ÉCOSCIENCE 13 (3): 342-350 (2006)

Climatic influences on fire in *Araucaria araucana–Nothofagus* forests in the Andean cordillera of south-central Chile[1]

Mauro E. GONZÁLEZ[2], Instituto de Silvicultura, Universidad Austral de Chile, Casilla 567, Valdivia, Chile,
e-mail: maurogonzalez@uach.cl
Thomas T. VEBLEN, Department of Geography, University of Colorado, Boulder, Colorado 80309, USA.

Abstract: Tree-ring records of fires were used to examine the effects of inter-annual climatic variability on fire occurrence in forests dominated by the fire-adapted *Araucaria araucana* in the Andes of south-central Chile. Instrumental as well as tree-ring proxy records of climate indicate that low moisture availability is the main factor influencing fire occurrence. Years of widespread fire are strongly associated with warmer and drier summers. Years of extensive fire also tend to be favoured by one or two preceding years of dry climatic conditions. The El Niño–Southern Oscillation (ENSO) and its strong influence over large-scale climatic features is an important factor promoting fire activity. Years of high fire activity coincide with warm and dry summers following El Niño events. Fire in the Araucarian region is strongly related to inter-annual climatic variation associated primarily with the coupled effect of ENSO events and variations in the intensity and latitudinal position of the southeast Pacific anticyclone.

Keywords: *Araucaria*, Chile, climatic variation, dendroecology, fire history, southern oscillation.

Résumé : Les cicatrices de feux dans les cernes des arbres ont été utilisées pour étudier les effets de la variabilité climatique interannuelle sur la fréquence des feux dans des forêts dominées par *Araucaria araucana*, une espèce adaptée au feu, dans les Andes du centre sud du Chili. Des données climatiques instrumentales ainsi que des données indirectes obtenues par la dendrochronologie indiquent qu'une faible humidité est le facteur principal influençant la fréquence des feux. Les années de grands feux sont fortement associées à des étés plus chauds et plus secs. Ces années sont favorisées par des conditions climatiques sèches au cours de l'année ou des deux années qui précèdent. Le phénomène ENSO (El Niño-Southern Oscillation) et sa forte influence sur le climat à grande échelle est un important facteur favorisant l'activité des feux. Les années où l'activité des feux est importante coïncident avec les étés chauds et secs qui font suite aux événements El Niño. Le feu dans la zone de l'*Araucaria* est fortement lié à la variation climatique interannuelle associée principalement à l'effet couplé d'événements ENSO et de variations dans l'intensité et la position de l'anticyclone du sud-est du Pacifique.

Mots-clés : *Araucaria*, Chili, dendroécologie, histoire des feux, Oscillation Australe, variation climatique.

Nomenclature: Marticorena & Rodríguez, 1995.

Introduction

Strong linkages between climatic variation and fire regimes across seasonal or annual to multi-decadal or century scales have been demonstrated by means of charcoal sediments and tree-ring records (Clark, 1990; Johnson & Larsen, 1991; Swetnam, 1993; Heyerdahl, Brubaker & Agee, 2002; Huber & Markgraf, 2003). Climate variations affect fire regimes through their influences on fuel types and quantities, fuel conditions, and ignition patterns (Flannigan & Harrington, 1988; Flannigan & Wotton, 1991; Granström, 1993). Multi-century tree-ring records have shown that fire regimes in western North America are sensitive to the broad scale changes in atmosphere-ocean conditions such as the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), which oscillate at annual and decadal scales, respectively (Swetnam & Betancourt, 1998; Veblen, Kitzberger & Donnegan, 2000; Norman & Taylor, 2003; Westerling & Swetnam, 2003; Hessl, McKenzie & Schellhaas, 2004).

In the temperate latitudes of southern South America, tree-ring–based studies of fire history in relation to broad-scale atmospheric patterns are currently only available for the northern Patagonian region on the eastern side of the Andes in Argentina. In northern Patagonia, in the rain shadow of the Andes there is a steep west-to-east decline in precipitation; mesic *Nothofagus* forests in the Andes give way eastwards to xeric woodlands dominated by the conifer *Austrocedrus chilensis,* which is a good tree-ring recorder of fire scars and of climatic variation. In northern Patagonia, years of widespread fire tend to coincide with reduced annual or spring–summer precipitation and with warmer springs–summers; major fire years also tend to lag episodes of increased moisture availability, which promote the growth of fine fuels, by one to a few years (Kitzberger & Veblen, 2003).

Annual and multi-decadal variation in wildfire occurrence in Patagonia has been linked to conditions in the tropical Pacific (ENSO) and to variations in mid- to high-

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[1] Rec. 2005-05-09; acc. 2005-12-06.
Associate Editor: Konrad J. Gajewski.

[2] Author for correspondence.

latitude atmospheric circulation patterns (Kitzberger, Veblen & Villalba, 1997; Kitzberger & Veblen, 1997; Veblen *et al.,* 1999; Kitzberger & Veblen, 2003). At *circa* 40° to 43° south in western South America east of the Andes, increased fire occurrence is associated with a more intense and southerly located southeastern Pacific anticyclone, which blocks the influx of Pacific moisture into the continent at this latitude (Kitzberger, Veblen & Villalba, 1997). ENSO events are a major influence on the subtropical anticyclone, which in turn influences moisture availability and fire activity (Aceituno, 1988; Kiladis & Diaz, 1989). Years of widespread fires tend to be associated both with late stages of the cold phase of the Southern Oscillation (SO; La Niña) and with warmer summers during the year following El Niño events (Kitzberger & Veblen, 1997; Veblen *et al.,* 1999). Thus, transitions from La Niña to El Niño events favour widespread fire occurrence. Similarly, lower precipitation, associated with increased wildfire, has been linked to below average sea level pressure at 50–60° south in the South American–Antarctic Peninsula sector of the southern ocean (Veblen *et al.,* 1999). High-pressure blocking events in this westerly circulation produce a northward incursion of cold polar fronts and are associated with high rainfall, based on tree-ring reconstruction of pressure and precipitation for the period 1746 to 1984 (Villalba *et al.,* 1997). Conversely, low pressure at 50–60° south is associated with low precipitation and increased fire in northern Patagonia (Veblen *et al.,* 1999).

In southern South America, the availability of fire-scar–recording tree species is limited. To date, comprehensive analyses of fire-climate relationships have been based mainly on tree-ring records of fire in *Austrocedrus* forests from east of the Andes (Kitzberger & Veblen, 2003) and have not been complemented by extensive tree-ring studies of fire history in Chilean forests (but see Lara *et al.,* 1999 and Aravena *et al.,* 2003). On the western side of the Andes in south-central Chile, the long-lived conifer *Araucaria araucana* is a fire-adapted species capable of forming fire scars and consequently is a potential source of long-term fire records in these forests (Veblen *et al.,* 1995). Recent research on fire ecology and spatial variations in fire severity in Andean forests in south-central Chile at *circa* 39° south has demonstrated the feasibility of tree-ring dating of fire scars on this conifer and the associated angiosperms *Nothofagus pumilio* and *N. antarctica* (González, Veblen & Sibold, 2005). Dendroecological evidence of past fires also provides the basis in the current study for examining long-term variations in fire occurrence in relation to local climatic variations and their potential teleconnections to broad-scale atmosphere–ocean conditions in the tropical and southeastern Pacific regions.

Araucaria araucana forests occur in the coastal mountains of Chile (*circa* 37° 40' to 38° 40' S) and on the western (Chilean) and, less extensively, on the eastern (Argentinean) side of the Andes (37° 45' to 40° 20'; Veblen *et al.,* 1995). The *Araucaria* forests studied here are located to the west and mostly to the north of the Argentinean *Austrocedrus* forests where fire history has previously been examined (Veblen *et al.,* 1995; Kitzberger & Veblen, 2003). The *Austrocedrus* woodlands studied in Argentina are at the juncture of the Andean foothills and the Patagonian plains (Kitzberger & Veblen, 2003), whereas the *Araucaria* forests studied here are located in the centre of the Andes and at higher elevations (1100 to 1500 m *versus* 500 to 1060 m). Thus, in the current study area, the Mediterranean-type precipitation regime results in abundant winter snow fall, providing a reliable source of moisture for spring plant growth. Nearby climate stations indicate that the region receives 2000 to 4500 mm precipitation annually, with nearly two-thirds falling during the winter and early spring (May–September; Miller, 1976). In contrast, the *Austrocedrus* forests studied in Argentina occur where mean annual precipitation varies from *circa* 800 to 2000 mm (Barros *et al.,* 1983; Kitzberger & Veblen, 2003). Towards the drier end of its distribution, the fire regime of *Austrocedrus* woodlands is limited by fuel abundance (Kitzberger, Veblen & Villalba, 1997; Veblen *et al.,* 1999) such that years of widespread fire often follow years of above average moisture availability by one to several years.

The differences in the locations and climate of dry *Austrocedrus* woodlands studied in northern Patagonia (Kitzberger & Veblen, 2003) and the *Araucaria* forests studied here create the opportunity to increase our understanding of the effects of climatic variation on fires across the Andes in this region. For example, the abundant and reliable snow fall in the *Araucaria* forests implies that fires are less likely to be limited by lack of fuels. Thus, years of more widespread fire are more likely to be related solely to drought in the months immediately preceding (winter–early spring) or coinciding with the fire season (late spring–summer) than with lagged effects of preceding moist periods. The more northerly location of this study area also implies that conditions in the tropical Pacific, rather than high-latitude circulation anomalies, should be more influential on drought and fire. In this study of the fire history of *Araucaria–Nothofagus* forests in south-central Chile we address the following questions: (1) How is fire occurrence related to variation in seasonal temperature and precipitation? and (2) How is fire occurrence related to broad-scale atmospheric conditions in the tropical Pacific (*i.e.,* ENSO)? We seek to understand how inter-annual climatic variation influences fire occurrence in this region of *Araucaria–Nothofagus* forests and to link the climatic variation to broad-scale atmospheric circulation anomalies.

Methods

STUDY AREA

The study area is located in the Andes of south-central Chile (39° 35' S, 71° 31' W) at elevations of 1100 to 1500 m on the north side of Lanin volcano in Villarrica National Park (Figure 1). The area is dominated by a west-coast maritime climate characterized by both high winter precipitation and relatively dry summers. Fires mainly occur during December–March. The nearest climatic station is Puesco at 700 m asl and circa 5 km northwest of the study area. According to the short record at Puesco (1987–2001), mean annual precipitation is 3150 mm, with 65% occurring in winter (between May to September), mainly as snow (Dirección General de Aguas, Ministerio de Obras Públicas, Chile). Since precipitation originates mainly from orographic uplift of westerly cyclonic storms, it is probably substantially

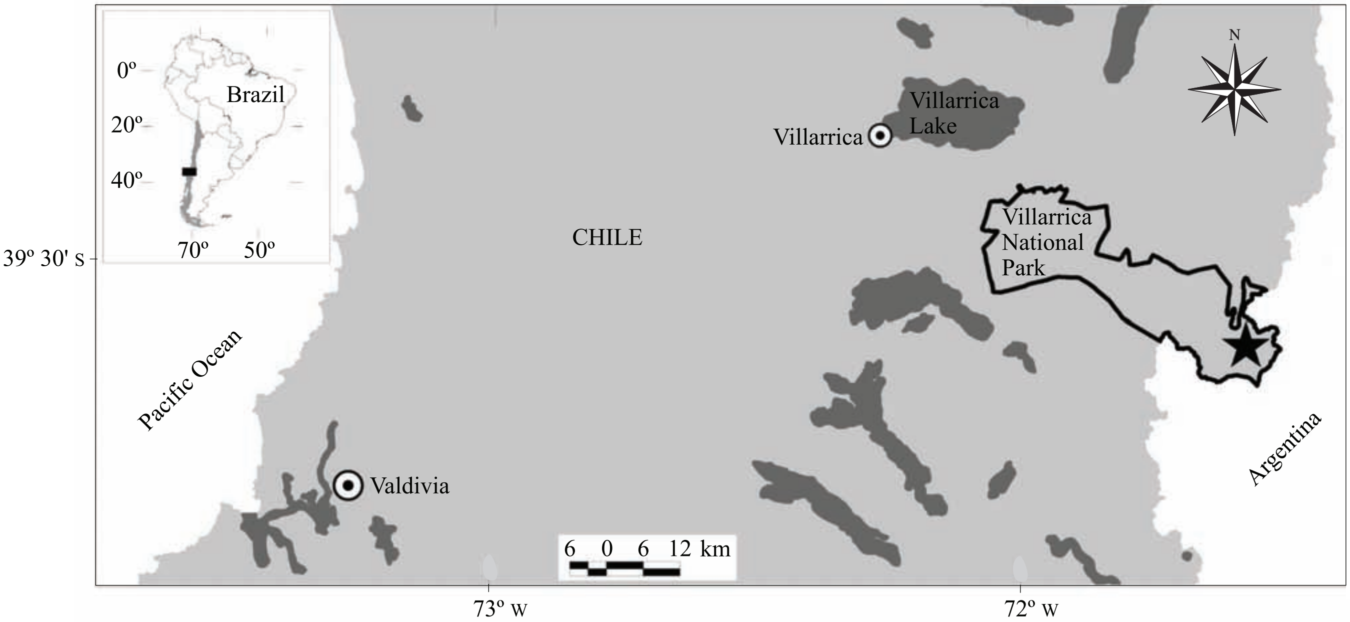

Figure 1. Map showing the area sampled for fire history in Chile.

greater at the elevation of the study area. The mean annual temperature at Puesco is 9.3 °C, with a minimum and maximum of 4.6 °C (July) and 13.9 °C (February), respectively.

Seasonality of temperature and precipitation in this region is strongly controlled by variations of the southeast Pacific anticyclone. During the summer a high-pressure cell is positioned along the west coast of Chile at 40° to 45° S, blocking the movement of moist air into the continent. During the winter it moves northward to be positioned at 35° to 40° S while cyclonic storms in the westerlies bring high precipitation into the continent (Schwerdtfeger, 1976; Taljaard, 1972; Pittock, 1980; Aceituno, 1988). Interannual climatic variability in south-central Chile is strongly related to changes in the intensity and latitudinal position of the Pacific anticyclone associated with ENSO variability. During warm El Niño events (the negative phase of the Southern Oscillation), greater winter westerly flow and precipitation occur on the Pacific coast of south-central Chile. Coincident with this phase of the SO, the anticyclone is weaker and shifted northward (Aceituno, 1988). In contrast, during cool La Niña events (the positive phase of SO), the anticyclone is stronger and positioned southward, blocking the westerlies and decreasing winter and spring precipitation. El Niño events are associated with above-average winter–spring precipitation and warmer summers, whereas La Niña events are associated with lower winter–spring rainfall and cooler, wetter summers (Aceituno, 1988; Kiladis & Diaz, 1989; Rutllant & Fuenzalida, 1991; Montecinos & Aceituno, 2003).

The vegetation of the study area ranges from mesic forests towards the west to more xeric woodlands towards the eastern side of the Andes. At this elevation (*circa* 1100 to 1500 m asl), populations of the long-lived conifer *Araucaria* occur in pure stands or in mixed forest types along with *Nothofagus*. *Araucaria* commonly occurs in mixed stands with the deciduous *N. pumilio*. On southern aspects, *Araucaria* also can occur mixed with the evergreen *N. dombeyi* and occasionally the deciduous *N. alpina*. At the bottom of the Lanin valley, which is subject to cold air drainage and has poorly developed and coarsely textured soils, *Araucaria* is commonly associated with *N. antarctica*. In more complex topography, mostly pure *Nothofagus pumilio* forests dominate the more mesic west and south part of the watershed.

Fire history chronology

In the study area, forest patches were intensively searched for fire-scarred *Nothofagus pumilio*, *N. antarctica,* and *Araucaria araucana* trees and partial cross-sections of single and multiple fire scars were extracted. Whenever possible, samples were collected in clusters of two or more trees to facilitate cross-dating. Locations of fire-scarred trees were recorded on a topographic map (1:25,000) using a hand-held global positioning unit (GPS). Processing of wedge samples followed standard procedures (Arno & Sneck, 1977; McBride, 1983). Fire dates were verified by visually cross-dating against marker rings from master tree-ring chronologies of the area and other nearby sites (R. Villalba: Estancia Pulmari; V. La Marche: Lago Tromen; R. Holmes: Estancia Mamuil Malal; International Tree-Ring Data Bank, NOAA). Fire scars from trees with suppressed growth were cross-dated by measuring ring widths and using the COFECHA computer program (Holmes, 1983). The numbers of samples included in the fire–climate analysis for *Nothofagus pumilio*, *N. antarctica,* and *Araucaria* were 74, 11, and 59, respectively. According to convention, the calendar dates of annual rings in the southern hemisphere are assigned to the years in which ring formation begins (Schulman, 1956).

Tree-ring chronologies

For the pre-instrumental period, a tree-ring index of moisture availability was derived from an *Araucaria arau-*

cana tree-ring chronology. Cores used to develop the ring-width chronology were visually and quantitatively cross-dated using tree-ring chronologies from nearby areas (same as indicated above).

The ring-width chronology developed for *Araucaria araucana* was standardized to reduce ring-width variances among and within cores by transforming ring widths into dimensionless index values (Fritts, 1976; Cook & Holmes, 1984; Cook & Kairiustis, 1990). The ARSTAN program was used to produce a residual chronology by successively fitting two trend lines or curves to the time series (double detrending) to remove the maximum amount of low frequency trend, thereby improving the estimate of the climatic signal in the series (Cook & Holmes, 1984). Residual chronologies are used in dendroclimatic studies because removal of the serial autocorrelation is required for some statistical analyses (Villalba, Veblen & Ogden, 1994).

ANALYSES OF CLIMATIC INFLUENCES ON TREE GROWTH

To establish the influence of climatic variation on tree growth of *Araucaria araucana* trees, we used correlation function analysis to compare variations in ring widths with monthly temperature and precipitation data from a combined regional climate record (Fritts, 1976; Blasing, Solomon & Duvick, 1984; ITRDB Program Library, 2002). A normalized regional climate record was created by averaging monthly standard deviations from climate stations at Temuco, Concepción, Valdivia, Punta Galera, and Collunco (Table I). Each record was evaluated for consistency by successively testing it for homogeneity against all other stations (Mann-Kendall homogeneity test; ITRDB Program Library, 2000). Furthermore, graphical comparisons showed similar patterns of mean monthly temperature and precipitation records across the climate stations.

In correlation function analysis, the statistical relationship between ring width and each monthly climatic variable is examined over the period common to the chronology and the instrumental climatic record (Villalba, Veblen & Ogden, 1994). For this analysis, we examined the relationship between ring indices and monthly climate data for a sequence of 17 months starting with January of the previous growing season and ending with May of the current growing season (*i.e.,* at the end of the current growing season).

TEMPERATURE AND PRECIPITATION RESPONSE TO SOUTHERN OSCILLATION INDEX (SOI)

Seasonal temperature and precipitation data were analyzed for their response to SOI using correlation functions (ITRDB Program Library, 2002). Correlation functions were determined separately for the predictands seasonal temperature and precipitation, with monthly SOI as the predictor. The SOI is based on differences in standardized sea-level pressure between Tahiti and Darwin, Australia (Ropelewski & Jones, 1987). Positive values of SOI indicate La Niña (cold) events and negative values indicate El Niño (warm) events. Similarly, the relationship between seasonal climate variables and monthly SOI was examined for a sequence of 17 months (*i.e.,* January of the previous year to May of the current year).

TABLE I. Climate stations used for comparing tree-growth response to climate variation. Sources: Servicio Meteorológico de Chile and Argentina; National Climatic Data Center, USA.

Station name	Location (Lat. and Long.)	Elevation (m)	Period of record Temperature	Period of record Precipitation
Collunco	39° 56', 71° 08'	875	1912–1989	1912–1989
Concepción	36° 46', 73° 06'	50	1951–1997	1876–1998
Punta Galera	40° 00', 73° 45'	40	1899–1960	-
Temuco	38° 42', 72° 44'	114	1951–1997	1963–1997
Valdivia	39° 48', 73° 21'	50	1941–1990	1853–1973

ANALYSES OF CLIMATIC INFLUENCES ON FIRE OCCURRENCE

To relate fire years with inter-annual climatic variation and the El Niño Southern Oscillation (ENSO), we used Superposed Epoch Analysis (SEA; Grissino-Mayer, 1995). SEA determines the relationship between fire events and climatic data (or climatically sensitive tree-ring chronologies) in the years prior to, during, and succeeding fire years. For statistical testing, 1000 Monte Carlo simulations were performed to produce average climate conditions in the defined window of years encasing the fire year. Confidence limits at 95, 99, and 99.9% were determined by a bootstrap method based on the simulated events (Grissino-Mayer, 1995).

To identify the relationships between climate and fire, we used the regional normalized (departure from the mean) climate record (Table I) and climatically sensitive tree-ring records. To assess seasonal climate influences on fire occurrence, normalized climatic data of temperature and precipitation were seasonalized in three-month averages for spring (*i.e.,* September through November) and summer (*i.e.,* December through February) using the computer subroutine SEA (ITRDB Program Library, 2002). To investigate relationships between climate and fire over longer time periods, we used the tree-ring proxy record of *Araucaria araucana* (1585 to 2000 AD) assembled for this study. To determine the relationship between fire occurrence and ENSO activity, three records were used: a) a tree-ring reconstruction of mean December, January, February (DJF) SOI from sites in the southwestern USA, southern Great Plains, Mexico, and Java, Indonesia (1706–1977; Stahle *et al.,* 1998); b) an observed, standardized DJF SOI over the period 1876–1998 (Allan, Lindesay & Parker, 1996); and c) a tree-ring reconstruction of the Niño 3 Index of tropical Pacific sea surface temperatures (SSTs) for the months of December through February of each year based on data from northern Mexico and Texas, USA (1408–1978; Cook, 2000). Using Superposed Epoch Analyses, we compared the instrumental and proxy records against fire years with at least three fire-scarred trees.

Results

TREE-GROWTH RESPONSE TO TEMPERATURE AND PRECIPITATION

Below-average temperature in winter and summer of the current growing season favours radial growth of *Araucaria araucana* (Figure 2). The association of above-average growth with cool winters may reflect greater snowpack depth and therefore enhanced spring moisture. Cooler springs–summers (November–April) clearly favour increased growth as does higher January (summer) precipi-

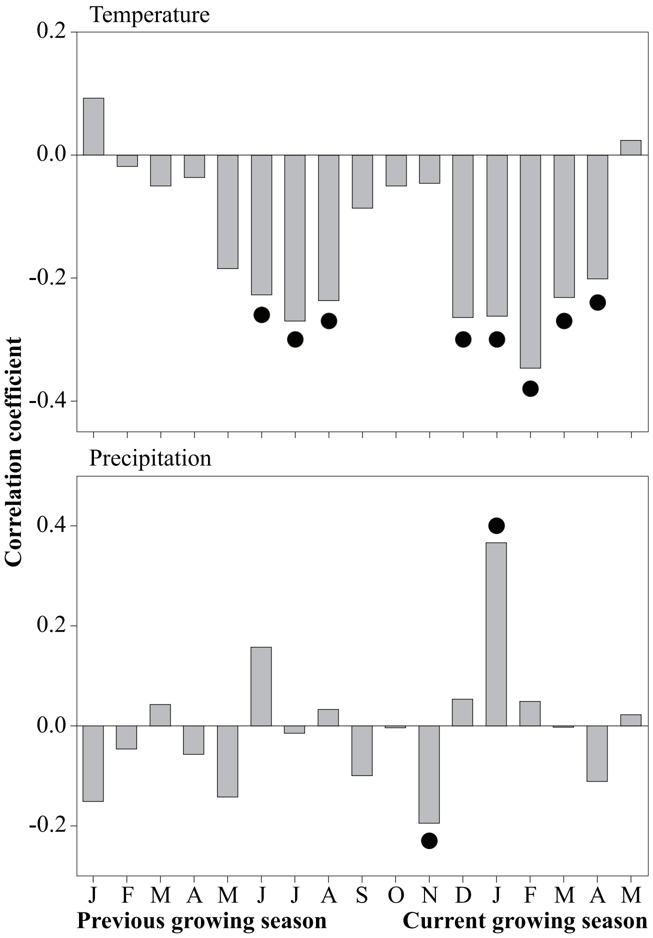

FIGURE 2. Correlation functions, based on residual chronologies, relating the effects of monthly mean temperature and precipitation (combined regional climate record; 1899–1997) on ring-width indices of *Araucaria araucana*. Positive correlation indicates that above-average tree growth is associated with above-average values of the climatic variable. Bars capped with dots indicate statistically significant correlations ($P < 0.05$).

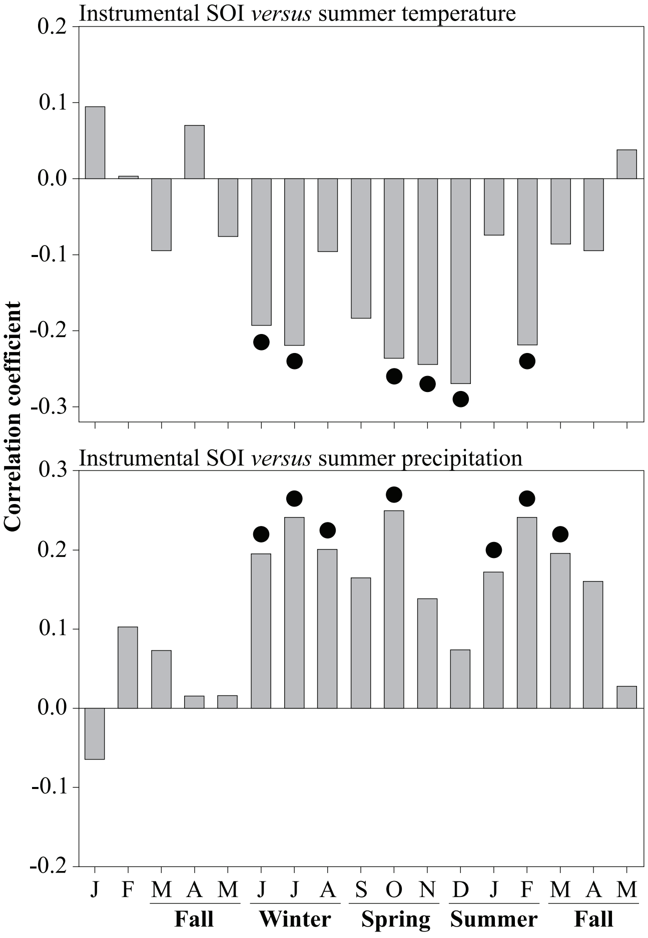

FIGURE 3. Correlation functions relating summer temperature and precipitation to monthly Southern Oscillation Index (observed SOI, 1876–1998). Bars capped with dots indicate statistically significant correlations ($P < 0.05$). Seasons are Fall = March–May; Winter = June–August; Spring = September–November; Summer = December–February.

tation (Figure 2). The negative correlation with November precipitation may reflect negative influences of cool temperatures or mechanical damage associated with late snow falls at the initiation of spring growth. Overall, the *Araucaria araucana* chronology represents a satisfactory proxy of variation in summer moisture availability in the current growing season.

TEMPERATURE AND PRECIPITATION RESPONSES TO THE SOUTHERN OSCILLATION

Summer temperatures and precipitation derived from the regional climate record are significantly associated with the monthly Southern Oscillation Index (SOI; Figure 3). There is a significant, negative correlation between summer temperatures and SOI (1902–1998) for winter (June and July), spring (October and November), and summer (December and February). Thus, above-average summer temperatures are related to negative SOI values (*i.e.,* El Niño) of the current summer and during most of the preceding seasons of the year. Analogously, summer precipitation is positively correlated with SOI (1877–1998) for the previous winter (June to August), spring (October), and the current summer (January to March). Thus, abundant summer rainfall is associated with positive values of SOI, which is indicative of La Niña conditions. Overall, the El Niño (La Niña) Southern Oscillation is strongly linked to the warmer (cooler) and drier (wetter) summer conditions in the region.

CLIMATE INFLUENCE ON FIRE OCCURRENCE

The total of *circa* 144 sections yielded 46 cross-dated fire-scar dates from 1446 to 1990 AD (González, 2002). An analysis of the influences of annual climatic variability was performed on the fire record for the period 1690–2000 (*i.e.,* starting in the years where at least four fire-scarred trees were present; the period of reliability *sensu* Grissino-Mayer, 1995).

Superposed Epoch Analysis of years with at least three fire-scarred trees in the study area indicated that summer precipitation (instrumental record; 1853–1997) is significantly below average during the fire year (Figure 4). Also, although not statistically significant, up to 2 y prior to and 1 after fire years, spring and summer precipitation tends to be below average. Analogously, spring and summer temperature tends to be above average during the fire, but this relationship is not statistically significant. The increased summer temperature 3 y after the fire event is probably

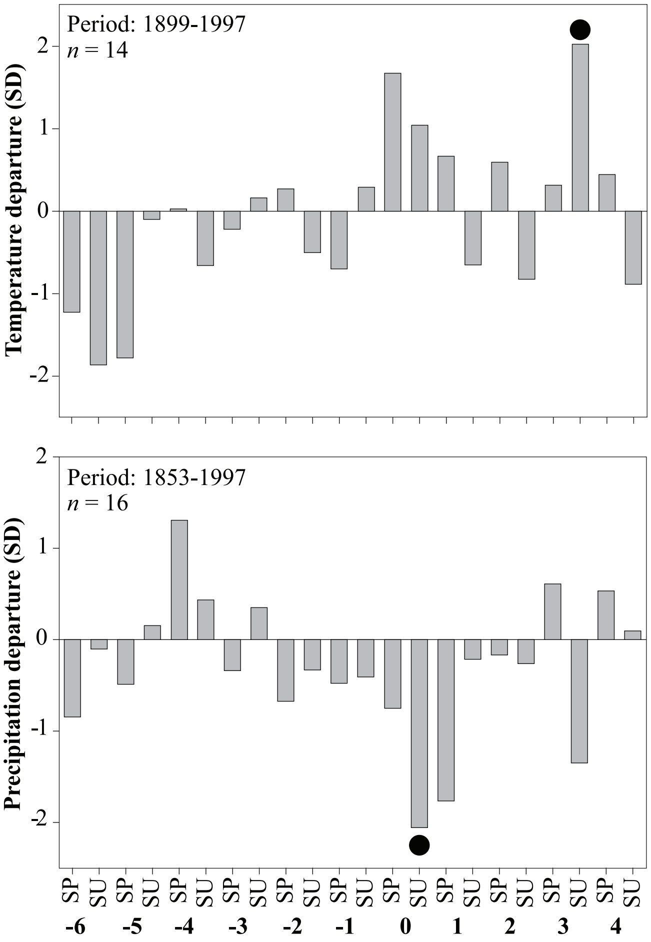

FIGURE 4. Spring and summer temperature and precipitation departures (SD) from compiled climate stations for 11-y windows (-6 to +4 y). Fire years (0) are years with at least three fire-scarred trees. Seasons are SP, spring (September–November); SU, summer (December–February). Bars capped with dots indicate statistically significant differences ($P < 0.05$).

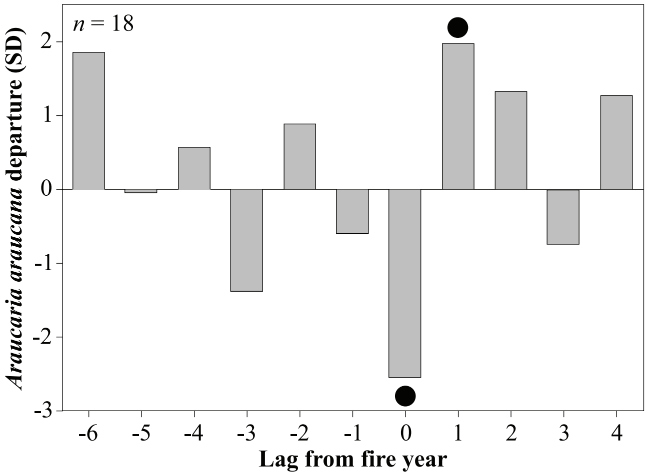

FIGURE 5. Mean departures (SD) from a tree-ring index of *Araucaria araucana,* from 1690 to 2000, for years prior to, during, and following fire years (0) with at least three fire-scarred trees. Positive values of the tree-ring index indicate high moisture availability. Bars capped with dots indicate statistically significant differences ($P < 0.05$).

an autocorrelation reflecting the periodicity of El Niño events. Overall, these results indicate that widespread forest burning is strongly associated with years of warmer and drier conditions, especially during the summer of the fire year (Figure 4). The pattern shown by fire years during the instrumental record is confirmed and extended to 1690 AD by Superposed Epoch Analysis of fire years against the *Araucaria* tree-ring chronology (≥ three trees scarred; Figure 5). Fire years are associated with below average growth of *Araucaria,* which indicates dry conditions, especially during the summer.

Over the period 1706–1977, years of widespread fire were years of negative departures for the tree-ring proxy record of SOI (Figure 6a). SOI shows significantly positive departures during the 2 y following the fire year. A similar pattern followed the observed summer (DJF) SOI and the sea surface temperature reconstruction of the Niño 3 Index of ENSO variability (Figure 6b and c). Overall, this pattern indicates that fire years coincide with strong/very strong El Niño events, represented by a warmer and drier summer (in the same dendrochronological year) that shifts to La Niña conditions in lag years 1 and 2. This pattern of fire occurrence during the late phases of El Niño events is consistent with the increased growth of *Araucaria* during the year following fire years (Figure 5).

Discussion

Instrumental as well as tree-ring proxy records of climate indicate that the presence of years with widespread fires in *Araucaria–Nothofagus* forests in south-central Chile depends on low moisture availability. Years of widespread fires are strongly associated with warmer and drier conditions during summer of the current growing season. Moreover, these results show that low fire-season rainfall in the preceding 1 or 2 y tends to increase fire occurrence. These results differ, as expected, from the xeric *Austrocedrus* woodlands in northern Patagonia, where preceding periods of increased moisture availability favoured fire, apparently by increasing fine fuel quantity (Kitzberger, Veblen & Villalba, 1997). Thus, in our study area, fire occurrence is less limited by fine fuel availability than it is by fuel desiccation. This is consistent with findings for wetter forest types on the eastern side of the Andes, where long and pronounced droughts are important in desiccating coarse fuels and thus favouring large fires (Kitzberger, Veblen & Villalba, 1997; Kitzberger & Veblen, 2003). In addition, widespread fires in the wet forest zone there have been associated with a more developed and southerly located Pacific anticyclone immediately prior to the fire season (winter–spring) and during the previous year (spring). Thus, successive summers of low moisture availability appear to promote sufficiently dry conditions favourable to these large fires.

The El Niño–Southern Oscillation (ENSO) is the primary source of variation on the southeast Pacific anticyclone, which in turn influences weather and fire activity in south-central Chile. In our study area, reconstructed and observed records of the SOI indicate a strong relationship between ENSO and fire activity. Years of widespread burning in this region are associated with negative departures of SOI

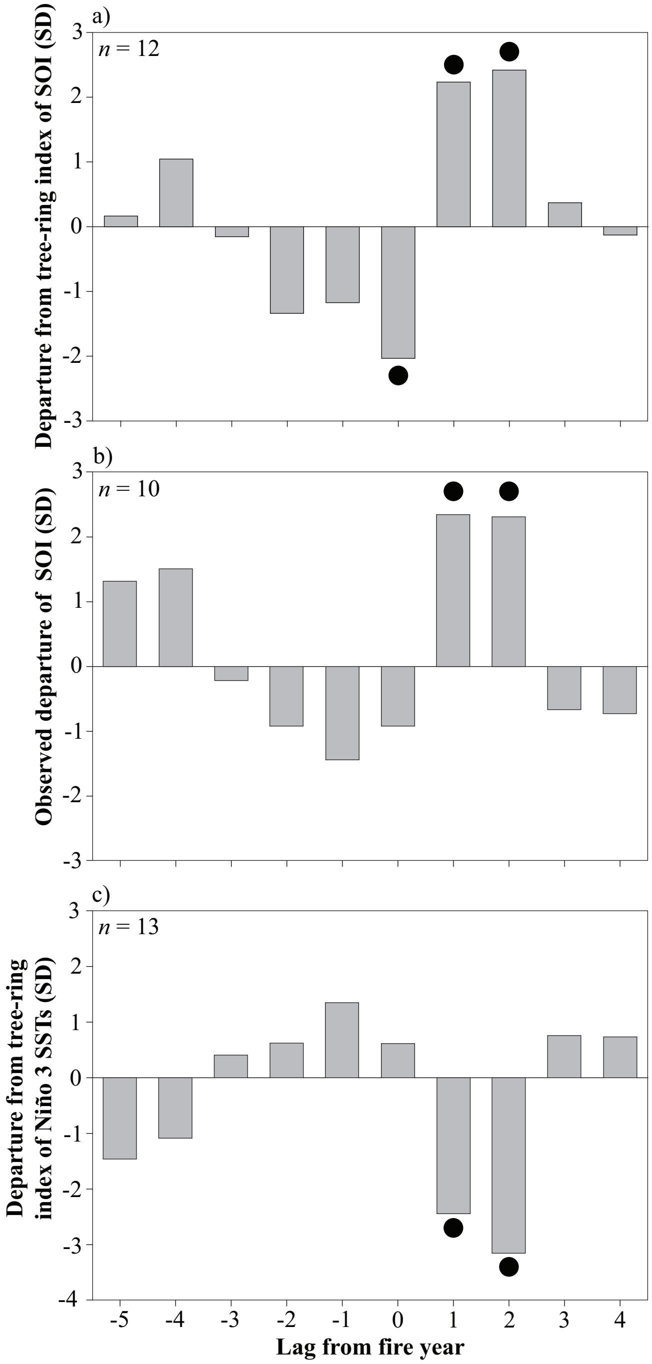

Figure 6. Mean departures (SD) from (a) a tree-ring reconstruction of the winter SOI from 1706–1977 (Stahle *et al.,* 1998); (b) observed December–January–February SOI over the period 1876–1998 (Allan, Lindesay & Parker, 1996); and (c) a tree-ring reconstruction of Niño 3 Sea Surface Temperatures (SSTs) for the months of December through February (1408–1978; Cook, 2000) for years prior to, during, and following fire occurrence. Fire years (0) are years with ≥ 10% and three fire-scarred trees. For figures a and b, positive and negative values indicate La Niña and El Niño conditions, respectively. The opposite applies for c. Bars capped with dots indicate statistically significant differences ($P < 0.05$).

during the fire season and with positive departures during the following 2 y. Sea surface temperatures (Niño 3 index) become significantly low in the 2 y following fire events. Overall, this implies that fire years occur during the late phases of El Niño events, when summers are warm and dry, and when the ENSO system is in transition to La Niña phase (Kiladis & Diaz, 1989; Diaz & Kiladis, 1992; Daniels & Veblen, 2000). This is consistent with the association of the negative SOI (*i.e.,* warm phase) with high winter–spring precipitation in the mid-latitudes of Chile (Aceituno, 1988; Rutllant & Fuenzalida, 1991) and with warmer summers in this region (Villalba, 1994; Montecinos & Aceituno, 2003). During El Niño events the strength and position of the Pacific anticyclone blocks zonal and meridional flow, resulting in low summer rainfall (Aceituno, 1988).

Average sea level pressure at 50–60° s in the southern ocean sector has been shown to affect precipitation and fire occurrence in northern Patagonia (40–43° s; Veblen *et al.,* 1999), but it could not be significantly linked to fire occurrence in the *Araucaria* forests (González, 2002). Nevertheless, the tendency for high-latitude atmospheric pressure to be negative during a 1- to 3-y period prior to fire years is consistent with the pattern established for northern Patagonia (González, 2002). Overall, circulation patterns at high latitude appear to have a smaller influence on drought and fire in the Araucarian region than they do at higher latitudes in northern Patagonia.

The results of the current study confirm and extend our understanding of the importance of ENSO variability as an influence on fire regimes in the temperate latitude forests of the southern Andes, as previously identified in northern Patagonia (Kitzberger & Veblen, 1997; Veblen *et al.,* 1999). In northern Patagonia, major fire years can be associated with either La Niña or El Niño conditions depending on the timing of the initiation of El Niño events (Veblen *et al.,* 1999). Years of widespread fire in northern Patagonia have been associated with late-initiating El Niño events that may bring warm summer temperatures without preceding increases in winter–spring precipitation. Alternatively, major fire years can result more directly from La Niña-induced dry winters–springs (Veblen *et al.,* 1999). In the *Araucaria* forests studied here, higher summer temperatures associated with El Niño events appear to play a greater role in creating conditions suitable for widespread fire. The apparently less variable influence of ENSO activity on fire in the *Araucaria* forests is probably also due to the lack of fire dependence on increases in fuel quantities associated with preceding wet periods. Although the importance of ENSO on climate and fire in our study is high, other atmospheric circulation anomalies over the Atlantic Ocean and at high latitudes and their teleconnections require further investigation.

The findings of the current study emphasize the importance of climatic variability at seasonal and inter-annual scales in governing years of fire occurrence. At multi-decadal time scales, not considered in the present study, trends in fire occurrence in this region are also associated with changes in the frequencies of ignitions set by humans. For example, an increase in fire frequencies after *circa* 1880 coincides with increased human activity in the region and is followed by the effects of fire exclusion after *circa* 1970 (González, Veblen & Sibold, 2005). Despite apparent changes in the frequencies of human-set fires during the past century, however, years of fire are still highly dependent on regional climatic variations associated with ENSO events.

Acknowledgements

For research assistance and advice we thank J. Sibold, J. Donnegan, and R. Villalba. Funding was provided by the International Foundation for Science of Sweden, Universidad Austral de Chile (bio-5-2005-8), the National Science Foundation of the USA (Award 0117366), the National Geographic Society (Awards 7155-01 and Grant 68-00), the Council for Research and Creative Work of the Graduate School of the University of Colorado (TTV), and Fundación Andes (Award C-13860). We thank CONAF for authorizing the sample collection in Villarrica National Park and Dirección General de Aguas (DGA) for providing the climatic data. Thanks also to E. Neira, who produced Figure 1.

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