of climatic changes on fire regimes, temporal scales of fire-climate interactions should match those of existing global circulation models which currently forecast on a monthly-to-yearly scale (Harte, Torn & Jensen, 1992). It is also important to consider the role of habitat differences in the sensitivity and nature of the responses of fire regimes to climatic variation. Although it is generally expected that drought favours the likelihood of ignition and spread of fires for most vegetation types, fire regimes of different ecosystem types such as mesic forests or semi-arid woodlands respond differently to...
climatic variations (Baisan & Swetnam, 1990; Agee, 1993; Swetnam, 1993).

This paper examines the influences of monthly-to-yearly weather variation on fire occurrence along a vegetation gradient from temperate Andean rain forests to xeric, open woodlands in northern Patagonia, Argentina. Previous findings indicate that low frequency (i.e. multi-decadal) variation in fire occurrence in this region is strongly correlated with human settlement and land-use changes (Veblen & Lorenz, 1988; Veblen; Kitzberger & Lara, 1992). In this paper, the influences of annual climatic variation on the fire regimes are examined for different vegetation types along this steep rainfall gradient. The analyses are based on a c. 50-year record of national park fire reports and instrumental climatic records, and on a c. 170-year tree-ring record of fire occurrence and climatic variation.

STUDY AREA

Fire chronologies derived from fire scars were developed in Nahuel Huapi National Park at c. 40°23' to 41°35'S in southwestern Argentina (Fig. 1). National Park records of fire occurrence (Bruno & Martin, 1982) were analysed for Lanín, Nahuel Huapi, Lago Puelo and Los Alerces National Parks (39°07' to 42°43'S; Fig. 1).

The climate of this area is dominated by a steep west-to-east decrease in precipitation due to the rain shadow effect of the Andes on the passage of moist Pacific air masses. Vegetation types reflect this climatic pattern, and occur as north–south orientated belts parallel to the Andes. Temperate montane rain forests occur on the western side of the Andes in Chile and extend as a narrow strip east of the continental divide into Argentina. These are typically dominated by the evergreen broadleaved tree Nothofagus dombeyi (Mirb.) Blume; other important broadleaved evergreen trees include Laureliopsis philippiana (Looser) Shod., Dasyphyllum diacanthoides (Less.) Cabr. and Weinmannia trichosperma Cav., and in the wettest areas the conifers Fitzroya cupressoides (Mol.) Johnston, Saxegothaea conspicua Lindl. and Pilgerodendron uviferum (D. Don) Florin are common. At higher elevations (>1000 m) or under lower levels of mean annual precipitation (< c. 3000 mm) forests are dominated almost exclusively by Nothofagus spp. Higher elevations are dominated by the
deciduous *Nothofagus pumilio* (Poepp. et Endl.) Krasser and lower elevations by *Nothofagus dombeyi*. In the northern part of our study area (north of c. 40°23'S) the deciduous *Nothofagus obliqua* (Mirb.) and *Nothofagus alpina* (Poepp. et Endl.) Oerst are also common at mid- to low-elevations. Dense thickets of bamboos (*Chusquea* spp.) characterize the understorey of all these forest types and are particularly abundant in the montane *Nothofagus dombeyi*-dominated forests. In areas of intermediate rainfall, *Nothofagus* spp. co-occur with the xeric conifers *Austrocedrus chilensis* (D. Don) Florin & Bout. or *Araucaria araucana* (Mol.) C. Koch (the latter north of 40°20'S); dominance by these xeric conifers increases towards the steppe boundary where mean annual precipitation is c. 800 mm. Extensive open woodlands of *Austrocedrus chilensis* are replaced eastwards by shrubs and bunchgrasses of the Patagonian steppe.

The climate of northern Patagonia (at c. 42°S) is characterized by a cool–wet season from April to September (Fig. 2a–c) which results from the incursion of cyclonic storms from the south east Pacific. During the spring and summer months (October–March), the south east Pacific subtropical anticyclone migrates from its winter position at the latitude of central Chile (c. 33°S) southwards to c. 40°S and blocks the westerly flow of moisture into the continent as far south as c. 45° (Schwerdtfeger, 1976; Pittock, 1980). This circulation pattern, in combination with the rainshadow effect of the Andes, results in relatively dry conditions on the eastern slopes of the Andes during spring and summer (Fig. 2a–c).

Interannual variability of rainfall is strongly related to the timing and extent of the southward migration of the Pacific anticyclone as well as to its intensity (Pittock, 1980). Year-to-year latitudinal shifts of one to two degrees of the mean position of the high pressure belt are accompanied by variations of 0.5°C in mean surface temperature and 10–20% in regional precipitation (Pittock, 1973). Annual climatic variation in south western Argentina and southern Chile is also influenced by the circum-Antarctic cyclonic belt. Antarctic weather indirectly controls the strength of the Southern Hemisphere westerlies which in turn affect the northward incursion of cold polar fronts (Schwerdtfeger, 1984). Interannual variability in cyclonic vortices over southern South America has a strong influence on fall and early winter precipitation over south western Argentina and southern Chile (Pittock, 1980). Consequently, drought periods in northern Patagonia are related to both the coincidence of southward positions of the Pacific anticyclone and weak polar cyclonic influence. In addition, the eastern slopes of the Andes can be influenced by humid air masses of tropical origin. This is more common to the north, but also affects our study area during summers when the blockage of westerlies by the Pacific anticyclone is most
TABLE 1. Description of fire history sample areas, number of fire-scar samples and associated number of fire dates for the entire (1722–1990) and dendrochronologically analyzed (post-1820) periods.

<table>
<thead>
<tr>
<th>Area</th>
<th>Vegetation type</th>
<th>Mean annual Precipitation (mm)</th>
<th>Topographic position</th>
<th>Number of samples/dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Austrocedrus chilensis woodland</td>
<td>900</td>
<td>W–E running valley</td>
<td>98/41</td>
</tr>
<tr>
<td>L2</td>
<td><em>A. chilensis</em> forest</td>
<td>1100</td>
<td>N-facing slopes</td>
<td>17/13</td>
</tr>
<tr>
<td>L3</td>
<td><em>A. chilensis</em>, <em>N. dombei</em></td>
<td>1200</td>
<td>W–E running valley</td>
<td>37/16</td>
</tr>
<tr>
<td>L4</td>
<td><em>A. chilensis</em>, <em>N. dombei</em></td>
<td>1400</td>
<td>N-facing slopes</td>
<td>18/13</td>
</tr>
<tr>
<td>L5</td>
<td><em>N. dombei</em> forest</td>
<td>2000</td>
<td>N-facing slopes</td>
<td>16/12</td>
</tr>
<tr>
<td>L6</td>
<td><em>N. dombei</em> forest with <em>Fitzroya cupressoides</em> and <em>Pilgerodendron uvifera</em></td>
<td>2200</td>
<td>W–E running lake basin</td>
<td>16/11</td>
</tr>
<tr>
<td>L7</td>
<td>Sphagnum bog with sparse <em>F. cupressoides</em> and <em>P. uvifera</em></td>
<td>3000</td>
<td>N–S running valley bottom</td>
<td>7/6</td>
</tr>
<tr>
<td>S1</td>
<td><em>A. chilensis</em> woodland</td>
<td>900</td>
<td>NW-facing slope</td>
<td>61/24</td>
</tr>
<tr>
<td>S2</td>
<td><em>A. chilensis</em> woodland and forest</td>
<td>900</td>
<td>E-facing slope</td>
<td>23/14</td>
</tr>
<tr>
<td>S3</td>
<td><em>A. chilensis</em> woodland</td>
<td>900</td>
<td>S-facing slope</td>
<td>35/21</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>341/167</td>
</tr>
</tbody>
</table>

The fire season in northern Patagonia is coincident with the period of strongest water deficit which extends from October through April, and larger fires are concentrated in the summer months of January through March (Fig. 2d). Although most fires are set by humans, from 1938 to 1989 lightning ignited 15.4% of all fires and accounted for 21% of the area burned in Nahuel Huapi and Lanín National Parks (Bruno & Martín, 1982).

**METHODS**

*Fire scar chronology development*

Fire-scarred trees were collected in ten areas located along the west-to-east gradient between 40°38’S and 41°40’S in Nahuel Huapi National Park (Fig. 1). Seven areas (L1–7) of c. 1000 ha each were extensively searched, and three areas (S1–3) of c. 100 ha each were more intensively sampled (Fig. 1). Areas L1 and S1–S3 consist of open woodlands of *Austrocedrus chilensis*, L2 is an area of denser tree cover by the same species (i.e. xeric *Austrocedrus* forest), L3–L4 include a mixture of mainly *Nothofagus dombei* and *Austrocedrus*-dominated forests, and L5–6 are *N. dombei*-dominated rain forests. Areas L6 and L7 are located at the western end of Nahuel Huapi National Park, and due to the high moisture availability in addition to *N. dombei* they include the long-lived conifers *Fitzroya cupressoides* and *Pilgerodendron uvifera* (Table 1). These ten sample areas form a gradient from Andean rain forest to xeric woodland at the steppe ecotone. Wedges were extracted from single- and multiple-scarred live trees and the location of each sampled tree was recorded on 1:24,000 topographic maps. *Austrocedrus chilensis* and *Fitzroya cupressoides*, which have relatively thick bark, commonly survive moderate-intensity fires and dates of past fires can be precisely determined from their fire scars. In contrast, the thinned-bark *Nothofagus dombei* is less likely to survive moderate-intensity fires and its fire scars are more difficult to date precisely due to decay of the wood around the scar. Thus, areas of pure *N. dombei* stands (L4 and L5) yielded relatively few fire scars due to the scarcity of fire-scar-susceptible conifers (Table 1). These differences in abundances of fire-scar-susceptible tree species in different forest types are taken into account in the interpretations of fire-scar data in this study.

Processing of wedge samples and fire-scar dating followed standard procedures, including cross-dating with master tree-ring width chronologies (Stokes & Smiley, 1968; McBride, 1983). Fire years are given as the calendar year beginning during the fire season (October to April), which is consistent with the convention in dendrochronology in the Southern Hemisphere of assigning the date of an annual ring to the calendar year in which ring growth initiated (Schulman, 1956). Of the 362 fire scars dated to ± 1 year, 341 were dated to the exact year (Table 1) and are used in the present analyses. Master fire chronologies giving the number of dated fire-scar observations per year were constructed for each of the ten areas sampled, and a regional master chronology was developed by combining all sample areas.

**Analyses of climatic influences**

The influences of interannual climatic variability on fire regimes were analysed for two periods based on different datasets: (1) the 1940–88 period of Argentine National Park fire records and the instrumental weather record, and (2) the 1820–1974 fire-scar record and tree-ring width chronologies. For the former period, fire parameters were related to monthly climatic data from instrumental climatic records. For the latter period, variation in tree-ring widths was used as a proxy for moisture availability in spring and summer (see below for details).

**Instrumental weather/fire report records**

For Nahuel Huapi, Lanín, Lago Puelo and Los Alerces National Parks, areas burned each year during the period...
1940–88 were compiled from Argentine National Park Service fire records (Brunner & Martin, 1982; Argentine National Park Service, unpublished data). We classified fires as occurring in wet or dry areas based on their location and vegetation type. Wet forest fires were those occurring in Nothofagus-dominated forests, whereas dry area fires affected Austrocedrus chilensis- or Araucaria araucana-dominated forests and woodlands as well as shrublands and grasslands.

For the period 1940–88 Thornthwaite’s (1948) water balance and de Martonne’s (1926) aridity index were computed from mean monthly temperature and precipitation data from the Bariloche weather station (Fig. 1). The monthly indices (or their integration for multi-month periods preceding the fire season) were used as measures of the moisture status of live and dead coarse fuels. Strongly negative (deficit) values indicate a strong desiccating effect of climate on fuels. Based on studies conducted in other ecosystems, desiccation of both live and dead coarse fuels (i.e., >75 mm in diameter) requires prolonged periods of strong water deficit lasting at least several months (Rothermel, 1983). In contrast, medium and fine dead fuels can be desiccated by deficit values over a single month. Positive water balance during the growing season is believed to be favourable to the accumulation of fine fuels (Rothermel, 1983).

Preliminary analyses indicated negative exponential relationships between the area burned and integrated pre-fire season water availability. To investigate timing and duration of dry periods necessary for the occurrence and propagation of fire along the rainfall gradient, annual areas burned (log-transformed) were correlated with 5-month integrated moisture availability starting during the current fire season and extending back 2 years prior to the fire season (Fig. 3). Additionally, climatic conditions during the summer of years with and without lightning-ignited fires (based on National Park reports) were compared by t-tests of the means for 1–4 month periods from December through March.

Broad-scale synoptic weather patterns were compared for years of high fire activity vs. years of no or little fire activity. Two indicators of atmospheric circulation patterns were compared for high vs. low fire activity years: sea-level atmospheric pressure and latitudinal position of the south east Pacific anticyclone. Mean monthly atmospheric pressures from Punta Galera on the coast of Chile at 40°S (Fig. 1) were compared over the period 1911–60. Mean latitudinal positions of the surface subtropical high pressure belt along the Chilean coast were compared over the period 1943–62 (data from Pittock, 1980).

The dendrochronological record

Two types of fire records were compiled from fire-scar dates: (1) a master fire chronology indicating presence or absence of fire in a given year and (2) a record of annual variation in an index of regional fire activity. We derived a regional fire index (RFI) by assigning a rank of 0–4 to each year according to the following criteria: (0) no fires recorded in that year; (1) a single fire-scarred tree found; (2) two or more fire-scarred trees found in the same small (c. 100 ha) sampling area; (3) two or more fire-scarred trees found in a single large (c. 1000 ha) sampling area or in different small sampling areas; and (4) two or more fire-scarred trees in different large sampling areas (for this purpose S1, S2 and S3 were considered part of the same large sampling area as L1).

For the pre-instrumental period, a tree-ring index of moisture availability was derived from five A. chilensis tree-ring chronologies from sites near the forest–steppe ecotone (Fig. 1). Four of the chronologies (Cuyuq Manzano, Cerro Los Leones, Rucachori, and Estancia Teresa) were based on tree-ring collections by LaMarche et al. (1979), but were re-analysed by Villalba (1990) using standard contemporary dendrochronological methods (see below). Prior analysis (Villalba, 1990) had shown that reduced growth of A. chilensis indicated warm and dry springs and early summers which also corresponded to more southerly locations of the south east Pacific anticyclone. For this study, the four chronologies from LaMarche et al. (1979) were combined with an additional A. chilensis chronology from one of the fire-scar sampling areas (S2). Ring-width chronologies were produced using standard dendrochronological techniques and the computer program ARSTAN (Cook & Holmes, 1984; Cook, 1985). Principal components analysis (Cooley & Lohnes,
1971) was performed on the residuals from autoregressive modelling of the tree-ring series (Cook, 1985). Mean monthly temperature, precipitation and water balance were correlated with the amplitudes of the first axis from the principal components analysis of *A. chilensis* chronologies. The results (Fig. 3) indicate that the regional pattern of growth for this tree species is positively correlated with spring and summer precipitation and water balance, and negatively correlated with temperature of the previous and current growing seasons (Fig. 3). Thus, the amplitudes of the first principal component axis are used as a tree-ring index of moisture availability during the current and previous fire seasons. Positive values of the index indicate above average moisture availability, and negative values indicate below average moisture availability.

Tree-ring reconstructed moisture conditions during and prior to different fire events were analysed by superposed epoch analysis (Bauman & Swetnam 1990; Swetnam & Betancourt, 1990; Swetnam, 1993). Mean values of the previously described tree-ring index of moisture availability (i.e. the amplitude of the first principal component axis) were calculated for an 8-year window starting 5 years prior to and ending 2 years after each fire event for the period 1820–1974. The pre-1820 period was not analysed because of the small number of fires (only fourteen fire dates accumulated over the 1722–1820 period). The resulting time series pattern of moisture availability associated with fire years was statistically evaluated by running 1000 Monte Carlo simulations that randomly picked dates of simulated events, calculated expected means and provided 95%, 99% and 99.9% bootstrap confidence intervals against which mean values of the tree-ring index during fire years were evaluated. To adjust for varying numbers of fires, the number of simulated events equals the number of actual events (Mooney & Duval, 1993; Swetnam, 1993). Separate superposed epoch analyses were performed for all fire years dated by fire scar and all non-fire years, separately for the xeric woodland and for the mesic forests, and for both vegetation regions combined. To discriminate between years of abundant and extensive fires, the same analyses were performed for years of different regional fire indexes.

**RESULTS**

**Instrumental weather/fire report records: 1940–88**

In the Nothofagus forest zone, in ten of the forty-nine years analysed the area burned was >1000 ha, resulting in an average of 2.1 years per decade characterised as years of ‘high fire activity’. Years of ‘low fire activity’ (<10 ha burned) occurred 29 times, or on average 6.0 years per decade in the same zone. In contrast, in the dry vegetation zone during the 1940–88 period there were only 4 years during which >1000 ha burned, or on average 0.8 years per decade of high fire activity. There were only 21 years during which the area burned was <10 ha, or on average 4.4 years per decade of low fire activity. Thus, in the dry vegetation zone years of moderate fire occurrence were more common (4.8 such years per decade). The strongly bimodal distribution of area burned in Nothofagus forests may be an indicator of a climatic threshold beyond which the area burned in a given year increases abruptly.

Correlation analysis showed in general a stronger relationship between annual area burned and climatic variables in wet Nothofagus forests than in xeric Austrocedrus woodlands and grasslands (Fig. 4). In the dry vegetation zone, annual area burned correlates only weakly ($r = -0.24$, $P < 0.05$) with the mean temperature of the previous two growing seasons and the mean precipitation of the current fire season. In the wet vegetation zone, annual area burned correlates significantly with the mean temperature of the previous two growing seasons and the mean temperature of the current fire season ($r = -0.4, P < 0.001$).
FIG. 5. Intensity and location of the subtropical anticyclone in the south east Pacific during years of high vs. low fire activity in wet Nothofagus forests in Nahuel Huapi and Lanín National Parks, northern Patagonia. (a) Mean (+SE) sea level atmospheric pressure (millibars) at Punta Galera Chile (1911–60) over 23 months prior to the fire season. (b) Mean (+SE) latitudinal position of the anticyclone (1943–62) along coastal Chile over the 23 months prior to the fire season. High fire activity years had >100 ha burned (1940–88) or a regional fire index of 4. Low fire activity years had <10 ha burned or a regional fire index of 0. Sample sizes in (a) and (b), respectively, are fifteen and nine for high fire years and twenty and nine for low fire years. Pressure data are from Pitts (1980).

$P<0.05$ with the five-month moving average of aridity indices centered on December (i.e. the Oct.–Feb. period) of the current fire season. This negative correlation corresponds to a more or less immediate response of fire to drought conditions during the fire season. In contrast, in the Nothofagus forest zone, area burned is much more strongly, negatively correlated with the aridity index for the Oct.–Feb. period of the current fire season ($r = -0.45$, $P<0.001$). In these wet forests, there is a significant correlation with all 5-month periods beginning in August to November and ending in December to March of the current fire season ($P<0.05$). Area burned in the wet forests also correlates negatively with the aridity index during the August to December period one year prior to the fire season (Fig. 4). Long and pronounced drought periods including months which normally are moist (e.g. August to October) appear to be important in desiccating the coarse fuels of these forests. In the dry vegetation zone, in strong contrast, area burned is positively correlated with spring and summer aridity indices 1 and 2 years prior to the fire season. Although these correlations are not statistically significant ($P>0.05$), their consistency suggests that fire in this zone is favoured by increased production of fine fuels (e.g. grasses) during moister growing seasons 1–2 years prior to a drier than average fire season.

For the wet forest area, years of high vs. low fire activity are characterised by somewhat different synoptic weather patterns (Fig. 5). Years of high fire activity (i.e. >100 ha burned or a RFI of 4) in the wet forest zone are associated with higher atmospheric pressure during the previous winter and spring on the coast of Chile at the same latitude (Fig. 5a). The higher atmospheric pressure indicates a more intensely developed and more southerly located subtropical high pressure cell in the southeast Pacific during winter and spring (Fig. 5b). Additionally, and consistent with the prior analysis (Fig. 4), a more southerly position of the Pacific anticyclone during the winter–spring immediately prior to the fire season and also during the spring of the previous year is associated with high fire activity in Nothofagus forests. Thus, blockage of westerly storm tracks by a more southerly located Pacific anticyclone in some years creates dry conditions for
TABLE 2. Comparison of fire season climatic variables that maximized the significance of t tests of differences in means for years with (+) and without (−) lightning-ignited fires in Nahuel Huapi, Lanin, Lago Puelo and Los Alceres National Parks over the period 1940–88. Climatic data are from the Bariloche Airport station.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Significance</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec–Feb mean temperature</td>
<td>P&lt;0.001</td>
<td>&gt;T_{Dec-Feb}(−)</td>
</tr>
<tr>
<td>February temperature</td>
<td>P&lt;0.005</td>
<td>&gt;T_{Feb}(−)</td>
</tr>
<tr>
<td>Dec–Feb integrated water balance</td>
<td>P&lt;0.01</td>
<td>&lt;WB_{Dec-Feb}(−)</td>
</tr>
<tr>
<td>February water balance</td>
<td>P&lt;0.01</td>
<td>&lt;WB_{Feb}(−)</td>
</tr>
<tr>
<td>December precipitation</td>
<td>P&lt;0.05</td>
<td>&lt;P_{Dec-Feb}(−)</td>
</tr>
</tbody>
</table>

widespread fires.

Mean climatic parameters were compared for fire seasons with and without lightning-ignited fires. For the period 1940–88, mean monthly temperature, precipitation and water balance were compared for fire seasons (December to February) in which lightning-ignited fires occurred vs fire seasons lacking lightning-ignited fires (Table 2). Years in which lightning-ignited fires occurred had significantly warmer (P<0.001) and drier (P<0.05) summers (particularly during the month of February) and had more negative water balances (P<0.01) than those in which no lightning-ignited fires occurred. The more southerly location of the subtropical anticyclone allows the incursion of tropical air masses from the north east; this results in greater convective activity and, therefore, in more thunderstorms and lightning. Thus, the southward shift of the high pressure belt promotes greater fire occurrence in the wet forest zone both by creating drier weather which desiccates fuel and by increasing the frequency of lightning.

Dendroclimate/fire-scar records: 1820–1974

A total of 327 fire scars were dated precisely mainly on Austrocedrus chilensis and Nothofagus dombei and less commonly on Fitzroya cupressoides and Pilgerodendron uviferum from 1820 to 1990 (Fig. 6). The tree-ring indices of spring and summer moisture availability derived from the A. chilensis ring-width chronologies (Fig. 3) permitted analysis of the influences of annual climatic variability on fire occurrence for the period 1820–1974.

For all sampling areas combined, the mean tree-ring moisture availability index during fire years is significantly below the long-term mean (P<0.001, 74 events), and that for non-fire years is significantly above the average (P<0.001, 82 events) (Fig. 7a, b). Given the growth responses of A. chilensis to climatic fluctuation (Fig. 3), this indicates that fires historically occurred during unusually hot and dry spring/early summers whereas unusually wet and cool spring/early summers generally lacked fires. Drought conditions during the previous year had a similar but weaker (P<0.05) influence on fire occurrence.

The influence of annual climatic variation on fire extent was evaluated by comparing mean tree-ring index values for years of different RFI indexes. Years of greatest fire extent (RFI>3) coincided with years of strong regional moisture deficit as indicated by low mean indices of moisture availability (P<0.001, fifty-three events; Fig. 7c). In contrast, mean tree-ring indices of moisture availability for years of only localized fires (RFI ≤2) did not differ significantly from the average moisture availability (P>0.05, twenty-one events).

In order to analyse the differential influence of climate variability on fire occurrence for different vegetation zones along the rainfall gradient, fire data were partitioned into two composite fire chronologies: a chronology for wet Nothofagus dombei-dominated forests (areas L4–7), and a chronology for xeric Austrocedrus forests and open woodlands (areas L1–3 and S1–3 (Table 1; Fig. 6). In both vegetation zones, mean tree-ring indices of moisture availability are significantly below average for fire years (P<0.001, 27 and 60 years, respectively). Nothofagus forest fire years, however, had a lower mean moisture availability index (−1.22) than fire years in the xeric zone (−0.82). Although the difference between these means was not statistically significant, they are consistent with the analysis of the 1940–88 instrumental record which showed that fires in the wet forest zone are associated with more intense drought than are fires in the xeric zone (Fig. 4). Over the period 1722–1974 tree-ring data indicate that only 55 of the 252 years, or 2.2±1.4 years per decade fell below an index of −1.22. In contrast, mean indices < −0.82, which imply potential opportunities for fires in the xeric zone, occurred in 76 of 252 years, or 3.0±1.5 years per decade. An interesting difference between fires in the wet forests and xeric woodlands, is that the latter tend to be preceded by a significantly moister growing season 2 years earlier (P<0.05), and then by drier conditions 1 year prior to and during the year of the fire season (Fig. 7f). This implies that increased production of fine fuels (mainly growth of grasses) 2 years prior to the fire season results in greater accumulation of fuels. When such periods of above-average moisture are followed by a 2-year period of below average moisture availability the likelihood of fire in the xeric zone is increased.

DISCUSSION

Influences of annual climatic variation on fire regimes

Both the historic (1940–88) and tree-ring records (1820–1974) of fire and climatic variation show differences in fire regime response to climatic variation between Nothofagus rain forests and xeric Austrocedrus woodlands. Fire in Nothofagus
rain forests is highly dependent on drought during the spring and summer of the same year in which fires occur and is less strongly favoured by drought during the spring of the previous year. The occurrence of fire in dry vegetation types near the steppe ecotone is less dependent on drought because even during years of normal weather fuels are thoroughly desiccated during the dry summer. In xeric *Austrocedrus* woodlands, fire occurrence and spread are promoted by droughts during the fire season and also appear to be favoured by above-average moisture conditions during the preceding one to two growing seasons which enhances fuel production. Thus, in the xeric woodlands fire is not simply dependent on drought but is favored by greater climatic variability over time scales of several years.

The differences in sensitivity of fire occurrence to climatic variation are consistent with the fuel characteristics of the wet forests and dry vegetation types. The wet forests are dominated by tall *N. dombeyi*, an evergreen broadleaved species with high wood water content. The typically deep soils of these forests are derived from volcanic ash and have high soil moisture storage capacities. Without intense droughts, the coarse woody fuels remain moist. In fact, our field observations as well as historical photographs (Veblen & Lorenz, 1988) show that the spread of fires which ignited in xeric vegetation types often stops abruptly where they encounter mesic forests. Once ignited, however, fire spread in the *Nothofagus* forests is facilitated by the horizontal continuity of fuels. Greater fuel continuity probably explains the four-fold greater frequency of years between 1940 and 1988 in which more than 1000 ha burned in *Nothofagus* forests compared to dry vegetation types. The greater frequency of years of moderate area burned (10 to 1000 ha) in the dry vegetation zone is probably at least partially a consequence of less continuous fuels. For example, we have observed that fires that ignite in the highly fire-prone shrublands (Veblen & Lorenz, 1988; Veblen *et al.*, 1992) sometimes do not spread into adjacent xeric grasslands where fuel is limited, especially by livestock grazing.
FIG. 7. Mean tree-ring index moisture availability for all vegetation types during fire years (a), non-fire years (b), years of extensive fires (c), years of localized fire (d) and for fire years in wet Nothofagus forests (e) and fire years in dry vegetation types (f). The 8-year window includes values for 5 years prior to and 2 years after the fire season. Years of extensive fires have regional fire indices (RFI) ≥3, and years of localized fires have RFIs of 1 or 2. Bootstrap 95, 99 and 99.9% confidence intervals derived from Monte Carlo simulations indicate the significance of departures from the long-term mean (1820–74) (*P<0.05, **P<0.01, ***P<0.001). Sample sizes are 74 in (a), 81 in (b), 27 in (c), 60 in (d), 53 in (e) and 21 in (d).

In the Nothofagus forests, the dominance of the understoreys by 2–6-m-tall Chusquea bamboos, probably influences their susceptibility to fire under varying climatic conditions. These bamboos have high annual levels of micro-litter production and high standing crops (Veblen, 1982), which provide abundant and easily desiccated fine fuels. The life cycle of these bamboos could confound the detection of influences of climatic variability on fire occurrence. For example, the bamboos synchronously flower and die over areas of at least hundreds of km² at variable intervals (but of at least several decades). Massive flowerings and deaths of Chusquea reported in the Nahuel Huapi area about 1900 and 1940 (Pearson, Pearson & Gomez, 1994) must have provided immense quantities of dry fuel, which probably further promoted fire occurrence for the following several years. Although in a normal summer the bamboo understory of the Nothofagus forests remains relatively moist and adds to the fire resistance of these forests, during intense drought or after a synchronous flowering the abundant bamboo fuels probably increase the likelihood of crown fires.

In contrast to the Nothofagus forests where mean annual precipitation is well over 2000 mm, the Austrocedrus woodlands occur under mean annual precipitation of ca. 700–1700 mm (Barros et al., 1983). In the dry Austrocedrus woodlands, soils are thin and their moisture storage capacity is relatively low so that even during normal summer droughts fuels become extremely dry. In this zone the herbaceous vegetation becomes sufficiently dry in all years so that fire occurrence may be more controlled by ignition frequency than by fuel moisture conditions. However, fuel production and accumulation also influence fire occurrence in this semiarid environment. Moister conditions 1–2 years prior to the fire season appear to favour fire by promoting the growth of grasses and other fine fuels. This implies that in such xeric habitats, fire occurrence is not simply related to drought, but to greater climatic variability at time scales of a few years. Similarly, in moderately xeric coniferous forests in the south western United States wetter than average conditions characterize the two years prior to fire occurrence (Baisan & Swetnam, 1990).
The analyses presented here of the influence of climatic variation on fire regimes in northern Patagonia consider two overlapping time periods: 1940–88, based on instrumental weather records and documentary fire records; and 1820–1974, based on tree-ring records of fire and moisture availability. There are, however, slight differences in the instrumental and tree-ring datasets in the relationship of fire to the previous year's climatic conditions. Although the tree-ring record shows the influence of drought during the previous year when all fires are considered, in the wet forests no such influence was detected even though it was evident in the instrumental record. Similarly, in the xeric vegetation zone the tree-ring record shows a positive correlation of fire with moisture availability 2 years prior to the fire season, whereas the instrumental record shows a positive correlation (but not statistically significant) for both 1 and 2 years prior to the fire season. Possible methodological explanations for these discrepancies are slight differences in the recording of fire in the xeric vegetation types between the two datasets. For example, the National Parks' fire records include grassland fires, whereas in the tree-ring record it would not have been possible to record all grassland fires due to the absence of trees. Thus, the tree-ring record of fire in the dry vegetation zone failed to record some grassland fires, which would be expected to be more sensitive to fine fuel accumulation during moister periods. A second potential methodological explanation for the discrepancy between the results of the tree-ring and the instrumental records is the correlation of the radial growth of *Austrocedrus* with climatic variables over 2 years (Fig. 3). Thus, separation of the climatic effects on tree growth (and, hence, on the moisture availability index) of consecutive years may not be feasible.

The region between c. 39°S and 42°S in northern Patagonia lies near the southern limit of influence of the summer position of the subtropical south east Pacific anticyclone that strongly governs the influx of moist Pacific air into the continent. Year-to-year variations of continental-scale circulation patterns influence local climate and, in turn, affect fire regimes in northern Patagonia. When the Pacific anticyclone is strong and located further south, it blocks the inflow of moist westerlies into northern Patagonia and produces drier than normal conditions. The blocking of wet westerlies not only creates conditions favourable to fuel desiccation, but also allows the incursion of humid tropical air masses from the north east which promotes convective activity and lightning ignitions. Similar large-scale circulation anomalies have been shown to influence the occurrence of fire in the southern Canadian Rocky Mountains (Johnson & Wowchuck, 1993) and the Southwest US (Swetnam & Betancourt, 1990).

**Climatic v. human-caused changes in fire regimes in northern Patagonia**

Charcoal particles in sedimentary samples from northern Patagonia to Tierra del Fuego establish the antiquity of fire in this region to at least as early as 10,000 years BP (Heusser, 1987; Heusser et al., 1988). Although the proportion of prehistoric fires ignited by lightning v. those set by humans is not known, it is evident that with the arrival of aboriginal humans the frequency of burning increased (Heusser, 1987).

Variation in fire occurrence in northern Patagonia at a multi-decadal scale over the past two centuries has previously been correlated with changes in settlement and land use practices of the human population (Veblen & Lorenz, 1988; Veblen et al., 1992). Prior to the 1890s, the Indian population frequently set fires in the *Austrocedrus* woodlands and adjacent steppe for hunting purposes. From c. 1890 to 1920 extensive areas of wet forests were burned by European settlers in a failed effort to convert forests to cattle pasture. This increase in burning in the late nineteenth century is clearly reflected by fire scars (Fig. 6) and also in a thick charcoal layer in sediments at c. 41°S (Markgraf, 1984). Following the 1920s, fire suppression has become increasingly effective (Fig. 6). Given this general understanding of the role of humans in modifying fire regimes in northern Patagonia, the results of the present analysis are important in refining our understanding of the roles of humans v. climate in changing fire occurrence.

During the period of national park records (1940–88), human-set fires accounted for 85% of all fires and 79% of the area burned, and during the period covered by the tree-ring record of fires (i.e. since 1820) it is also likely that most fires were set by humans. Despite the preponderance of anthropogenic fires, annual climatic variation can still have a controlling influence on the occurrence and spread of fire, especially in the rain forest zone. For example, in the rain forest area L6, the year 1827 was exceptional in recording eighteen fire scars (of a total of twenty-four scars for the 1820–1974 period) which coincided with extreme moisture deficit during that year (tree-ring moisture availability index of −2.5). Thus, whether set by humans or set by lightning, extensive burning in this vegetation type coincided with unusual climatic conditions. The role of extreme drought in promoting fire in the wet forest zone may override the effects of fire suppression. For example, during the fire suppression period the average number of years during which more than 1000 ha burned in the wet forest zone of the four National Parks has been 2 years per decade over the 1940–88 period; this is the same as the long-term average number of climatically defined opportunities for high fire activity in the wet forest zone (i.e. years with tree-ring moisture availability indices < −1.22) over the past 270 years.

Fire occurrence in the xeric vegetation zone, in contrast, is less constrained by climatic conditions and may be more dependent on human-caused ignitions. For example, during the 1850–99 period of increased fire frequency in the xeric *Austrocedrus* woodland zone (Fig. 6), the average moisture availability index was slightly above the long-term average (0.2). Thus, at a time-scale of 50 years climatic variation does not appear to account for this increase in fire frequency. The increase in burning beginning in the 1850s reflects increased Indian-set fires associated with the migration of Indians from southern Chile into northern Patagonia, and the increase in the 1890s reflects white settlement (Veblen et al. 1992). Nevertheless, during this half century of increasing human activity in northern Patagonia individual years of high fire activity coincide with low values of the tree-ring moisture index. For example, peaks in fire occurrence in 1877, 1893, and 1897 coincide with moisture index values of −2.9, −3.3, and −2.1, respectively.

Following the demise of the Indian population in the 1890s
white settlers intentionally burned forests in their attempt to create range for livestock, and consequently fires continued to be frequent and extensive until about 1920 (Fig. 6). The instrumental climatic record beginning in 1906 indicates that one of the severest droughts on record occurred from ca. 1911–17 (Veblen & Lorenz, 1988). Extensive fires associated with this drought were reported by contemporary observers (Willis, 1914; Rothkugel, 1916). Interestingly, most of the forests affected by those fires were wet Nothofagus forests, which reinforces the idea of a stronger climatic control on fire in wet as opposed to dry forest types. Thus, temporal variation in fire occurrence along this rain forest-to-xeric woodland gradient reflects both anthropogenic and climatic influences.

Studies of fire regimes and climatic variation, based both on historical records and on tree-ring or sedimentary evidence for prehistoric periods, are needed for the assessment of possible ecological effects of anthropogenic climate change (Overpeck et al., 1990). However, fire regimes in most regions are likely to reflect the effects of both climatic variation and changes in human activities. Nevertheless, it is often tempting to interpret changes in fire regimes simplistically as reflecting exclusively climatic variation or human activities. The results of the present study are an initial step in a developing strategy for distinguishing the potentially confounding influences of humans and climatic variation on long-term records of fire in northern Patagonia. An understanding of annual-scale climatic influences on fire frequency and extent is fundamental to explaining longer-term variations in fire regimes. This strategy also requires an understanding of differences between major vegetation types (e.g. rain forests vs xeric woodlands) in the nature of and sensitivity of responses of their fire regimes to climatic variation. This understanding provides the potential for utilizing longer-term datasets from different vegetation types to distinguish between human and climatic influences on fire regimes at multi-decadal to centennial scales along this rain forest-to-xeric woodland gradient.

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