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FIRE HISTORY IN NORTHERN PATAGONIA: THE ROLES OF HUMANS AND CLIMATIC VARIATION

Thomas T. Veblen,[1] Thomas Kitzberger,[2] Ricardo Villalba,[3] and Joseph Donnegan[1]

[1]*Department of Geography, University of Colorado, Campus Box 260, Boulder, Colorado 80309 USA*
[2]*Departamento de Ecología, Universidad Nacional del Comahue, Estafeta Postal Universidad, 8400 Bariloche, Argentina*
[3]*Departamento de Dendrocronología e Historia Ambiental, IANIGLA, CC 330, 5500 Mendoza, Argentina*

Abstract. The effects of humans and climatic variation on fire history in northern Patagonia, Argentina, were examined by dating fire scars on 458 trees at 21 sites in rain forests of *Fitzroya cupressoides* and xeric woodlands of *Austrocedrus chilensis* from 39° to 43° S latitude. Climatic variation associated with fires was analyzed on the basis of 20th-century observational records and tree ring proxy records of climatic variation since approximately AD 1500. In the *Austrocedrus* woodlands, fire frequency increases after about 1850, coincident with greater use of the area by Native American hunters. Increased burning, particularly in the zone of more mesic forests, is also strongly associated with forest clearing by European settlers from about 1880 to the early 1900s. The marked decline in fire frequency during the 20th century coincides with both the demise of Native American hunters in the 1890s and increasingly effective fire exclusion.

Strong synchroneity in the years of widespread fire at sample sites dispersed over a north–south distance of ~400 km indicates a strong climatic influence on fire occurrence at an annual scale. Tree ring reconstructions of regional precipitation and temperature show a steeply declining influence of climatic variability on fire occurrence from annual to multidecadal scales. It is the interannual variability in climate, rather than variations in average climatic conditions over longer periods, that strongly influences fire regimes in northern Patagonia. Although climatic variability overrides human influences on fire regimes at an interannual scale, human activity is an equally important determinant of fire frequency at multidecadal scales.

Climatic conditions conducive to widespread fire in both xeric *Austrocedrus* woodlands and *Fitzroya* rain forests are typical of the late stages of La Niña (cold phase of the Southern Oscillation) events, as indicated by trends in the Southern Oscillation Index and eastern tropical Pacific sea surface temperatures during the 1–2 years before and after fire event years. Years of extreme fire occurrence are associated both with dry winter–springs of La Niña events and with the warm summers following El Niño events. Years in which the southeast Pacific subtropical anticyclone is intense and located farther south than normal are years of enhanced drought and fire. Similarly, years of widespread fire in northern Patagonia are associated with variations in mean sea level atmospheric pressure at about 50°–60° S latitude in the South American–Antarctic Peninsula sector of the Southern Ocean, as reconstructed from tree rings for AD 1746–1984. Precipitation and, hence, fire regimes in northern Patagonia are significantly influenced by high-latitude blocking events, which drive westerly cyclonic storms northward. Variations at decadal to centennial time scales in major circulation features, such as ENSO activity and the meridionality of regional air flow at high latitudes, as well as changes in the degree of coupling of these features, influence climate and fire regimes of northern Patagonia.

Key words: anthropogenic influences; Argentina; Austrocedrus chilensis; *climatic variation; dendroecology; El Niño; fire history;* Fitzroya cupressoides; *global change; Patagonia; Southern Oscillation; tree rings.*

Introduction

Spatial and temporal variation of fire occurrence in landscapes is highly sensitive to changes in both climate and land use. For most landscapes, however, the relative roles of these components of global environmental change, in altering fire regimes, are poorly understood. Across a range of temporal and spatial scales, climatic variation and human activities influence fire regimes through their effects on ignition sources and fuel characteristics (Flannigan and Wotton 1991, Renkin and Despain 1992, Agee 1993, Granström 1993, Turner and Romme 1994). Reconstructions of fire regimes, based on stratigraphic charcoal and/or tree ring records, have demonstrated strong associations between fire occurrence and climatic variation at interannual to multidecadal scales (Clark 1989, 1990, Baisan and Swetnam 1990, Swetnam 1990, 1993, Johnson

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and Larsen 1991, Larsen 1996). Similarly, in some ecosystems, humans have changed fire frequencies, which, in turn, have altered fuel conditions and, thus, fire intensity and spread (Kershaw 1986, Savage and Swetnam 1990, Agee 1993, Covington and Moore 1994, Lehtonen and Huttunen 1997). Given that most landscapes and fire regimes have been altered to some degree by human activities, the distinction between anthropogenic vs. climatic influences on fire regimes is difficult. In this paper, we consider both humans and climate as sources of variation in fire regimes along a gradient from rain forest to xeric woodland, within a region of essentially homogeneous climatic variation. We stress the importance of both spatial and temporal scale in disentangling anthropogenic from climatic influences on fire regimes and in linking climate-induced changes in fire regimes to broad-scale climatic mechanisms.

Interannual climatic variations are likely to influence fire regimes through their effects on lightning frequencies and fuel desiccation, whereas longer term (decadal or longer) climatic variation will have a greater impact on fuel types and loads (Rothermel 1972, Chandler et al. 1983, Agee 1993). Similarly, synchroneity of fire occurrence at an annual scale across a broad region is likely to be due to high-frequency climatic variation rather than human activities (Swetnam 1993). Sometimes annual-scale variation in regional fire regimes can be linked to variations in large-scale features of atmospheric circulation, such as the El Niño–Southern Oscillation (ENSO) and blocking events in the midlatitude westerlies (Leighton and Wirawan 1986, Swetnam and Betancourt 1990, 1992, Nicholls 1992, Johnson and Wowchuk 1993).

Within a region of homogeneous climate, variations in fire regimes are related to stand- and landscape-level differences in fuels, topography, and human activities (Turner and Romme 1994). In many ecosystems, humans have significantly altered fire regimes so that new patterns of vegetation and, therefore, fuels have developed. In some ecosystems, aboriginal populations formerly set fires for hunting and other purposes, thereby increasing fire frequency (relative to lightning ignitions). These frequent surface fires maintained relatively open, park-like conditions in areas that today support dense forests after decades of fire exclusion (Barrett and Arno 1982, Kershaw 1986, Christensen 1993, Clark and Robinson 1993, Covington and Moore 1994). To distinguish among controls of fire regimes operating at different spatial scales, observations must be made across a range of local to regional spatial scales (Risser 1987, O'Neill 1988).

This paper is part of a series of studies of disturbance regimes and forest dynamics as influenced by climatic variation and humans across a range of spatial and temporal scales in northern Patagonia (about 37°–43° S latitude in southwestern Argentina; Veblen and Lorenz 1988, Veblen et al. 1992*a*, Kitzberger et al. 1997, Villalba and Veblen 1997*a*, *b*, 1998, Kitzberger and Veblen 1997, *in press*). Ten new fire records, in combination with 11 previously published fire records (Kitzberger et al. 1997, Kitzberger and Veblen 1997), provide a regional network of 21 fire history sites over 3° of latitude that extends from rain forests to xeric woodlands. We examine spatial variations in this fire history network and compare temporal variations with a broad array of instrumental and proxy records of variations in regional climate and large-scale atmospheric circulation features. Specifically, we address the following issues: (1) intraregional spatial variability and synchroneity of different types of fire event years and their possible relationships to climatic variations vs. human activities; (2) influences of seasonal to multidecadal periods of precipitation and temperature anomalies on fire regimes; (3) potential differences between rain forest and xeric woodland habitats in the sensitivity of their fire regimes to climatic variation; and (4) effects on fire regimes of anomalies in large-scale atmospheric circulation features such as ENSO events and blocking events at higher latitude.

Study Area

The sites sampled for fire history are on the eastern slopes of the Andes in southwestern Argentina at about 39°22′–43°11′ S latitude (Fig. 1). Most of the sites are in one of four large Argentine National Parks: Lanin, Nahuel Huapi, Lago Puelo, and Los Alerces National Parks (from north to south), which, together, extend from Andean rain forests eastwards to Patagonian steppe. Prior to permanent white settlement in the 1890s, Native American hunters used fire to hunt guanacos (*Lama guanicoe*) and other game, mainly in the xeric, open habitats of the eastern part of our study area (Cox 1863, Fonck 1900, Furlong 1964). In the 1850s, the occupation of northern Patagonia by Native American hunters increased due to European settlement of adjacent southern Chile and the emigration of many Native Americans across the Andes into Argentina (Cox 1863). Between about 1890 and the 1920s, European settlers burned extensive areas of Andean forest in this region (Willis 1914, Rothkugel 1916). Since the creation of the national parks in the 1930s, however, a policy of fire exclusion has been in effect. Although most modern fires are set by humans, lightning is an important source of ignition. Lightning ignited 8% of all fires ($n = 722$ fires) and accounted for 16.4% of the area burned (total area burned = 118 560 ha) in the four national parks from 1938 to 1996 (Administración de Parques Nacionales, *unpublished data*).

The study area encompasses the eastern foothills of the Andes and the adjacent Patagonian plains at an elevation of ∼800 m. Soils are mainly derived from recent volcanic ash that overlies Pleistocene glacial topography. To the west, the Andean Cordillera reaches elevations of >2000 m and has a pronounced rain shadow effect on moist Pacific air masses flowing from west

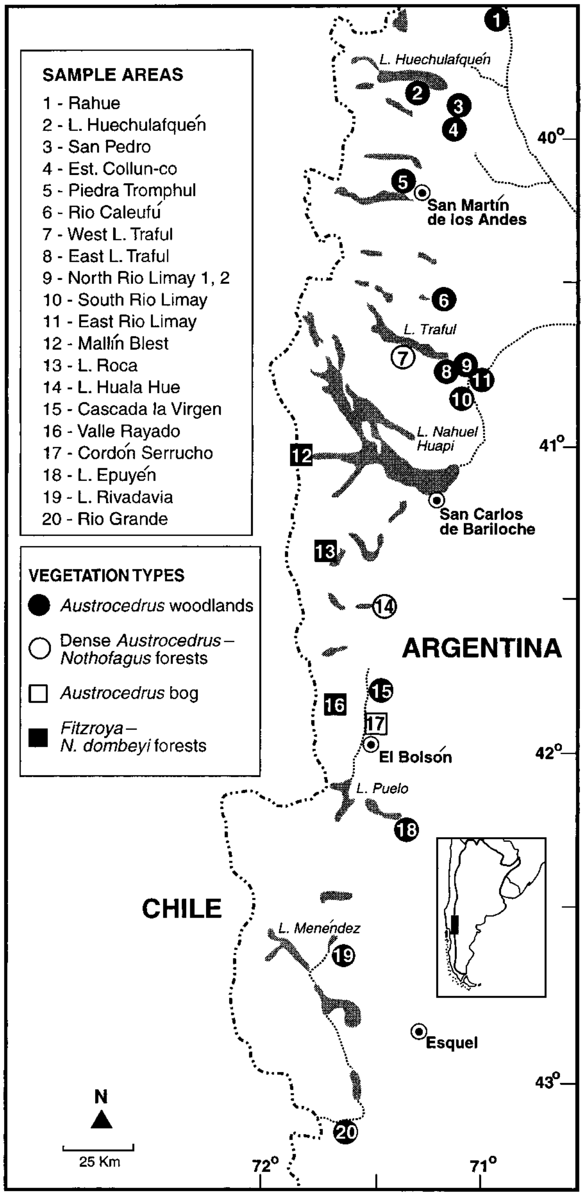

FIG. 1. Map showing the location of fire history sample sites. Details of the fire history sample sites are given in Table 1. Note that North Rio Limay was divided into two sites for analyses.

to east. Mean annual precipitation declines from >3000 mm near the continental divide to ~800 mm in the eastern foothills (Barros et al. 1983) and is reflected in a steep vegetation gradient from temperate rain forest to the Patagonian steppe (Veblen et al. 1992*a*). Toward the west, rain forests are dominated by 40–45 m tall evergreen *Nothofagus dombeyi* and have dense understories of 3–6 m tall bamboo (*Chusquea culeou*). The wettest areas (>3000 mm annual precipitation) south of about 41° latitude are dominated by the giant conifer *Fitzroya cupressoides*, which often attains ages >1500 yr (Lara and Villalba 1993, Veblen et al. 1995). Toward the east, *Austrocedrus chilensis* and *N. dombeyi* form extensive stands. Pure, dense stands of *Austrocedrus* occupy more xeric sites. At a mean annual precipitation of 800–1200 mm, *Austrocedrus* forms sparse woodlands near the ecotone with the Patagonian steppe (Barros et al. 1983).

In the zone of sparse *Austrocedrus* woodlands, mean monthly winter (June–August) temperatures are 2°–3°C, and summer (December–March) temperatures are 12°–14°C (data from the Bariloche Airport, 41°09′ S, 71°10′ W). Approximately 60% of the annual precipitation falls from May through August, and >90% of fires occur during the warm and dry season from October through March (Kitzberger et al. 1997). Seasonal and annual variations in precipitation in northern Patagonia (at about 40° S) are strongly influenced by changes in the intensity and latitudinal positions of the southeast Pacific anticyclone (Pittock 1973, 1980). In winter, the subtropical anticyclone is located near 33° S off the coast of central Chile, and steers westerly cyclonic storms into northern Patagonia. During the spring and summer months (November–March), the subtropical anticyclone migrates southwards to about 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. During the negative phase of the SO, the southeast Pacific subtropical anticyclone is weak and displaced to the north (Aceituno 1988). El Niño events are associated with higher than average winter–spring rainfall and warmer summers, and La Niña events are associated with the opposite conditions (Aceituno 1988, Kiladis and Diaz 1989).

The climate of northern Patagonia is also influenced by blocking events over the South America–Antarctic Peninsula sector of the Southern Ocean. The strength of teleconnections between middle and high latitudes in the South American sector varies with the degree of zonal vs. meridional air flow (Trenberth and Mo 1985, Villalba et al. 1997). There is a significant positive correlation between November–December precipitation in northern Patagonia and sea level atmospheric pressure at 50°–60° S in the South American–Antarctic sector of the Southern Ocean (Villalba et al., *in press*). High pressure at these latitudes is associated with blocking events in the westerly circulation, which drive cyclonic storms northward into northern Patagonia.

METHODS

Fire history chronologies

Master fire chronologies were developed from 20 sample sites that ranged in elevation from ~700 m to 1100 m (Fig. 1; Table 1). Each site was ~2 km^2 in area, except for North Limay (NL), where an area of ~4 km^2 was sampled. For comparison of fire intervals with the other sites, NL was divided into halves for computation of fire statistics, giving a total of 21 sites. Three of the sites were *Fitzroya*-dominated forest or bog in the western rain forest district, and 15 sites were sparse *Austrocedrus* woodlands near the ecotone with the steppe. One site of *Austrocedrus* bog was sampled near the ecotone with the steppe, and two sites of dense forests of *Austrocedrus* mixed with *Nothofagus dombeyi* and/or *N. antarctica* were sampled. Ring width variations in *Austrocedrus chilensis* from sites spanning the latitudes of the 21 fire history sample sites were highly correlated (i.e., all pairwise correlations were significant; $P < 0.05$) over the interval of AD 1775–1974, which implies a similar pattern of climatic variation (Villalba and Veblen 1997*b*).

All sample areas were searched for fire-scarred *Austrocedrus* trees, and partial cross sections were cut from live and dead trees until preliminary ring counts indicated many redundant dates (Arno and Sneck 1977). On sanded 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 master tree ring chronologies from nearby sites (McBride 1983). Fire scars from dead trees and from trees with severely suppressed growth were cross-dated by measuring ring widths and using the program COFECHA (Holmes 1983), which compares the ring width series with a master tree ring chronology from the nearby site. According to convention, the calendar dates of annual rings in the southern hemisphere are assigned to the year in which ring formation begins (Schulman 1956). Thus, a fire that occurs in midsummer (February) would be assigned to the preceding calendar year, because tree rings begin to form in October to December.

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. 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). High percentages of trees with fire scars of the same year indicate more widespread fires or larger relative areas burned during those years (Swetnam 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 a minimum of 2% and at least 10% of the recorder trees (i.e., ''fire-scar susceptible trees'' sensu Romme 1980) were scarred. We computed mean fire intervals (MFI; sensu Romme 1980) and standard deviations for CFIs.

Methods of relating fire history to climatic fluctuations

Observational fire and climatic records.—Data on areas burned each year, according to vegetation type and source of ignition (human vs. lightning), were compiled from Argentine National Park Service records from 1938 to 1996 for the Andean forests and adjacent steppe in national parks from about 39°22′ to 43°11′ S. Local climatic conditions during these fire event years were analyzed with superposed epoch analysis, based on the Bariloche Airport climate station, which is centrally located in our study area and is the only station in the region for which data are available through 1996. Two quantitative records were used as indicators of ENSO activity: the monthly Southern Oscillation Index (SOI) and sea surface temperature (SST). The SOI is based on differences in standardized sea level pressure between Tahiti and Darwin, Australia (Ropelewksi and Jones 1987), and is a broad-scale indicator of the SO. Positive values indicate La Niña (cold) events and negative values indicate El Niño (warm) events. Although closely coupled, not all Southern Oscillation events are associated with the regional El Niño (i.e., warming of the sea in the upwelling zone off the coast of southern Ecuador and Peru; Deser and Wallace 1987, Diaz and Pulwarty 1992). Consequently, SST for Niño regions 1 and 2, 80°–90° W and 0°–10° S off the west coast of South America, was used as an indicator of El Niño and La Niña events for the period 1950–1996 (National Oceanic and Atmospheric Administration). All climatic data (including the SOI and SST) were normalized for the respective periods of analysis. The other documentary record of ENSO activity was Quinn's (1992) compilation of regional El Niño events of moderate to very strong intensities for the period 1525–1987, based on observations of oceanographic and atmospheric conditions along the coast of southern Ecuador and Peru.

Superposed epoch analysis (Baisan and Swetnam 1990) was used to analyze mean climatic conditions for different types of fire event years (i.e., all fire years or years of greater fire extent based on percentages of trees scarred or hectares burned). Mean values of climatic parameters from instrumental records or tree ring proxy records were calculated for 5–9 year windows, including the year of the fire event. Mean values of climatic parameters during the fire event years were compared to variation in the complete record by performing Monte Carlo simulations that randomly pick years, calculate expected means, and provide 95% bootstrap confidence intervals (Mooney and Duval 1993, Grissino-Mayer 1995). In each case, the number of randomly selected years equals the number of actual fire years.

TABLE 1. Summary of information on fire history sample areas.

Study area	Site code	No. on map	Elevation (m)	No. dated series	Earliest fire scar date	Latest fire scar date	No. years with scars
Austrocedrus woodlands							
Rahue	Rahue	1	920	29	1439	1901	26
Lago Huechulafquen	Huechu	2	900	10	1641	1905	14
San PedroSn	Ped	3	880	6	1757	1854	6
Estancia Collun-co	Collun	4	850	16	1656	1908	13
Piedra Tromphul	Tromph	5	1060	15	1645	1957	21
Rio Caleufu	Caleuf	6	850	29	1592	1897	23
East Lago Traful	E Traf	8	1050	16	1867	1932	10
North Rio Limay 1	N Lim1	9	1060	49	1634	1980	29
North Rio Limay 2	N Lim2	9	1060	48	1747	1962	31
South Rio Limay	S Lim	10	1050	42	1641	1989	37
East Rio Limay	E Lim	11	1020	21	1573	1950	20
La Cascada la Virgen	C Virg	15	850	16	1810	1919	9
Lago Epuyen	Epuyen	18	600	17	1772	1923	15
Lago Rivadavia	L Riva	19	800	9	1783	1943	10
Rio Grande	R Gran	20	500	8	1871	1925	5
Dense *Austrocedrus–Nothofagus* forests							
West Lago Traful	W Traf	7	950	26	1897	1943	9
Laguna Huala Hue	Huala	14	900	28	1747	1950	9
Austrocedrus bog							
Cordon Serrucho	Serruc	17	750	7	1827	1980	6
Fitzroya–N. dombeyi forests							
Mallin Blest	Blest	12	950	4	1865	1950	6
Lago Roca	L Roca	13	850	27	1675	1952	7
El Valle Rayado	Rayado	16	1100	9	990	1877	6

Tree ring methods.—To examine possible intraregional variation in climate and fire history, composite *Austrocedrus* tree ring chronologies were created for the northern, central, and southern sample areas for comparison with fire history chronologies from the same areas. Four to six tree ring chronologies were selected for each sector from the 25 chronologies described in Villalba and Veblen (1997*b*) according to their proximity to fire history sample sites in each sector (Table 2). Mean residual chronologies were produced for each of the three sectors and were compared to temperature and precipitation records from nearby climate stations, using correlation function analysis (Blasing et al. 1984). Correlation coefficients were computed between ring indices and climate variables for a sequence of 17 months, starting with January of the previous growing season and ending with May of the year in which the ring was formed (i.e., at the end of the current growing season). For comparison with each composite *Austrocedrus* chronology, the climatic records used were Collun-co (1912–1989), Bariloche (1905–1990), and Esquel (1905–1988) for the northern, central, and southern sectors, respectively.

Fire occurrence was also related to three published

TABLE 2. Site and chronology characteristics of *Austrocedrus* tree rings used for the three composite chronologies.

Sector and site	Latitude (°S)	Longitude (°W)	Elevation (m)	No. trees	No. radii	Period (AD)
Northern sector						
Collunco	39°56′	71°08′	870	12	19	1596–1989
C. La Hormiga	40°03′	71°17′	920	13	26	1508–1989
C. Los Pinos	40°04′	71°02′	1100	29	40	1508–1989
P. Tromphul	40°07′	71°26′	1060	10	15	1823–1989
Central sector						
A. Minero	40°42′	71°16′	1050	10	16	1589–1991
Confluencia	40°42′	71°09′	1075	23	25	1723–1989
Cuyin Manzano	40°43′	71°08′	900	15	15	1543–1974
El Centinela	40°44′	71°06′	1050	30	39	1461–1989
Southern sector						
P. del Toro	41°32′	71°29′	1160	17	17	1741–1991
El Maiten	41°59′	71°15′	710	13	13	1690–1974
Est. Teresa	42°57′	71°14′	820	19	20	1540–1974
Nahuel-Pan	42°58′	71°13′	850	17	28	1567–1992
L. Terraplen	43°01′	71°34′	650	19	20	1700–1974
R. Futaleufu	43°11′	71°42′	470	8	19	1700–1992

Notes: Chronologies with periods ending in 1974 were collected by LaMarche et al. (1979) but were re-standardized by Villalba (1995). Descriptive statistics on all chronologies are given in Villalba and Veblen (1997*b*).

TABLE 3. Summary of fire interval statistics for the 1830–1929 period for all sample sites that had at least four recorder trees (i.e., fire-scarred trees) by 1830. Mean fire intervals (MFI) and their standard deviation (1 SD) are given in years for all fire years and for years in which scars occurred on ≥10% of the recorder trees (minimum of two fire scars).

	MFI		1 SD		Maximum fire interval		Minimum fire interval		Number of intervals	
Vegetation type and site name (and number)	All years	10% scarred	All years	10% scarred	All years	10% scarred	All years	10% scarred	All years	10% scarred
Austrocedrus woodlands										
Rahue (1)	9.8	19.7	5.6	11.6	16	32	3	9	6	3
Lago Huechulafquen (2)	9.0	46.0	8.7	···	29	46	3	46	8	1
Estancia Collun-co (4)	12.3	14.8	5.6	13.8	20	35	4	4	6	4
Piedra Tromphul (5)	5.2	20.3	2.6	6.8	10	28	2	15	13	3
Rio Caleufu (6)	17.3	21.5	7.2	0.7	22	22	9	21	3	2
East Lago Traful (8)	5.8	11.5	1.8	6.6	9	20	4	4	8	4
North Rio Limay 1 (9)	4.0	5.0	2.1	1.9	8	8	1	2	15	9
North Rio Limay 2 (9)	3.5	4.1	2.1	3.3	8	7	1	1	20	8
South Rio Limay (10)	5.1	8.8	4.1	5.9	14	16	1	1	18	6
La Cascada la Virgen (15)	15.6	21.3	8.1	2.5	24	24	6	19	5	3
Lago Epuyen (18)	8.2	13.7	4.0	8.3	15	30	2	7	11	6
Lago Rivadavia (19)	10.3	17.0	6.4	10.8	20	26	3	5	6	3
Rio Grande (20)	13.5	14.0	8.7	1.4	26	15	7	13	4	2
Austrocedrus–Nothofagus forests										
West Lago Traful (7)	6.0	8.3	3.4	3.5	12	12	4	5	5	3
Laguna Huala Hue (14)	5.0	6.0	2.8	···	8	6	2	6	5	1

Note: Ellipses indicate that the number of intervals was too small for computation of a statistic. Sites were only included if they had at least three intervals for all fires between 1830 and 1929.

records of climatic variation derived from tree rings: (1) reconstructions of spring (November–December), spring and summer (October–March), and annual (March–February) precipitation over the period AD 1599–1988 from 16 *Austrocedrus* tree ring chronologies from 39° to 43° S (Villalba et al., *in press*); (2) mean summer (December–February) temperatures reconstructed for the period AD 869–1983 from a *Fitzroya cupressoides* chronology in the west-central sector of our study area (Villalba 1990); and, (3) a reconstruction of spring–summer (November–February) mean sea level atmospheric pressure for AD 1746–1984 for the South American–Antarctic Peninsula region (~50°–60° S) derived from tree ring chronologies from Tierra del Fuego (54°–55° S) and New Zealand (39°–47° S; Villalba et al. 1997).

RESULTS

Fire regimes: spatial and temporal patterns

In the 21 sample areas, the number of cross-dated fire scar samples ranges from 4 to 49 trees, with a total of 458 sampled trees for the entire region (Table 1). Sixteen of the *Austrocedrus*-dominated sites have sample sizes large enough to allow comparison of fire interval statistics for 1830–1929, which is the 100-yr period prior to the beginning of modern fire exclusion (Table 3). For these 16 *Austrocedrus*-dominated sites, MFI varies from 3.5 to 17.3 yr for all fires and from 4.1 to 46 yr for years of widespread fire (i.e., years in which ≥10% of the recorder trees were scarred; Table 3). As expected, maximum and minimum intervals between consecutive fires are generally greater for major fire years than for all fire years.

Three *Austrocedrus* records and one *Fitzroya* record include at least four fire-scarred trees before 1700; these were used to compare fire regimes in these two habitat types from 1700 to 1929 (Table 4). At the *Fitzroya*-dominated site, MFIs are three- to fivefold greater than at the *Austrocedrus* sites. Similarly, fire history charts of the other two *Fitzroya* sites (Mallin Blest and Lago Roca) have relatively few fires in comparison with *Austrocedrus* woodlands, but were not analyzed due to small numbers of fire years (Fig. 2a). In the two *Fitzroya* stands, the infrequency of fire events is particularly evident for major fire years (Fig. 2b).

For all sites combined, the percentages of sites with scarred trees and of recorder trees scarred in each year indicate a substantial increase in fire frequency beginning about 1850, rising to a peak in the 1890s and followed by a dramatic decline beginning in the early 20th century (Fig. 3). Relatively few fire scars have been recorded since the 1920s (Fig. 2a), and the lack of years of widespread fire since the early 1900s is especially striking (Fig. 2b). For all 21 sites combined, the MFI (years of ≥10% recorder trees scarred) is 16.5 yr for the fire exclusion era (1930–1989), compared to 2.2 yr for the preceding period of equal length, 1880–1929 ($P < 0.05$; Kolmogorov-Smirnov test).

Most sites show an increase in fire occurrence beginning in the late 1840s (Fig. 2). For the 15 *Austrocedrus* woodland sites, MFI declined from 6.1 yr in 1750–1839 to 2.4 yr in 1840–1929 ($P < 0.05$; Kolmogorov-Smirnov test). The timing and extent of the 19th-century increase in burning varies among the individual sites. Most of the *Austrocedrus* woodland sites with long enough records to compare 18th- and 19th-century fire occurrence show increases in frequencies of all fire years beginning about 1850 (e.g., Rahue,

TABLE 4. Summary of fire interval statistics for sites with at least four recorder trees by 1700. Mean fire intervals (MFI) and their standard deviation (1 SD) are given in years for all fire years and for years in which scars occurred on ≥10% of the recorder trees (minimum of two fire scars).

Vegetation type and site name (and number)	MFI		1 SD		Maximum fire interval		Minimum fire interval		Number of intervals	
	All years	10% scarred	All years	10% scarred	All years	10% scarred	All years	10% scarred	All years	10% scarred
Austrocedrus woodlands										
Rahue (1)	17.2	38.2	9.5	25.5	39	84	3	9	20	9
Rio Caleufu (6)	12.2	39.8	9.5	38.2	31	107	2	15	18	5
East Rio Limay 1 (11)	19.8	49.0	12.8	22.6	45	85	6	32	14	5
Fitzroya–N. dombeyi forest										
Valle Rayado (16)	59.3	···	36.9	···	99	···	26	···	3	···

Note: Ellipses indicate that there were too few intervals for computation of a statistic.

Collun, Tromph, N Lim1, N Lim2, S Lim, Epuyen, L Riva). Years of widespread fire (≥10% trees scarred) at the same sites, however, show either a slight or no increase in the 1850s (Fig. 2b).

The record from Huala, a site of dense *Austrocedrus* and *Nothofagus* forest, does not show the mid-19th century increase in fire frequency, but does record a peak from 1890 to 1920 (Fig. 2a). The record from W Traf, the other site from dense *Austrocedrus* and *Nothofagus* forest, only begins in the 1880s, but also records numerous fires in the early 20th century.

Instrumental weather and fire report records: 1938–1996

The synchronous occurrence of fires in the same years over extensive areas (Figs. 3 and 4) indicates a strong influence of interannual climatic variation on fire occurrence. Comparison of national park fire records with climatic records over the period 1938–1996 indicates that during years of extensive forest burning, spring–summers and springs are warmer and drier, respectively, than the means ($P < 0.05$; Fig. 5a, b). In contrast, years of extensive grassland burning are not associated with significantly different ($P > 0.05$) temperatures or precipitation during the year of the fires (Fig. 5c, d). However, years of major grassland fires do follow above-average precipitation in the spring of the preceding year, which may favor more widespread burning a year later by enhancing the growth of fine fuels in grasslands. Lightning is relatively rare in northern Patagonia, and years in which at least two fires were ignited by lightning have warmer than average springs and summers during the fire season ($P < 0.05$; Fig. 5e). However, such years are not anomalous in precipitation (Fig. 5f).

Temporal patterns of seasonal SOI and SST (indicators of ENSO events), which are similar for both years of widespread forest burning and years of at least two lightning-ignited fires, indicate that, over the 1938–1996 period, La Niña events have been the dominant ENSO event promoting fire. Seasonal SOI reaches peak values during the summer and occurs one year prior to the fire season (Fig. 6a, c). Seasonal SST is low for over a year prior to the summer of major forest fire years, and it reaches its lowest values in the fall–winter of years with at least two lightning-ignited fires (Fig. 6b, d). Both patterns imply that major fire years are associated with late stages of La Niña events.

Tree ring records of fire and climate: AD 990–1989

Tree ring proxy records of climatic variation.—Correlations of *Austrocedrus* ring widths with monthly instrumental temperature and precipitation variations indicate a regionally consistent response to climatic variation for all three sectors of the study area (Fig. 7). Tree growth is negatively correlated both with summer temperatures of the previous growing season and with spring–summer temperatures of the current growing season. All sectors also show a strongly positive correlation with November precipitation of the current growing season. This indicates that the radial growth of *Austrocedrus* in xeric woodlands is favored by above-average moisture availability during the spring–summer one year prior to the growing season and during the current growing season. Overall, these results indicate that the three composite *Austrocedrus* chronologies are good records of past variation in moisture availability that can be used for describing climatic conditions of fire event years in each of the three respective sectors.

Fire-promoting weather.—Superposed epoch analyses were conducted for each sector, using the fire event years determined from the *Austrocedrus* woodland sites and the respective composite ring width chronology. Several criteria for selecting fire event years were used to identify years of successively more widespread fires: years of all fires, years in which ≥10% of recorder trees (with a minimum of two scars) were scarred at one or more sites, and years in which ≥10% of recorder trees (with a minimum of two scars) were scarred at two or more sites (Fig. 8). In each of the three sectors, the *Austrocedrus* tree ring index exhibits significantly negative (dry) departures during years of all fires (Fig. 8). The strength of these departures increases substantially for years in which ≥10% of the trees were scarred at two or more sites. Given that the growth of *Austro-*

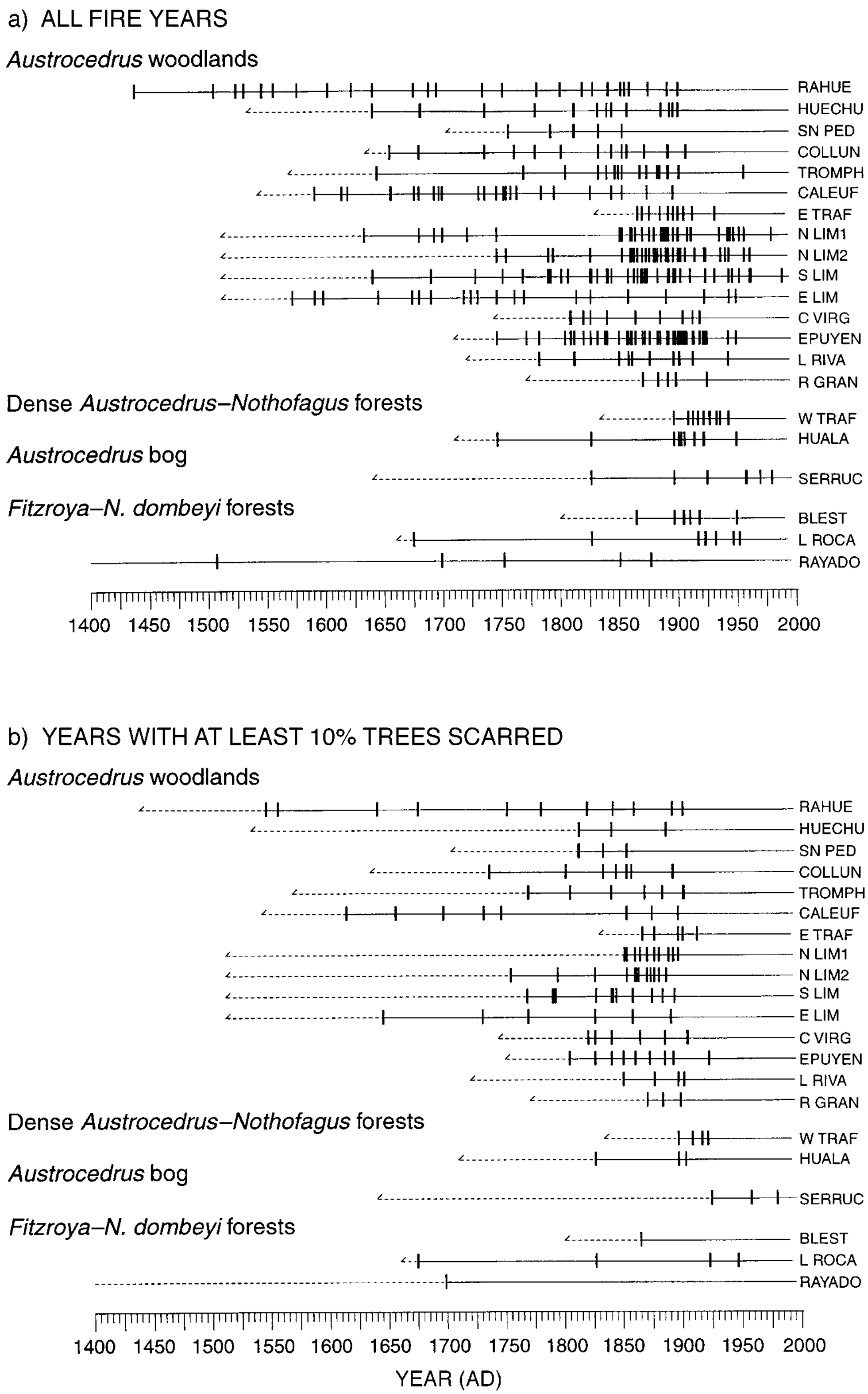

FIG. 2. Composite fire scar records indicating (a) years of any fire occurrence and (b) years in which ≥10% of the recorder trees (minimum two scars) recorded fire. Each horizontal line represents a different site, for which dates of fire scars are indicated by short vertical lines. Dashed lines indicate years prior to the occurrence of the first scar on that tree. Within each vegetation type, sites are arranged from north to south.

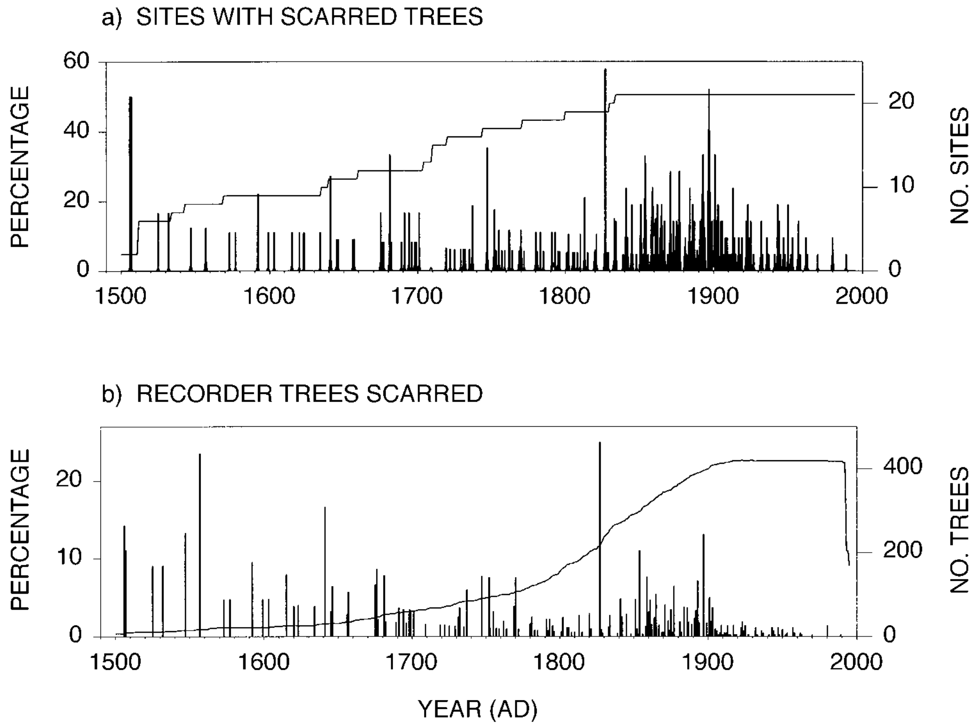

FIG. 3. Records, based on all 21 sites, showing (a) percentage of sites with scars per year and (b) percentage of samples (recorder trees) scarred per year. Sample depth lines give (a) the number of sites with recorder trees alive and (b) the total number of recorder trees alive in each year.

cedrus is significantly correlated with climatic variables during both the current and prior growing season, drought may occur during the fire year or in both the fire year and the previous year. However, results from the observational fire record for 1938–1996 (Fig. 5d) imply that drought during the fire year is more critical.

The *Austrocedrus* tree ring index shows significantly positive departures for years $t - 3$ and $t - 5$ in the central and southern sectors (Fig. 8). This implies that periods of greater moisture availability precede fire seasons by several years, similar to the pattern of above-average precipitation in year $t - 1$ for grassland fires, shown by the observational record (Fig. 5d). The central and southern sectors also show significantly positive (moist) departures of the *Austrocedrus* tree ring index during the year following years of most widespread burning (Fig. 8). This is consistent with the wetter than average year $t + 1$ for years of widespread forest burning during the observational period (Fig. 5b).

At the remote Rayado *Fitzroya* site, summer temperatures are significantly above average during the fire year; annual precipitation is below average, but not statistically significant (Fig. 9a, b). Thus, reduced moisture availability associated mainly with a temperature-induced increase in evapotranspiration during the summer of the fire year appears to promote fire in these rain forests. Both summer temperature and annual precipitation (derived from tree ring chronologies from unburned stands) are significantly above average for the year following the fire event year (Fig. 9a, b).

For all of the *Austrocedrus*-dominated sites ($n = 18$), reconstructed annual precipitation and summer temperature were compared for years in which ≥10% of trees were scarred in at least one site over the period 1600–1929 (i.e., prior to fire exclusion). Annual precipitation is significantly below average during the fire event year and the preceding two years, and summers are warmer than average during the fire year (Fig. 9c, d). Five years prior to the fire event year, reconstructed annual precipitation is high and summer temperatures are relatively low, consistent with the above-average moisture availability indicated by *Austrocedrus* ring widths in year $t - 5$ (Fig. 8). Similarly, the lack of significant departures of the ring width index in years $t - 1$ and $t - 2$ (Fig. 8) is consistent with those years being dry but not warm. Again, the year following the fire year is characterized by significantly above-average precipitation (Fig. 9d). Thus, for both the *Austrocedrus*-dominated sites and the *Fitzroya* site, years following fires have greater annual precipitation and a tendency toward warmer than average summers.

Relationships of fire to climatic variation at different time scales.—The importance of temporal scale in precipitation variability is revealed by comparing fire occurrence in the five wettest or driest November–December and October–March seasons over periods of 1, 5, 25, and 50 yr from 1599 to 1989, based on precip-

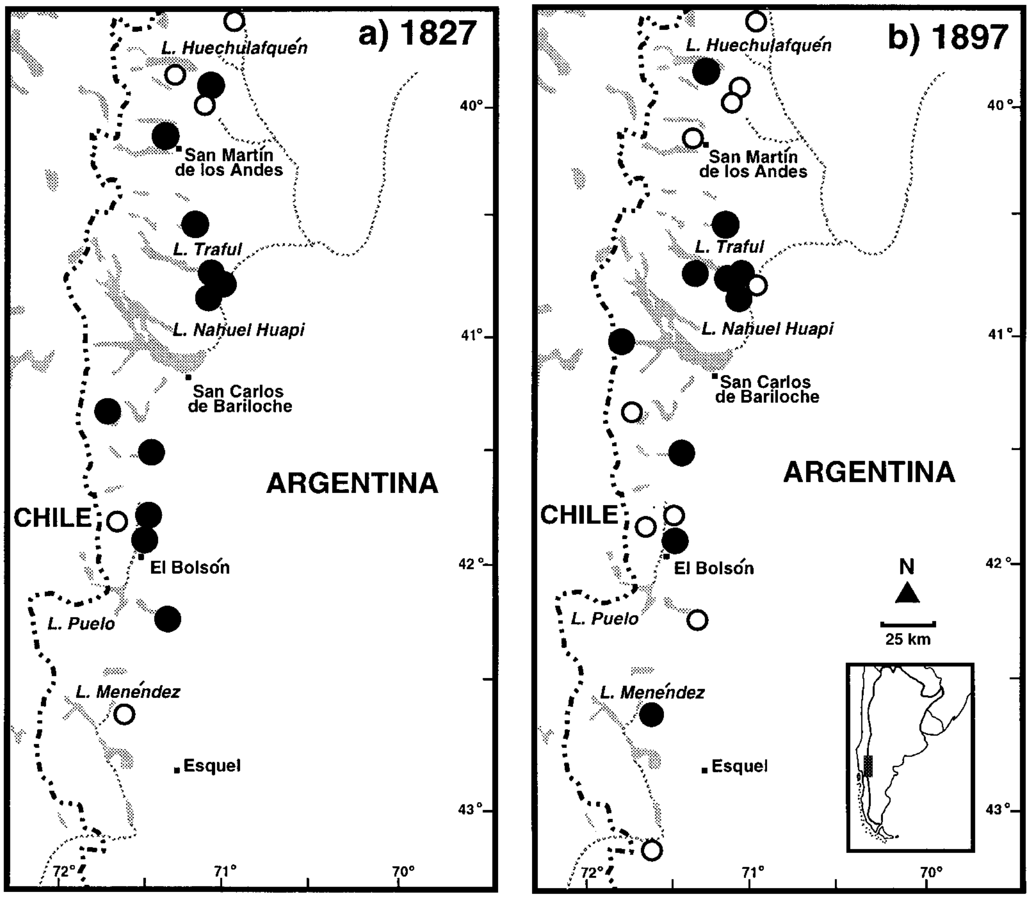

FIG. 4. Maps showing sites (solid symbols) that recorded fire (a) in 1827 and (b) in 1897. Open symbols are sites that had recorder trees at the date of the respective fire events but did not record fire.

itation reconstructions from *Austrocedrus* tree rings (Table 5). The five single years that were driest during November–December and October–March are years in which the number of sites recording fire is 91–445% above the average. Conversely, the five single years with the wettest springs are mostly years of little or no fire occurrence (Table 5). At a 5 yr time scale, however, there is no consistent relationship between fire extent and drought, even if the 1958–1962 period within the fire exclusion era is ignored. For wet 5 yr periods, there is a tendency (seven of nine cases) toward less fire, but, at time spans of 25 and 50 yr, the influence of precipitation on fire occurrence is not evident.

The correspondence of single years of extreme summer temperatures with variation in fire extent is less consistent than the annual-scale pattern for precipitation (Table 6). Although three of the five warmest summers coincide with high fire occurrence, no fire scars were recorded in the other two years. Four of the five years with the coolest summers were years of no recorded fire. Of the eight warmest 25- and 50-yr periods, only three were characterized by above-average fire extent.

Relationships of fire event years to hemispheric circulation anomalies

Superposed epoch analysis was used to relate variation from all 21 sites in percentage of recorder trees with scars in each year to the initiation of regional El Niño events (moderate to very strong events in Quinn 1992). The time period analyzed was 1520–1929, which corresponds to five years before the first El Niño event in Quinn's (1992) record, until the beginning of modern fire exclusion. This regional index of fire shows a significant positive departure during the year prior to the beginning of El Niño events (Fig. 10a). Given the tendency for La Niña and El Niño years to occur in consecutive years (Diaz and Kiladis 1992), this pattern indicates that years of more widespread fire are associated with late stages of La Niña events.

The 10 years of greatest fire occurrence (i.e., highest percentage of sites with fire-scarred trees) show a strong association of extreme fire years with ENSO activity (Table 7). All 10 years are associated with below-average spring, spring–summer, and annual precipitation, but the deficit of spring–summer precipitation is greater than the annual deficit. Summer tem-

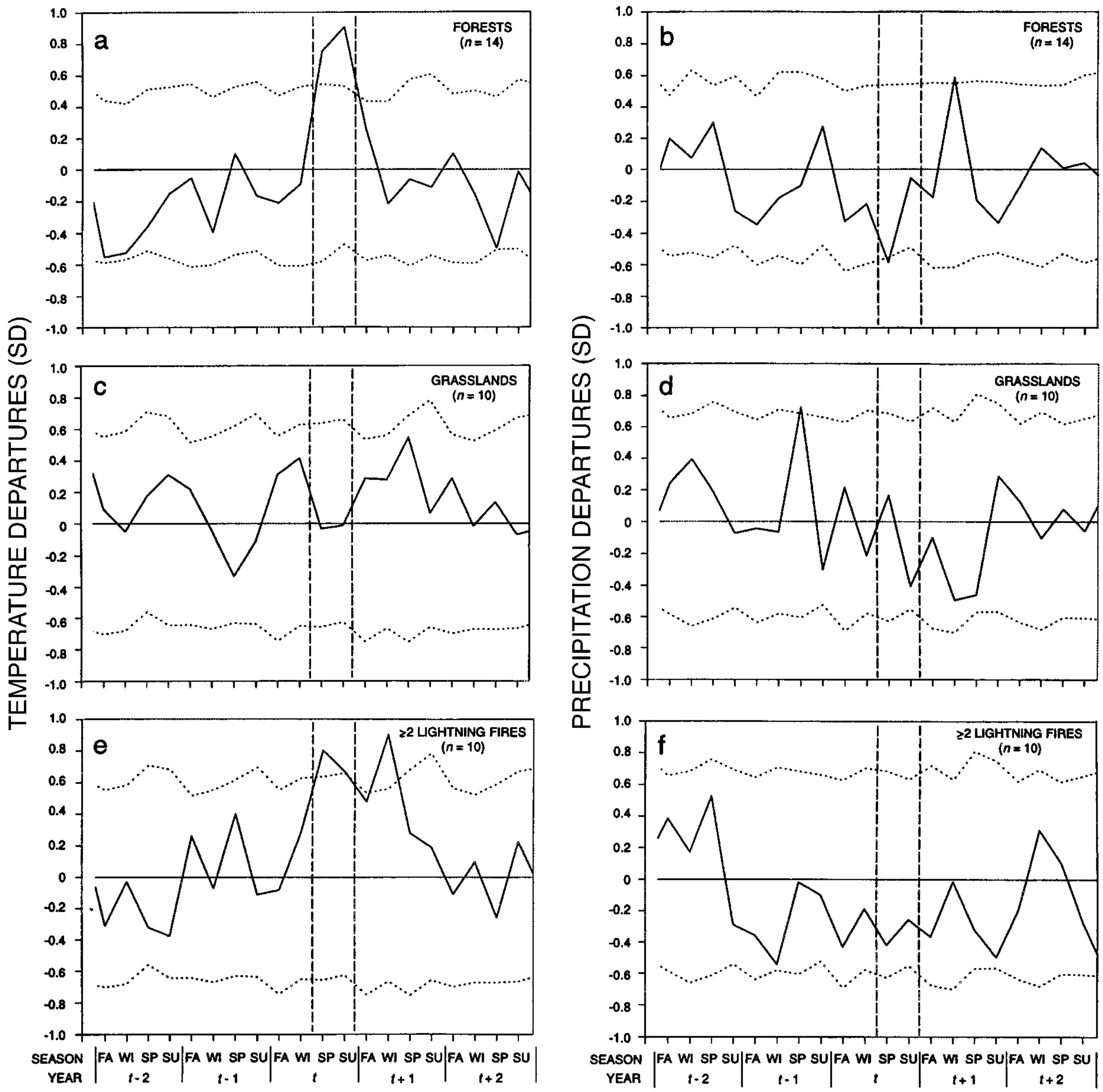

FIG. 5. Seasonal temperature and precipitation departures in standard deviations (SD) for 5-yr windows ($t - 2$ yr to $t + 2$ yr) centered on years of major forest fires (>1000 ha burned), major grassland fires (>10 ha burned), and ≥2 lightning-ignited fires in Lanin, Nahuel Huapi, Lago Puelo, and Los Alerces National Parks for 1938–1996. Seasons are abbreviated: FA, fall (April–June); WI, winter (July–September); SP, spring (October–December); and SU, summer (January–March). Dotted lines indicate bootstrap 95% confidence intervals based on 500 Monte Carlo simulations of the same number of years as fire event years (Mooney and Duval 1993). Vertical dashed lines indicate the fire season, and *n* indicates the number of fire event years. Fire data are from the Argentine National Park Service. Climatic data are from the Bariloche Airport station.

peratures associated with extreme fire years are much more variable, and three of the 10 event years had cooler than averge summers. According to historical descriptions of climatic conditions along the west coast of South America (Quinn 1992), six of the 10 years (1747, 1841, 1854, 1871, 1877, and 1897) coincide with moderate to very strong El Niño events (Table 7). Because the fire event years are dated in dendrochronological years (e.g., the 1871 dendrochronological year includes January–March 1872), they coincide with the warmer than average summers expected in the calendar year following El Niño events (Kiladis and Diaz 1989). For the four strong/very strong El Niño fire years, mean summer temperature is 1.11°C above the mean, whereas it is 0.19°C below the mean for the non-El Niño fire years ($P < 0.05$; *t* test). In three of the four fire years not coinciding with El Niño events, the fire year precedes an El Niño event by one year, as expected from the association of fire and late stages of La Niña events (Figs. 6 and 10a). The year 1893 is the only extreme

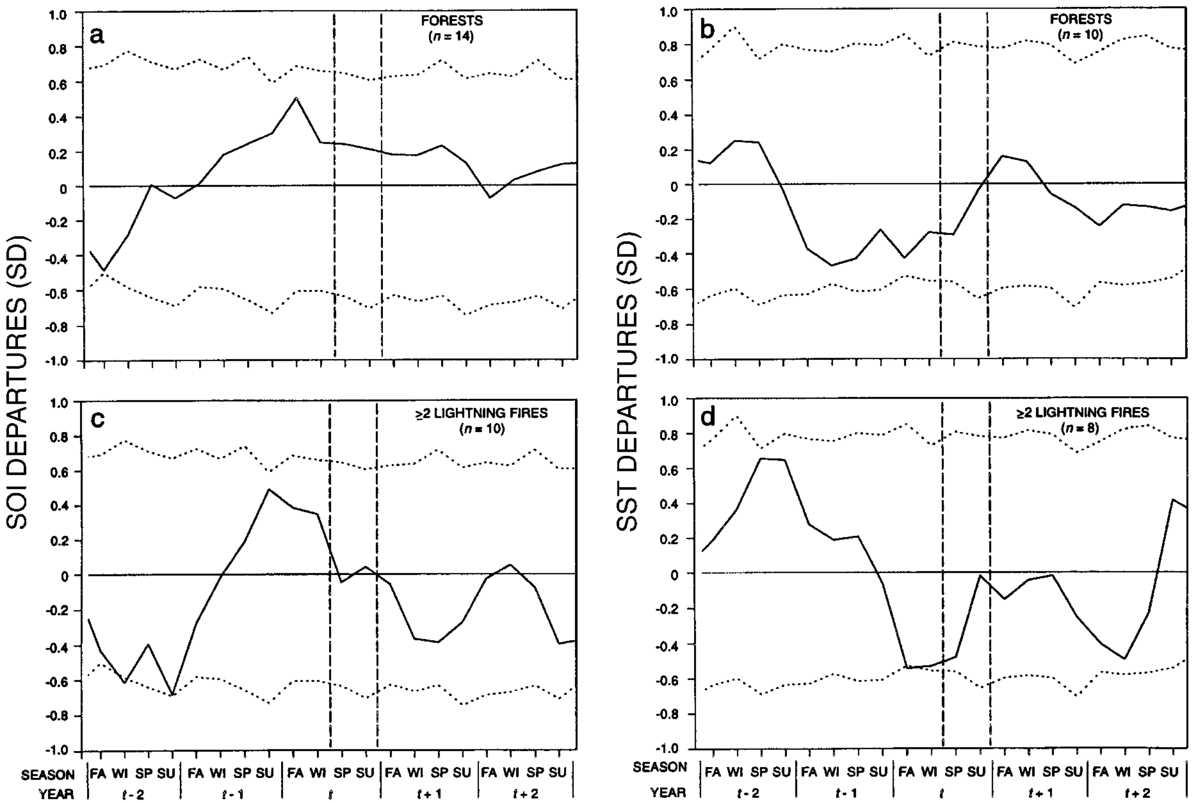

FIG. 6. Departures in standard deviations (SD) of seasonal Southern Oscillation Indices (SOI) and sea surface temperatures (SST) for 5-yr windows ($t - 2$ yr to $t + 2$ yr) centered on years of major forest fires (>700 ha burned) and years of ≥2 lightning-ignited fires in Lanin, Nahuel Huapi, Lago Puelo, and Los Alerces National Parks for 1938–1996 and 1950–1996, respectively. Seasons are abbreviated as in Fig. 5. Dotted lines indicate bootstrap 95% CIs based on 500 Monte Carlo simulations of the same number of years as fire event years (Mooney and Duval 1993). Vertical dashed lines indicate the fire season, and n indicates the number of fire event years. Fire data are from Argentine National Park Service. SOI and SST data are from the U.S. National Oceanic and Atmospheric Administration.

fire year that neither coincides with nor immediately precedes a regional El Niño event. However, it closely follows the very strong 1891 regional El Niño and, for the Pacific region in general, 1892 is considered a La Niña year (Diaz and Kiladis 1992). Thus, all 10 of the most extreme fire years either coincide with an El Niño or a La Niña event.

Years of widespread fire in *Austrocedrus*-dominated sites (i.e., ≥10% of trees scarred at one or more sites) are also associated with low mean sea level atmospheric pressure at latitudes 50°–60° S in the South American–Antarctic sector of the Southern Ocean (Fig. 10b). As we will discuss, such years are drier than the average in northern Patagonia.

DISCUSSION

Human influences

The most dramatic temporal change in fire occurrence in northern Patagonia is the abrupt decline in fire frequencies in the early 1900s, which immediately followed the demise of the Native American hunting population. Low fire frequency during the 20th century is attributed both to decreased intentional burning and, since about 1930, to fire exclusion. Fire frequencies began to increase at most *Austrocedrus* woodland sites after about 1850, and peaked in the late 19th century (Fig. 2a). The mid-19th century increase in all fires is coincident with increased use of the *Austrocedrus* habitat by Native American hunters as a result of immigration from the Chilean side of the Andes, stimulated by the European colonization of southern Chile (Cox 1863). Although most the sites of *Austrocedrus* woodlands show an increase in the occurrence of all fire years in the mid-1800s, for years of widespread fire (≥10% trees scarred), increases are either lacking or weaker (Fig. 2). Given that single years of widespread burning are more likely to be determined by weather than by year-to-year variation in the frequency of ignitions by humans, this suggests that the mid-19th century increase in all fires is at least partially attributable to an increase in human-set fires. This interpretation is supported by the lack of increase in fires in the mid-19th century at the more isolated E Lim site (Fig. 2a). This site is physically separated from neighboring sites that show the mid-19th century increase by the large Rio Limay, which may either have impeded fire spread or reduced human access.

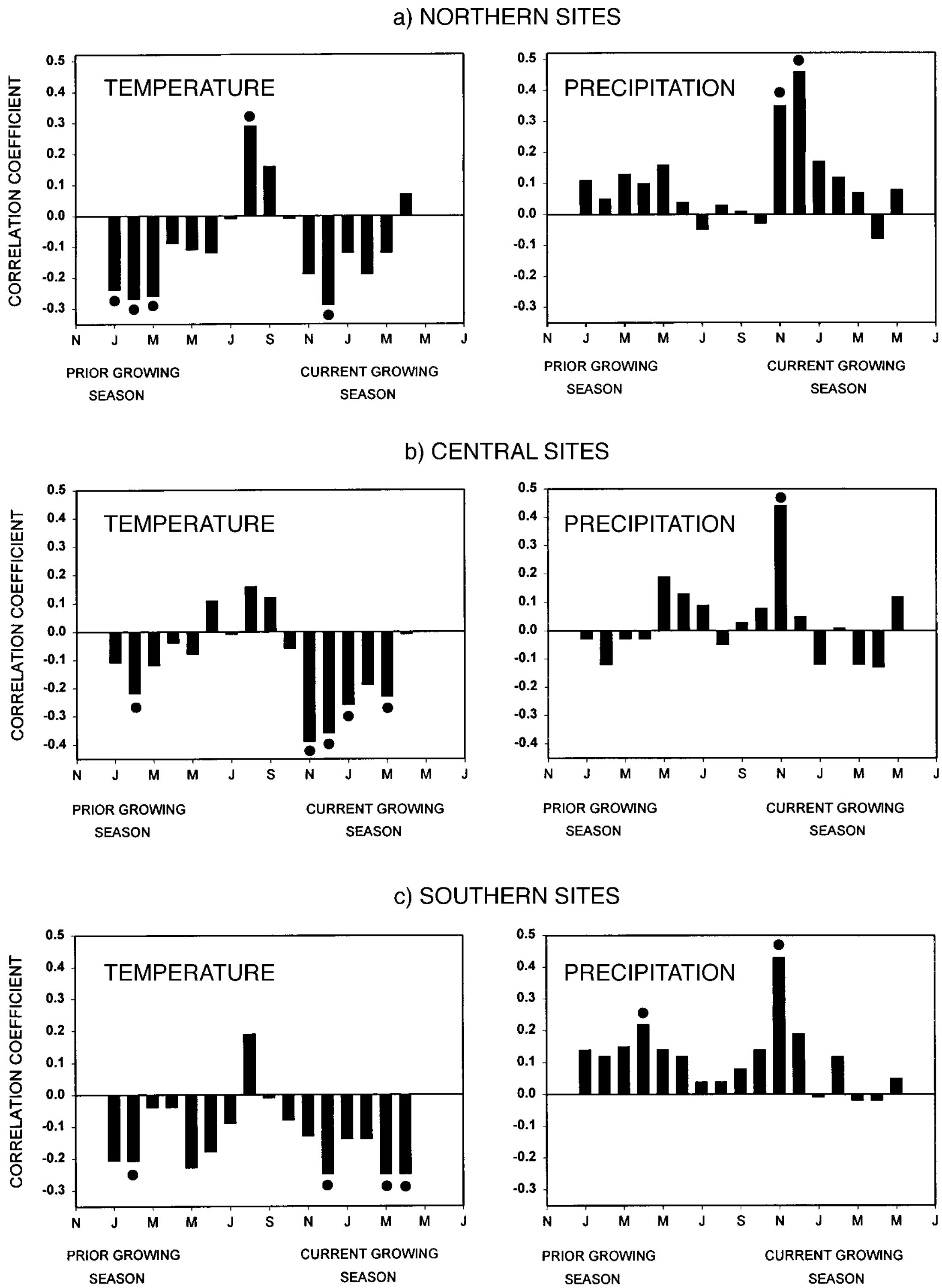

FIG. 7. Correlation functions, based on residual tree ring chronologies, relating variation in the radial growth of *Austrocedrus* to monthly mean temperatures and precipitation for the northern, central, and southern sectors. (Single-letter abbreviations of months are given at bimonthly intervals on the *x*-axes.) For each sector, mean ring width chronologies are based on 4–6 site chronologies and are related to the longest climatic record for each sector. Bars capped with dots indicate statistically significant correlations ($P < 0.05$). Tree ring chronologies used for the subregional composite chronologies are given in Table 2.

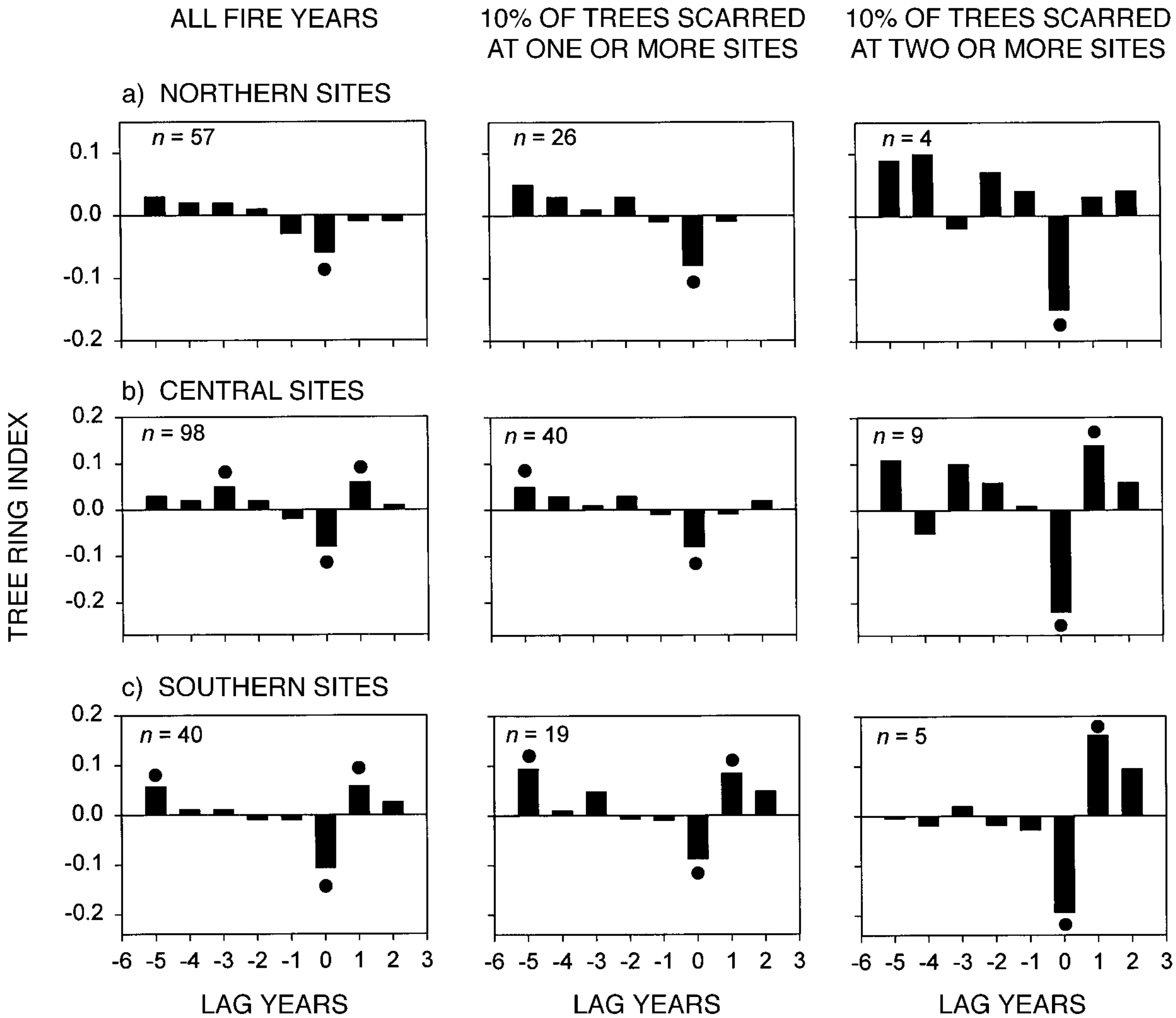

FIG. 8. Mean tree ring index for each subregional composite chronology for 5 yr prior to and 2 yr following fire event years (year 0) for xeric *Austrocedrus* woodlands in the (a) northern, (b) central, and (c) southern sectors of the area sampled for fire history in northern Patagonia. High values of the tree ring index indicate high moisture availability. Bars capped with dots are statisically different ($P < 0.05$) from means determined from 1000 Monte Carlo simulations based on the same number of years as the event years (Mooney and Duval 1993). Time periods start 5 yr prior to the date of the first fire event year and extend to the year of the most recent fire (1989). The number of fire event years is given by *n*.

High fire frequencies in the 1890s to early 1900s, especially at sites of dense *Austrocedrus* forests, but also at many open woodland sites, coincide with the period of extensive forest burning by European settlers in attempts to create cattle pasture (Willis 1914, Rothkugel 1916). This burning also resulted in the establishment of extensive even-aged, pure *Nothofagus* forests with cohort ages indicating a marked peak in burning about 1900 (Veblen et al. 1992*a*). These more densely wooded habitats were not generally utilized by Native American hunters, and fires set by Native Americans were probably rare, except for forest clearing of a few trans-Andean travel routes (Cox 1863, Fonck 1900, Furlong 1964). Consequently, fire records from the more mesic forests would not be expected to show the earlier increase in fire frequency associated with aboriginal immigration from Chile, even if remnant fire scar susceptible trees had survived the late 19th-century episode of increased burning. The Rayado site in *Fitzroya* rain forest is nearly inaccessible and not located near any trans-Andean travel routes; thus, it is unlikely to have been a site of fires set by either Native Americans or Europeans. The lack of any trend toward increased burning associated with human settlement of the region is consistent with the isolation of this site (Fig. 2a). In contrast, both Blest and L. Roca, the other two *Fitzroya* sites, are in areas of relatively easy access to Europeans, and were parts of important travel routes utilized by Europeans since the late 1800s. Both show marked increases in fire frequencies in the early 1900s (Fig. 2a).

Although not examined here, changes in fire regimes

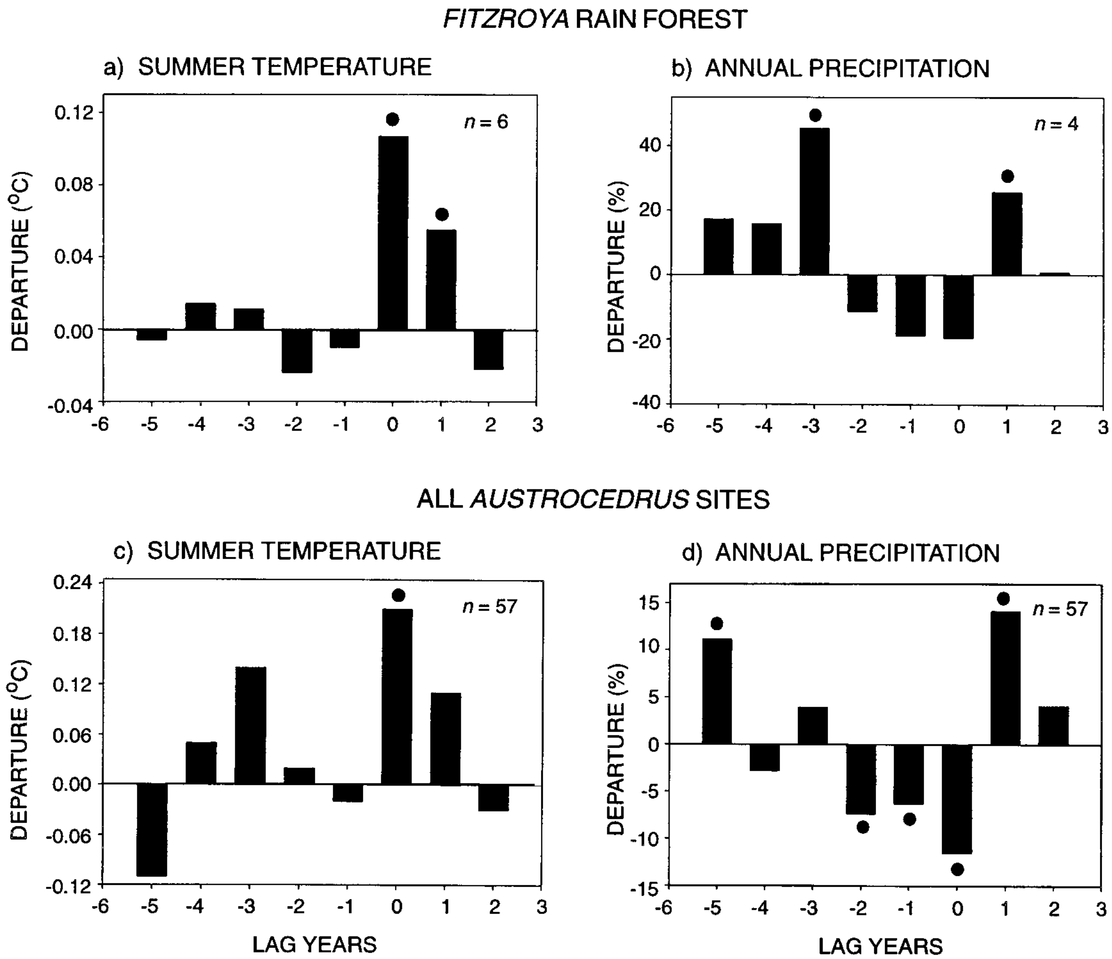

FIG. 9. Departures of reconstructed summer temperature and annual precipitation for fire years in the *Fitzroya*-dominated rain forest at El Valle Rayado (a and b), and for years in which ≥10% of recorder trees were scarred in one or more of 18 *Austrocedrus*-dominated forests and woodlands (c and d) for windows beginning 5 yr before and ending 2 yr after the fire year. Time periods analyzed are (a) AD 900–1983, (b) 1600–1987, and (c, d) 1600–1929. Bars capped with dots are statistically different ($P < 0.05$) from means determined from 1000 Monte Carlo simulations based on the same number of years as the event years (Mooney and Duval 1993). The number of fire event years is given by *n*. The reconstructed summer temperature time series is from Villalba (1990), and the reconstructed annual precipitation is from Villalba et al., *in press*.

by European settlers also have had important secondary impacts on fuel conditions and the potential for fire spread. For example, during the fire exclusion era, the increase in tree density in *Austrocedrus* woodlands and invasion of trees into the steppe have created more contiguous woody fuels (Veblen et al. 1992*a*, Kitzberger and Veblen, *in press*), so that sites previously supporting only surface fires are now susceptible to stand-replacing fires. Conversely, the extensive burning of mesic forests in the 1890s to 1920s resulted in vast areas of even-aged, regenerating *Nothofagus–Austrocedrus* forests. During the first few decades of stand development, these young stands may be less susceptible to fire spread, but as stands reach ages of 60–100 yr, self-thinning produces abundant, intermediate-sized fuels that may favor fire spread. Thus, some of the decline in fire frequency during the 20th century may reflect human-induced changes in fuel conditions.

Influences of temperature and precipitation

Instrumental climatic records indicate that years of widespread forest fires coincide with drier and warmer than average spring–summers, but that fire occurrence in grasslands is not significantly related to weather during the year of the fire season. In the grassland zone, summer drought is severe enough in normal years to permit burning, whereas summers in the forest zone are only sufficiently dry in exceptional years to permit widespread burning. Years of extensive grassland burning, however, do tend to follow wetter than normal springs one year prior to the fire season, which may increase the availability of fine fuels through enhanced growth of grasses.

There is a sharply declining influence of precipitation and temperature on fire occurrence from annual to multidecadal periods. Although annual precipitation anom-

TABLE 5. Regional fire characteristics for the five driest and wettest seasonal (November–December and October–March) events and for the five nonoverlapping wettest and driest 5-yr, 25-yr, and 50-yr periods, based on moving averages over the period 1599–1989.

Five driest periods						Five wettest periods					
	Nov–Dec			Oct–Mar			Nov–Dec			Oct–Mar	
Period (AD)	Precip.† (SD)	Sites‡ (%)	Period	Precip. (SD)	Sites (%)	Period (AD)	Precip. (SD)	Sites (%)	Period	Precip. (SD)	Sites (%)
1-yr periods											
1943	−1.63	+312	1682	−1.66	+91	1600	+1.26	−100	1941	+1.44	+9
1813	−1.60	+382	1943	−1.43	+336	1945	+1.23	+9	1920	+1.24	−100
1682	−1.59	+91	1841	−1.35	+445	1868	+1.22	−100	1811	+1.24	−100
1962	−1.47	+118	1913	−1.31	+445	1941	+1.14	+9	1940	+1.12	−100
1599	−1.46	+154	1962	−1.22	+118	1760	+1.08	−100	1760	+1.07	−100
5-yr periods											
1817–1821	−0.63	−28	1680–1694	−0.60	+91	1868–1872	+0.56	+74	1937–1941	+0.69	−78
1680–1684	−0.54	+91	1958–1962	−0.47	−35	1938–1942	+0.55	−78	1634–1638	+0.60	−49
1910–1914	−0.47	+118	1744–1748	−0.46	+62	1808–1812	+0.55	−28	1944–1948	+0.53	−53
1743–1747	−0.47	+62	1663–1667	−0.45	−100	1944–1948	+0.46	+53	1808–1812	+0.50	−28
1958–1962	−0.45	−35	1910–1914	−0.44	+118	1926–1930	+0.45	−78	1617–1621	+0.49	−50
25-yr periods											
1895–1919	−0.20	+143	1895–1919	−0.20	+143	1925–1949	+0.26	+1	1925–1949	+0.26	+1
1804–1828	−0.19	+9	1662–1686	−0.19	−31	1868–1892	+0.18	+92	1630–1654	+0.21	−48
1662–1686	−0.15	−31	1697–1721	−0.11	−63	1630–1654	+0.15	−48	1719–1743	+0.14	−42
1733–1757	−0.13	−6	1803–1827	−0.11	−1	1720–1744	+0.12	−49	1868–1892	+0.12	+79
1695–1719	−0.07	−56	1731–1755	−0.10	−4	1600–1624	+0.10	−59	1963–1987	+0.10	−83
50-yr periods											
1798–1847	−0.10	−5	1655–1704	−0.11	−21	1926–1975	+0.12	−34	1928–1977	+0.14	−26
1875–1924	−0.10	+132	1875–1924	−0.10	+132	1605–1654	+0.10	−59	1605–1654	+0.14	−59
1644–1693	−0.09	−39	1818–1867	−0.07	+50	1843–1892	+0.09	+88	1851–1900	+0.05	+121
1737–1786	−0.05	−21	1710–1759	−0.03	−39		§				
	§		1761–1810	−0.02	−36						

† Precipitation departures are in standard deviations and are from Villalba et al. (*in press*).
‡ Percentage departures from the 1599–1989 mean number of sites.
§ Precipitation was above the long-term mean for all other nonoverlapping 50-yr periods.

alies strongly influence the regional extent of fire at 1- and 5-yr time scales, climatic influences over longer periods are weak or inconsistent. In fact, at 25- and 50-yr time scales, maximal fire occurrence coincides with periods of above-average precipitation in the late 19th to early 20th century (e.g., 1868–1892, 1843–1892, and 1851–1890 in Table 5), which was a time of increased intentional burning by humans. Nevertheless, the inclusion within the post-1930 fire exclusion era of several 1- and 5-yr periods of spring–summers that were among the wettest since 1599 may have contributed to the decline in fire extent during the present century.

ENSO influences

Although multidecadal average precipitation and temperature do not strongly influence fire occurrence, variations in fire regimes at a 50-yr time scale have been tentatively associated with variations in ENSO activity, which affects interannual variability in moisture availability (Kitzberger and Veblen 1997). Monthly SOI, over the period of 1882–1989, indicates that major fire years tend to coincide with the late stages of La Niña events (Kitzberger and Veblen 1997). The larger and more varied data sets on climatic variation and fire history in the current study strongly support our preliminary finding of ENSO influences on fire occurrence in northern Patagonia. Observational records of fire and indicators of ENSO from recent decades indicate that summers of major forest fires follow fall–winters of positive SOI and cooler SST in the eastern tropical Pacific, which indicate La Niña conditions (Fig. 6). Similarly, comparison with the documentary record of regional El Niño events (Quinn 1992) shows that fire occurrence is greater during the year immediately prior to the initiation of El Niño events (Fig. 10a), which tends to be the late stage of La Niña events (Kiladis and Diaz 1989). This is consistent with the above-average annual precipitation that characterizes the year following fire years, based on the long-term tree ring record of climate and fire in both the *Fitzroya* forests and in *Austrocedrus*-dominated forests and woodlands (Figs. 8 and 9).

Consideration of the 10 years of most widespread fire since 1740 (Table 7) indicates that years of major fires also coincide with the warm summers that follow strong/very strong El Niño events. Thus, there are two ENSO-related patterns associated with years of extreme burning: (1) warmer summers in the calendar year following El Niño events (which is the same year as the dendrochronological year); and (2) reduced winter–spring precipitation during La Niña events preceding extreme fire years.

The positive association of fire event years in *Aus-*

TABLE 6. Regional fire characteristics for the five warmest and coolest seasonal (summer) events and for the five non-overlapping warmest and coolest 5-yr, 25-yr, and 50-yr periods, based on moving averages over the period 1599–1983.

Five warmest summers			Five coolest summers		
Period	Temp.† (SD)	Sites‡ (%)	Period	Temp. (SD)	Sites (%)
1-yr period					
1655	+3.62	−100	1736	−2.35	−100
1877	+3.43	+554	1971	−2.14	−100
1699	+3.31	+91	1655	−2.09	−100
1718	+3.31	−100	1947	−2.04	+118
1851	+3.28	+335	1610	−2.02	−100
5-yr period					
1718–1722	+2.71	−41	1655–1659	−2.41	−17
1665–1669	+2.60	−100	1641–1645	−2.30	+67
1877–1881	+2.43	+96	1826–1830	−2.28	+165
1766–1770	+2.37	−20	1947–1951	−2.20	+52
1698–1702	+2.06	+52	1899–1903	−1.95	+270
25-yr period					
1755–1779	+2.18	−41	1636–1660	−2.31	−42
1874–1898	+2.03	+136	1927–1951	−1.83	+6
1668–1689	+2.00	−32	1601–1625	−1.67	−60
1839–1863	+1.61	+81	1785–1809	−1.35	−35
1698–1722	+0.98	−64	1886–1910	−1.20	+176
50-yr period					
1744–1793	+1.94	−20	1601–1650	−2.50	−55
1833–1882	+1.93	+70	1899–1948	−1.95	+55
1651–1700	+1.00	−28	1783–1832	−1.09	−4
	§		1688–1737	−0.37	−34
				§	

† Temperature departures, in standard deviation, are from Villalba et al.(*in press*).
‡ Percentage departures from the 1599–1983 mean number of sites with scars.
§ Temperature was below the long-term mean for all other nonoverlapping 50-yr periods.

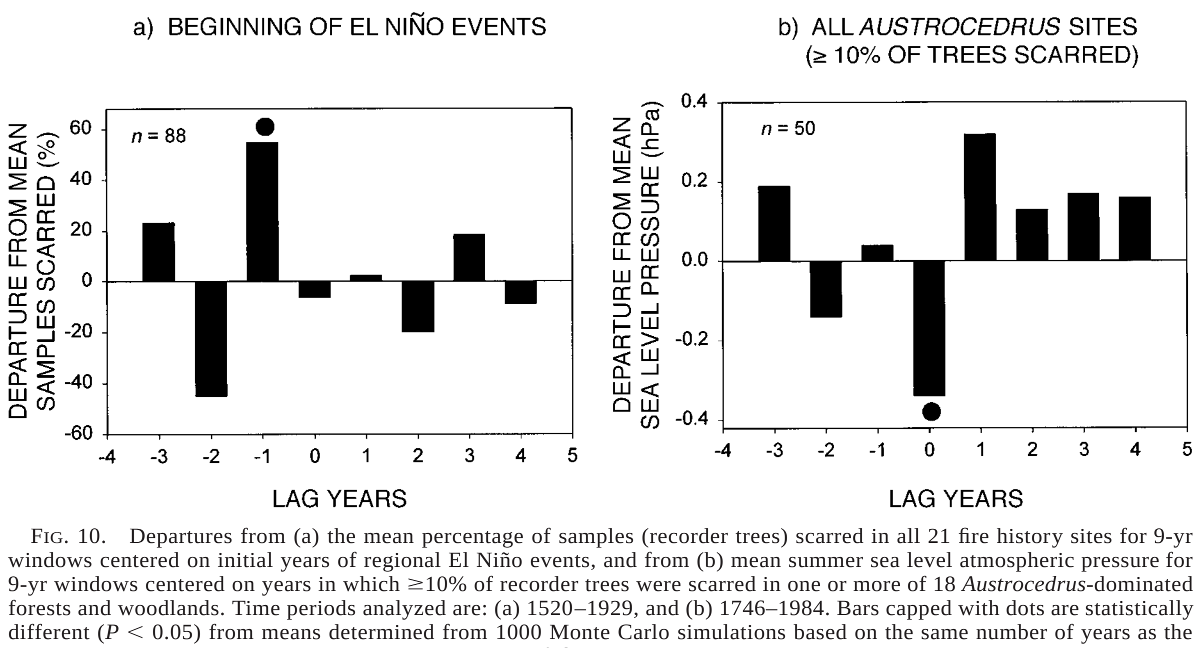

FIG. 10. Departures from (a) the mean percentage of samples (recorder trees) scarred in all 21 fire history sites for 9-yr windows centered on initial years of regional El Niño events, and from (b) mean summer sea level atmospheric pressure for 9-yr windows centered on years in which ≥10% of recorder trees were scarred in one or more of 18 *Austrocedrus*-dominated forests and woodlands. Time periods analyzed are: (a) 1520–1929, and (b) 1746–1984. Bars capped with dots are statistically different ($P < 0.05$) from means determined from 1000 Monte Carlo simulations based on the same number of years as the event years (Mooney and Duval 1993). The number of fire event years is given by *n*. The reconstructed mean sea level pressure time series is for 50°–60° S in the South American–Antarctic Peninsula sector of the Southern Ocean (Villalba et al. 1997).

TABLE 7. The 10 years of most widespread fire and their climatic characteristics for the period 1740–1995.

Year	Sites† (%)	Scars‡ (SD)	Regional El Niño§	Intensity‖	Precipitation (1 SD)¶ Nov–Dec	Oct–Mar	Annual	Summer temp. (°C)
1747	36	+3.4	1747	S+	−0.91	−1.06	−0.24	+0.87
1827	61	+10.7	1828	VS	−1.06	−1.02	−0.47	−0.79
1841	24	+2.1	1841	M?	−1.24	−1.39	−0.76	+1.37
1854	31	+4.7	1854	M	−0.25	−0.12	−0.21	−0.46
1859	25	+3.3	1860	M	−0.43	−0.10	−0.49	+0.47
1871	21	+1.7	1871	S+	−0.51	−0.41	−0.87	+0.38
1877	26	+2.8	1877–1878	VS	−1.36	−1.21	−0.73	+2.12
1893	32	+3.1	1891	VS	−1.33	−1.01	−0.78	+0.34
1897	52	+5.6	1897	M+	−0.42	−0.19	−0.06	+1.07
1901	30	+2.1	1902	M+	−0.49	−0.34	−0.65	−0.77
Mean	34.2	+4.0			−0.80	−0.69	−0.53	+0.77
1 SD	13.0	2.7			0.43	0.50	0.28	0.95

† Percentage of the 21 sample sites with recorder trees alive that record fire in that year.
‡ Departures, in standard deviations, from the 1599–1989 mean number of recorder trees scarred per year.
§ Date of the previous regional El Niño event, taken from Quinn (1992). The question mark for 1841 indicates that this date was not listed in Quinn (1992) but was included in a more recent analysis by Ortlieb (1994).
‖ Intensities of El Niño events are given as: M, moderate; S, strong; and VS, very strong.
¶ Departures, in standard deviations, from the 1599–1989 regional annual precipitation for northern Patagonia, taken from the tree ring reconstruction of Villalba et al. (*in press*).

trocedrus woodlands with above-average moisture availability 3–5 yr prior to the fire season (Figs. 8 and 9) falls within the common return intervals of ENSO events and anomalies in high-latitude circumpolar circulation (Mann and Park 1994, White and Peterson 1996). Thus, it may reflect the autocorrelation of ENSO events at time scales of 3–5 yr, rather than a causal relationship between increased fuels and greater fire hazard. For example, the tendency for fire event years at the Rayado site to follow wet years by 3 yr (Fig. 9b) is unlikely to be due to increased fuels in rain forest vegetation. On the other hand, the positive association shown by the observational record (1938–1996) for fire events in grasslands with above-average spring precipitation 1 yr prior to the event, and the lack of such a relationship for forests, suggest that there is a causal relationship between increased growth of fine fuels and increased grassland fire. Many of the open woodland sites of *Austrocedrus* are more similar to grasslands than to mesic forests in their fuel characteristics, and it is likely that increased moisture availability enhances the fire hazard several years later.

The strength of the relationship between ENSO events and climate is known to have varied at hemispherical and global scales over decadal and centennial time scales (Diaz and Pulwarty 1994). In northern Patagonia, although spring and summer temperature variations are significantly correlated with the SOI for the interval 1909–1981, the correlation is nearly absent during the 1930s and 1940s (Villalba and Veblen 1998). The relationship between climate and ENSO forcing in northern Patagonia is highly variable according to the timing and strength of events (Villalba 1994). Thus, despite the statistically significant associations demonstrated here, variation in fire regimes in northern Patagonia can only partially be explained by ENSO forcing.

Association of fire years with other circulation features

Variation in fire regimes in northern Patagonia is strongly related to the intensity and latitudinal position of the subtropical anticyclone of the southeast Pacific (Kitzberger et al. 1997). When the anticyclone is more intense and located farther south off the coast of southern Chile, fewer cyclonic storms enter the continent at about 40° latitude, resulting in drought and more fire in northern Patagonia. Major fire event years in northern Patagonia are also associated with below-average atmospheric pressure at 50–60° S in the South American–Antarctic Peninsula sector of the Southern Ocean (Fig. 10b). Lower pressure reflects lack of blocking highs that otherwise increase precipitation in northern Patagonia by steering westerly cyclonic storms northwards into the continent. Again, the strength of the relationship between precipitation in northern Patagonia and sea level atmospheric pressure at high latitudes has varied markedly; it is stronger during the 20th century than during the previous roughly 150 yr (Villalba et al., *in press*). Similarly, interannual variability in precipitation has been greater during the 20th century than during the previous three centuries (Villalba et al., *in press*), which may reflect variations in both high-latitude circulation features and ENSO activity.

Variation in the southeast Pacific anticyclone and high-latitude atmospheric circulation is also linked to ENSO events (Diaz and Kiladis 1992). Major blocking highs southwest of South America at about 55° S, 90° W tend to coincide with warm SO events (Rutllant and Fuenzalida 1991). Thus, precipitation anomalies in northern Patagonia are linked to both ENSO events and high-latitude circulation features, which themselves may be coupled. In the circumpolar flow at about 55° S, interannual variations in sea level atmospheric pressure, SST, and sea ice extent have been shown to have a periodicity of 4–5 yr for 1979–1994 (White and Peterson 1996). Over the interval 1746–1984, mean sea level atmospheric pressure has a peak oscillation of ~3.4 yr (Villalba et al. 1997). Such a close association between the oscillatory behaviors of circumpolar circulation and the SO has led to a postulated relationship to El Niño activity in the equatorial Pacific (White and Peterson 1996, Villalba et al. 1997). Variations at decadal to centennial time scales in major circulation features such as ENSO activity and the meridionality of regional air flow at high latitudes, as well as changes in the degree of coupling of these features, are important influences on climate and fire regimes of northern Patagonia.

At much longer time scales, increased fire has also been linked to periods of greater climatic variability. 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, Markgraf and Anderson 1994). The greater late-Glacial variability has been attributed to fluctuations in the extent of Antarctic sea ice, which, in turn, influence the latitudinal position of the westerly storm tracks. The variability of the late-Holocene appears to be related to the onset of ENSO as an important influence on mid-latitude climates along the west coast of South America (McGlone et al. 1992, Markgraf and Anderson 1994).

Conclusions

Changes in fire frequencies at multidecadal time scales in northern Patagonia strongly coincide with changes in human activities since the mid-19th century. In contrast, interannual variations in fire regimes closely track regional climatic variability, which accounts for the synchronous occurrence of major fire years over a north–south distance of ≥400 km. Although climatic variability overrides human influences on fire regimes at an interannual scale, human activity can be of equal or greater importance in determining fire frequency at multidecadal scales. However, by focusing on years of widespread fire that are mainly controlled by climate, it is feasible to relate changes in fire regimes and climate at decadal to centennial scales.

Interannual variation in both regional climate and fire extent in northern Patagonia is linked to variations in several potentially coupled, large-scale atmospheric features. Climatic conditions conducive to widespread fire in both rain forests and xeric woodlands are closely related to ENSO events. Years in which the southeast Pacific subtropical anticyclone is more intense and is located further south are also years of greater drought and fire. Despite the significant influence of tropical Pacific atmospheric phenomena, ENSO activity is not the sole determinant of fire weather in northern Patagonia. Years of widespread fire are also associated with an absence of atmospheric blocking events at about 50°–60° S that otherwise steer cyclonic storms northwards into northern Patagonia.

Similar to the association of drought and fire demonstrated here, other studies in northern Patagonia (Villalba and Veblen 1997*a*, 1998) show that the establishment of seedlings and mortality of adult trees of *Austrocedrus* are strongly associated with variations in ENSO and in the strength and position of the southeastern Pacific anticyclone. For example, the predominance of the negative mode of the Southern Oscillation (i.e., El Niño conditions) since the late 1970s is reflected by warmer summers and a lack of *Austrocedrus* seedling survival in dry habitats (Villalba and Veblen 1997*a*). However, tree ring proxy records indicate that over the past roughly 250 yr, there have been important variations at decadal to centennial time scales in major circulation features, such as ENSO activity and blocking events at high latitudes, and also in the relationships of climate in northern Patagonia to these circulation features. In order to understand possible impacts of global climate change on regional fire regimes and forest dynamics, it is important to consider past variations in large-scale atmospheric circulation features and fluctuations in the strengths of their influences on regional climates.

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Literature Cited

Aceituno, P. 1988. On the functioning of the Southern Oscillation in the South American sector. Monthly Weather Review **116**:505–524.

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C, USA.

Arno, S. F., and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. U.S. Department of Agriculture Forest Service General Technical Report **INT-42**.

Baisan, C. H., and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Canadian Journal of Forest Research **20**: 1559–1569.

Barrett, S., and S. Arno. 1982. Indian fires as an ecological influence in the northern Rockies. Journal of Forestry **80**: 647–651.

Barros, V., V. Cordón, C. Moyano, R. Méndez, J. Forquera, and O. Pizzio. 1983. Cartas de precipitación de la zona oeste de las provincias de Rio Negro y Neuquén. Report to the Facultad de Ciencias Agrarias, Universidad Nacional del Comahue, Cinco Saltos, Neuquén, Argentina.

Blasing, T. J., A. M. Solomon, and D. N. Duvick. 1984. Response functions revisited. Tree-Ring Bulletin **44**:1–15.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. Fire in forestry. Volume 1. Forest fire behavior and effects. John Wiley, New York, New York, USA.

Christensen, N. L. 1993. Fire regimes and ecosystem dynamics. Pages 233–244 *in* P. J. Crutzen and J. G. Goldammer, editors. Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires. John Wiley, Chichester, UK.

Clark, J. S. 1989. Effects of long-term water balances on fire regime, north-western Minnesota. Journal of Ecology **77**:989–1004.

———. 1990. Fire and climate change during the last 750 yr in northwestern Minnesota. Ecological Monographs **60**: 135–159.

Clark, J. S., and J. Robinson. 1993. Paleoecology of fire. Pages 193–213 *in* P. J. Crutzen and J. G. Goldammer, editors. Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires. John Wiley, Chichester, UK.

Covington, W. W., and M. Moore. 1994. Southwestern ponderosa forest structure. Journal of Forestry **92**:39–47.

Cox, G. 1863. Viajes a las regiones septentrionales de Patagonia 1862–1863. Anales de la Universidad de Chile **23**: 3–239 and 437–509.

Deser, C., and J. M. Wallace. 1987. El Niño events and their relationship to the Southern Oscillation. Journal of Geophysical Research **92**:14189–14196.

Diaz, H. F., and G. N. Kiladis. 1992. Atmospheric teleconnections associated with the extreme phases of the Southern Oscillation. Pages 7–28 *in* H. F. Diaz and V. Markgraf, editors. El Niño: historical and paleoclimatic aspects of the southern oscillation. Cambridge University Press, Cambridge, UK.

Diaz, H. F., and R. S. Pulwarty. 1992. A comparison of the Southern Oscillation and El Niño signal in the tropics. Pages 175–192 *in* H. F. Diaz and V. Markgraf, editors. El Niño: historical and paleoclimatic aspects of the southern oscillation. Cambridge University Press, Cambridge, UK.

Diaz, H. F., and R. S. Pulwarty. 1994. An analysis of the time scales of variability in centuries-long ENSO-sensitive records in the last 1000 years. Climatic Change **26**:317–342.

Dieterich, J. H. 1980. The composite fire interval—a tool for more accurate interpretation of fire history. Pages 8–12 *in* M. A. Stokes and J. H. Dieterich, editors. Proceedings of the Fire History Workshop, 20–24 October 1980, Tucson, Arizona. USDA Forest Service, General Technical Report **RM-GTR-81**.

Flannigan, M. D., and B. M. Wotton. 1991. Lightning-ignited forest fires in northwestern Ontario. Canadian Journal of Forest Research **21**:277–287.

Fonck, F. 1900. Viajes de Fray Francisco Menéndez a Nahuelhuapi. C.F. Niemeyer, Valparaiso, Chile.

Furlong, G. 1964. Nícolas Mascardi, S. J. y su carta relación (1670). Ediciones Theoria, Buenos Aires, Argentina.

Granström, A. 1993. Spatial and temporal variation in lightning ignitions in Sweden. Journal of Vegetation Science **4**: 737–744.

Grissino-Mayer, H. D. 1995. Tree-ring reconstructions of climate and fire history at El Malpaís National Monument, New Mexico. Dissertation. University of Arizona, Tucson, Arizona, USA.

Heusser, C. J. 1987. Fire history of Fuego-Patagonia. Quaternary of South America and Antarctic Peninsula **5**:93–109.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin **43**: 69–75.

Johnson, E. A., and C. P. S. Larsen. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. Ecology **72**:194–201.

Johnson, E. A., and D. R. Wowchuk. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. Canadian Journal of Forest Research **23**:1213–1222.

Karoly, D. J. 1989. Southern Hemisphere circulation features associated with El Niño–Southern Oscillation events. Journal of Climate **2**:1069–1090.

Kershaw, A. P. 1986. Climatic change and aboriginal burning in north-east Australia during the last two glacial/interglacial cycles. Nature **322**:47–49.

Kiladis, G. N., and H. F. Diaz. 1989. Global climate anomalies associated with extremes in the Southern Oscillation. Journal of Climate **2**:1069–1090.

Kitzberger, T., and T. T. Veblen. 1997. Influences of humans and ENSO on fire history of *Austrocedrus chilensis* woodlands in northern Patagonia, Argentina. Ecoscience **4**:508–520.

Kitzberger, T., and T. T. Veblen. *In press.* Fire-induced changes in northern Patagonian landscapes. Landscape Ecology.

Kitzberger, T., T. T. Veblen, and R. Villalba. 1997. Climatic influences on fire regimes along a rain forest-to-xeric woodland gradient in northern Patagonia, Argentina. Journal of Biogeography **24**:35–47.

LaMarche, V. C., R. L. Holmes, P. W. Dunwiddie, and L. G. Drew. 1979. Tree-ring chronologies of the Southern Hemisphere. Volume 1: Argentina. Chronology Series V. Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, USA.

Lara, A., and R. Villalba. 1993. A 3620-year temperature record from *Fitzroya cupressoides* tree rings in southern South America. Science **260**:1104–1106.

Larsen, C. P. S. 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1989. The Holocene **6**:449–456.

Lehtonen, H., and P. Huttunen. 1997. History of forest fires in eastern Finland from the 15th century AD—the effects of slash-and-burn cultivation. The Holocene **7**:223–228.

Leighton, M., and N. Wirawan. 1986. Catastrophic drought and fire in Borneo tropical rain forest associated with the 1982–1983 El Niño Southern Oscillation event. Pages 75–102 *in* G. T. Prance, editor. Tropical rain forest and the world atmosphere. Westview Press, Boulder, Colorado, USA.

Mann, M. E., and J. Park. 1994. Global-scale modes of surface temperature variability on interannual to century time scales. Journal of Geophysical Research **99**:25819–25833.

Markgraf, V., and L. Anderson. 1994. Fire history of Patagonia: climate versus human cause. Revista do Instituto Geográfico do Sao Paulo **15**:33–47.

McBride, J. R. 1983. Analysis of tree rings and fire scars to establish fire history. Tree-Ring Bulletin **43**:51–67.

McGlone, M. S., A. P. Kershaw, and V. Markgraf. 1992. El Niño/Southern Oscillation climatic variability in Australasian and South American paleoenvironmental records. Pages 435–462 *in* H. F. Diaz and V. Markgraf, editors. El Niño: historical and paleoclimatic aspects of the southern oscillation. Cambridge University Press, Cambridge, UK.

Mooney, C. Z., and R. D. Duval. 1993. Bootstrapping: a nonparametric approach to statistical inference. Sage University Paper Series on Quantitative Applications in the Social Sciences 95. Newbury Park, California, USA.

Nicholls, N. 1992. Historical El Niño/Southern Oscillation variability in the Australasian region. Pages 151–173 *in* H. F. Diaz and V. Markgraf, editors. El Niño: historical and paleoclimatic aspects of the southern oscillation. Cambridge University Press, Cambridge, UK.

O'Neill, R. V. 1988. Hierarchy theory and global change. Pages 29–45 *in* T. Rosswall, R. G. Woodmansee, and P. G. Risser, editors. Scales and global change. Wiley, New York, New York, USA.

Ortleib, L. 1994. Precipitaciones en Chile central y eventos ENOS en los siglos XVI–XIX. Revista Chilena de Historia Natural **67**:463–486.

Pittock, A. B. 1973. Global meridional interactions in the stratosphere and troposphere. Quarterly Journal of the Royal Meteorological Society **99**:424–437.

———. 1980. Patterns of climatic variation in Argentina and Chile. I. Precipitation, 1931–60. Monthly Weather Review **108**:1347–1361.

Quinn, W. H. 1992. A study of Southern Oscillation-related climatic activity for A.D. 622–1990 incorporating Nile River flow data. Pages 119–149 *in* H. F. Diaz and V. Markgraf, editors. El Niño: historical and paleoclimatic aspects of the southern oscillation. Cambridge University Press, Cambridge, UK.

Renkin, R. A., and D. G. Despain. 1992. Fuel moisture, forest type and lightning-caused fire in Yellowstone National Park. Canadian Journal of Forest Research **22**:37–45.

Risser, P. G. 1987. Landscape ecology: state of the art. Pages 3–14 *in* M. G. Turner, editor. Landscape heterogeneity and disturbance. Springer-Verlag, New York, New York, USA.

Romme, W. R. 1980. Fire history terminology—report of the ad hoc committee. Pages 135–137 *in* M. A. Stokes and J. H. Dieterich, editors. Proceedings of the Fire History Workshop, 20–24 October 1980. USDA Forest Service, General Technical Report **RM-GTR-81**.

Ropelewski, C. F., and P. D. Jones. 1987. An extension of the Tahiti-Darwin Southern Oscillation index. Monthly Weather Review **115**:2161–2165.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Research Paper **INT-115**.

Rothkugel, M. 1916. Los Bosques Patagónicos. Ministerio de Agricultura, Buenos Aires, Argentina.

Rutllant, J., and H. Fuenzalida. 1991. Synoptic aspects of the central Chile rainfall variability associated with the Southern Oscillation. International Journal of Climatology **11**:63–76.

Savage, M., and T. W. Swetnam. 1990. Early 19th century fire decline following sheep pasturing in a Navajo ponderosa pine forest. Ecology **71**:2374–2378.

Schulman, E. 1956. Dendroclimatic change in semiarid America. University of Arizona Press, Tucson, Arizona, USA.

Schwerdtfeger, W. 1976. Introduction. Pages 1–12 *in* W. Schwerdtfeger, editor. World survey of climatology. Elsevier, New York, New York, USA.

Swetnam, T. W. 1990. Fire history and climate in the Southwestern United States. Pages 6–17 *in* J. S. Krammes, technical coordinator. Effects of fire management of southwestern natural resources: Proceedings. USDA Forest Service, General Technical Report **RM-191**.

———. 1993. Fire history and climate change in giant sequoia groves. Science **262**:885–889.

Swetnam, T. W., and J. L. Betancourt. 1990. Fire–southern oscillation relations in the southwestern United States. Science **249**:1017–1020.

Swetnam, T. W., and J. L. Betancourt. 1992. Temporal patterns of El Niño/Southern Oscillation–wildfire teleconnections in the southwestern United States. Pages 259–270 *in* H. F. Diaz and V. Markgraf, editors. El Niño: historical and paleoclimatic aspects of the Southern Oscillation. Cambridge University Press, Cambridge, UK.

Trenberth, K. E., and K. C. Mo. 1985. Blocking in the Southern Hemisphere. Monthly Weather Review **113**:3–21.

Turner, M. G., and W. H. Romme. 1994. Landscape dynamics in crown fire ecosytems. Landscape Ecology **9**:59–77.

Veblen, T. T., B. R. Burns, T. Kitzberger, A. Lara, and R. Villalba. 1995. The ecology of the conifers of southern South America. Pages 120–155 *in* N. J. Enright and R. S. Hill, editors. Ecology of the southern conifers. Melbourne University Press, Melbourne, Australia.

Veblen, T. T., T. Kitzberger, and A. Lara. 1992. Disturbance and forest dynamics along a transect from Andean rain forest to Patagonian shrubland. Journal of Vegetation Science **3**:507–520.

Veblen, T. T., and D. C. Lorenz. 1988. Recent vegetation changes along the forest/steppe ecotone in northern Patagonia. Annals of the Association of American Geographers **78**:93–111.

Villalba, R. 1990. Climatic fluctuations in northern Patagonia during the last 1000 years as inferred from tree-ring records. Quaternary Research **34**:346–360.

———. 1994. Tree-ring and glacial evidence for the Medieval Warm Epoch and the Little Ice Age in southern South America. Climatic Change **26**:183–197.

———. 1995. Climatic influences on forest dynamics along the forest–steppe ecotone in northern Patagonia. Dissertation. University of Colorado. Boulder, Colorado, USA.

Villalba, R., E. R. Cook, R. D. D'Arrigo, G. C. Jacoby, P. D. Jones, M. J. Salinger, and J. Palmer. 1997. Sea-level pressure variability around Antarctica since AD 1750 inferred from subantarctic tree-ring records. Climate Dynamics **13**: 375–390.

Villalba, R., E. R. Cook, G. C. Jacoby, R. D. D'Arrigo, T. T. Veblen, and P. D. Jones. *In press.* Tree-ring based reconstructions of precipitation in Patagonia since AD 1600. The Holocene.

Villalba, R., and T. T. Veblen. 1997*a.* Regional patterns of tree population age structures in northern Patagonia: climatic and disturbance influences. Journal of Ecology **85**: 113–124.

Villalba, R., and T. T. Veblen. 1997*b.* Spatial and temporal variation in tree growth along the forest–steppe ecotone in northern Patagonia. Canadian Journal of Forest Research **27**:580–597.

Villalba, R., and T. T. Veblen. 1998. Influences of large-scale climatic variability on episodic tree mortality at the forest-steppe ecotone in northern Patagonia. Ecology **79**:2624–2640.

White, W. B., and R. G. Peterson. 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. Nature **380**:699–702.

Willis, B. 1914. El norte de la Patagonia. Dirección de Parques Nacionales, Buenos Aires, Argentina.