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Fire history in the *Araucaria araucana* forests of Argentina: human and climate influences

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Abstract. Little is known about drivers and trends of historic fire regimes in the *Araucaria araucana* forests of south-western Argentina. Fire history in these forests was reconstructed by the analysis of 246 fire-scarred partial cross-sections from this fire-resistant tree collected at 10 sites in Neuquén, northern Patagonia. Fire chronologies showed an increase in fire occurrence during the nineteenth century and a sharp decrease since the early twentieth century. The creation of Lanín National Park in 1937, the change in human activities, and the active suppression of wildfires led to a significant increase in mean fire intervals since 1930. In addition to these multidecadal to centennial scale drives of fire frequency, interannual variability in wildfire activity was associated with El Niño–Southern Oscillation. Years of widespread fire are related to negative departures of both Niño 3.4 and Pacific Decadal Oscillation indexes (i.e. La Niña conditions), as well as coincident phases of positive Southern Annular Mode and La Niña events. Temporal variations in the *Araucaria* fire history in Argentina clearly show the combined effect of human and climate influences on fire regimes. A comparison with previous fire history studies in the *Araucaria* forests of Chile reveals substantial differences related to differences in human activities on both sides of the Andes and the earlier implementation of protected areas in Argentina.

Additional keywords: dendroecology, fire scars, Patagonia, tree rings.

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Introduction

Fire activity is mainly driven by weather–climate, fuels, topography, ignition agents and humans (Johnson 1992; Swetnam 1993; Flannigan and Wotton 2001). Climatic variations and human activities influence fire regimes through their effects on fuel characteristics and ignition sources (Flannigan and Wotton 1991; Turner and Romme 1994; Marlon *et al.* 2008). Reconstructions of fire history have demonstrated strong associations between regional fire occurrence and climatic variation from interannual to multidecadal scales (Baisan and Swetnam 1990; Swetnam 1993; Kitzberger *et al.* 1997; Veblen *et al.* 1999). Superimposed on this regional climate influence on fire activity are human effects, which tend to be more localised and evident at time scales of decades or longer. Anthropogenic effects are complex and commonly include the increased frequency of ignition, land-use practices such as livestock grazing and active suppression of natural fires (Kershaw 1986; Savage and Swetnam 1990; Agee 1993; Lehtonen and Huttunen 1997). Since most landscapes and fire regimes have been altered to some degree by human activities, it is difficult to discriminate between anthropogenic and climatic influences on fire regimes (Veblen *et al.* 1999; Holz and Veblen 2011*a*).

Araucaria araucana, an evergreen coniferous tree native to south-central Chile and south-western Argentina, has a great potential for recording fire history. Due to its thick bark, trees withstand fires of low and medium intensity (Alfonso 1941; Tortorelli 1942; Veblen 1982; Burns 1993). In addition, *Araucaria* trees over 800 years old have been dated (LaMarche *et al.* 1979; Mundo *et al.* 2012), allowing long-term analyses of fire occurrence. In Villarrica National Park, IX Region of Chile, González *et al.* (2005) and Quezada (2008) used dendrochronological techniques to reconstruct fire history of the *Araucaria* forests in Quillelhue (39°35′S, 71°31′W; ~5 km from the international border with Argentina) and in Quetrupillán (39°29′S, 71°45′W; ~22 km north-west of Quillelhue) respectively. Both fire-history reconstructions indicate that human activities have altered fire regimes in the *Araucaria* forests. A significant increase in fire occurrence in Villarrica National

Park since the Euro-Chilean settlement era (post-1880) was recorded in comparison to the pre-settlement era when Native Americans inhabited the region. On the basis of instrumental records and ring-width chronologies as climate proxies, González and Veblen (2006) noted that moisture availability is the major factor influencing the fire occurrence in the *Araucaria* forests in Chile. Extensive fire years were strongly associated with warm and dry summers in relation to droughts one or 2 years prior to the event. The authors noted that the interannual variability in El Niño–Southern Oscillation (ENSO) has been a major forcing of fire activity in the region.

In the Argentinean sector of northern Patagonia (38–43°S), fire histories have been reconstructed in the xeric *Austrocedrus chilensis* forests and in the mesic *Fitzroya cupressoides* and *Nothofagus dombeyi* forests using dendrochronological methods (Kitzberger and Veblen 1997; Kitzberger *et al.* 1997; Veblen *et al.* 1999). At most *Austrocedrus* woodland sites, fire frequencies increased since ~1840 and peaked in the late nineteenth century. The mid-nineteenth century increase in fires in xeric woodlands is coincident with increased use of the *Austrocedrus* habitats by Native American hunters and the immigration across the Andes of Mapuche indigenous people, stimulated by an earlier European colonisation of southern Chile compared with the Argentinean lake region (Cox 1863). The 1890s to early 1900s was a period of extensive forest burning by European settlers to create cattle pasture (Moreno 1897; Willis 1914; Rothkügel 1916). Since ~1920, fire frequency decreased in both xeric and mesic forests due to the decrease in intentionally set fires, the reduction of fuel as a consequence of increased grazing by livestock and the active suppression of fires (Veblen *et al.* 2003). The synchronous occurrence of fires in the same years over extensive areas indicates a strong influence of interannual climatic variations on fire (Veblen *et al.* 1999). The increase of major fire years in the mid-1800s coincides with greater interannual climatic variations (Kitzberger and Veblen 2003). Thus, both humans and climatic variations appear to be responsible for increased burning after the mid-1800s. Both the documentary and tree-ring records of fire in northern Patagonia reflect strong influences of ENSO activity (Kitzberger and Veblen 1997; Veblen *et al.* 1999). Years of extreme fire occurrence were associated with both dry winter–springs of La Niña events and warm summers following El Niño events.

In contrast to the *Austrocedrus* forests, fire history in the more northerly *Araucaria* forests of Argentina has not been reconstructed using dendroecological methods. Early 20th- and 19th-century observers in the *Araucaria* forests of northern Patagonia in Argentina reported intentionally set fires to facilitate the collection of the large, edible *Araucaria* seeds (Rothkügel 1916; Tortorelli 1947). However, it is unclear whether synchronous changes in fire frequency in the *Araucaria* forests occurred simultaneously in Argentina and Chile and in the *Austrocedrus* forests farther south in Argentina. Here we asked whether the low fire-frequency periods recorded in the Chilean *Araucaria* and in the northern Patagonia *Austrocedrus* forests were synchronous with reduced fire occurrence in the *Araucaria* forests of Argentina. Specifically, we investigated whether the early 20th-century Euro-Argentinean settlement era and the establishment of Lanín National Park in 1937 altered the Native American fire regime in the *Araucaria* forests. We also explored how drivers of large-scale atmospheric circulation and their contingencies influence fire occurrence in the *Araucaria* forests of Argentina.

To answer these questions we: (1) reconstructed the fire history in 10 *Araucaria* sites in Argentina using dendrochronological methods, (2) analysed the frequency of these events over time and their relationships to major temporal changes in land use, (3) determined the climatic variables related to the occurrence of fires in the region and (4) assessed the individual and combined effects of large-scale climate forcings (ENSO, Pacific Decadal Oscillation and Southern Annular Mode) on fire occurrence.

Methods

Study area

Physiographically, the area encompasses the Argentinean Andes, the foothills and the adjacent Patagonian plains at a mean elevation of ~800 m. To the west, the Andes Cordillera reaches elevations over 2000 m and has a pronounced rainshadow effect on Pacific air masses bringing moisture to the region. Mean annual precipitation declines from >3000 mm near the continental divide to ~800 mm in the eastern foothills (Barros *et al.* 1983). Rainfall mainly occurs during the colder period of the year (April to September), with summer (December to February) being dry. Mean January and July air temperatures are 18 and 7.5°C (De Fina 1972; Heusser *et al.* 1988). Soils of the Andean *Araucaria* forests are derived from layers of recent (i.e. post-glacial) volcanic ash deposits (Casertano 1963). *Araucaria* also grows on well developed soils derived from metamorphic and sedimentary rocks (Peralta 1980).

Within the study area, *Araucaria* occurs in pure stands and in mixed forests with *Austrocedrus chilensis* and *Nothofagus* spp. The extensive Andean populations of *Araucaria* occur from the upper tree-line at ~1500 to 1800 m down to 900 m, with scattered occurrences down to 600 m (Veblen 1982). From 1200 m to the tree line, *Araucaria* forms mixed forests with *Nothofagus pumilio*. At the upper tree-line, *Araucaria* is often a striking feature of the landscape, maintaining tall, erect trunks whereas its common associate, *N. pumilio* adopts a 'krummholz' form (Eskuche 1968; Hueck 1978). In lower valleys, on drier, north-facing slopes, *Araucaria* mixes with the small tree *Nothofagus antarctica*. These mid-slope communities are probably post-fire stands (Burns 1993). Towards the east, where rainfall ranges from 1000 to 1500 mm year^{-1}, *Araucaria* occurs in woodlands with *Austrocedrus*, the small broadleaf tree *Lomatia hirsuta* and steppe shrub species. The easternmost stands of *Araucaria* occur as isolated groups of trees at 70°35′W at elevations ranging from 1600 to 1700 m (Veblen *et al.* 1995).

The sites sampled for developing the fire histories are located on the eastern slopes of the Andes in north-western Patagonia, Argentina, from 37 to 40°S (Fig. 1, Table 1). Sampling in the *Araucaria* forests was conducted at 10 sites from March 2006 through February 2008. Sampling sites were located in order to adequately represent habitat variation along elevation and precipitation gradients in the *Araucaria* district (Fig. 1). Elevation, slope and aspect for each site are presented in Table 1. All sites correspond to *Araucaria* pure stands, except for the Remeco site, where isolated *Austrocedrus chilensis* and *Nothofagus antarctica*

Fig. 1. Map showing the 10 areas sampled for developing the fire history of *Araucaria* forests in Argentina (see Table 1 for site code definition). NOR, RUC, MIN, PIN and TRO are located inside Lanín National Park.

trees occur. On the basis of the tree-ring growth patterns observed in nearby undisturbed sites (Mundo *et al.* 2012), sample sites were grouped into eastern and western groups. Eastern sites (Caviahue, Paso del Arco, Rahue and Nahuel Mapi) are located at high altitudes (>1400 m) to the east of 71°05′W. On the other hand, the western sites (Remeco, Ñorquinco, Ruka Choroy, Minchén, Pinalada Redonda and Paso Tromen) are located at low altitudes (<1300 m) to the west of the 71°05′W meridian. The Mapuche (indigenous inhabitants of south-central Chile and south-western Argentina) communities of Ñorquinco and Aigo are close to the Ñorquinco and Ruka Choroy sampling sites respectively. In contrast, other sites are located far from human settlements. In consequence, significant variations in the histories of human use are expected between sites. It is also noteworthy that the Paso Tromen site is located 0.2 km to the west of the international border between Argentina and Chile, and only 6 km south-west of Quillelhue, the site used by González *et al.* (2005) to reconstruct *Araucaria* fire history in Chile.

Field sampling

All sampling areas were intensively searched with the goal of sampling at least 20 fire-scarred trees. The exact fire dates were determined by extracting partial cross-sections from fire-scarred trees (Arno and Sneck 1977; McBride 1983) (Fig. 2). The sampling size per site varied between 0.178 and 56.969 ha (Table 1). Due to the lack of fire-scarred trees, the number of samples was lower than 20 at the Caviahue and Pinalada Redonda sites (7 and 18). However, both sites were included in our study because of its geographical representativeness. Information recorded for each sampled tree included: species, diameter at breast height, number of visible fire scars and the scar face azimuth. Location (geographical coordinates) of each fire-scarred tree sampled was recorded using a GPS unit. Maximum height above the ground for each fire scar was also estimated.

The processing of partial cross-sections followed standard dendrochronological procedures (Stokes and Smiley 1968; Arno and Sneck 1977; McBride 1983). Samples were air-dried and sanded to create polished surfaces to facilitate the identification of the annual rings under the stereo microscope (10–50×). Dates of rings containing fire scars were determined by counting backwards from the outermost ring and visually verified by cross-dating against marker rings from reference chronologies (Mundo *et al.* 2012). Fire scars from trees showing periods of severely suppressed growth were cross-dated quantitatively using the program COFECHA (Holmes 1983). This software statistically compares the ring-width series from the cross-section with a master tree-ring chronology from a nearby site.

According to Schulman's (1956) convention for the Southern Hemisphere, calendar years of annual rings are assigned to the year in which ring formation begins. Whenever possible, we determined the seasonality of scars. This assessment was made based on the position of the scar within the ring (Dieterich and Swetnam 1984). Five seasonal categories for fire scars were established (modified from Baisan and Swetnam 1990): E, early (first one-third of the ring); M, middle (second one-third of the ring); L, late (third one-third of the ring); D, dormant season (appearing between growth rings); and U, undetermined. We assumed that a fire scar in the seasonal category E was formed from October to December, M from January to February and L during March. Dormant season fires could occur in any month from April through September, but most National Parks records in northern Patagonia indicate that most dormant season fires occur in April and May.

Data analyses

Spatial and temporal analyses of fire

We used the program FHX2 (Grissino-Mayer 1995) to calculate standard fire statistics, including composite mean fire interval (MFI; mean time between successive fires in a specified search area) and point fire interval (recurrence of fire for an individual tree). Both means and the Weibull median probability

Table 1. Site characteristics of areas sampled for *Araucaria* fire history
The longitude and latitude coordinates correspond to the centroids of the polygons defined by the sampled trees and calculated by the convex hull method

Site	Code	Group	Latitude	Longitude	Area (ha)	Elevation (m ASL)	Slope (°)	Aspect	Number of samples
Caviahue	CAV	Eastern	37°51′18.3″S	71°02′19.1″W	0.178	1683	6	E (94°)	7
Paso del Arco	PAR	Eastern	38°49′57.1″S	71°03′21.5″W	14.403	1433	4	E (101°)	22
Remeco	REM	Western	39°04′00.4″S	71°19′49.7″W	1.231	1111	22	W (258°)	20
Ñorquinco	NOR	Western	39°09′21.2″S	71°15′13.1″W	7.326	1170	15	N (344°)	40[B]
Ruka Choroy	RUC	Western	39°14′01.7″S	71°10′24.1″W	4.320	1270	9	N (307°)	23
Minchén	MIN	Western	39°15′17.9″S	71°13′12.8″W	6.412	1287	6	NE (24°)	40[B]
Pinalada Redonda	PIN	Western	39°18′35.4″S	71°17′06.3″W	0.970	1094	11	NE (52°)	18
Rahue[A]	RAH	Eastern	39°23′36.5″S	70°47′39.8″W	7.852	1463	8	SE (141°)	22
Nahuel Mapi	MAP	Eastern	39°32′26.7″S	71°02′26.6″W	56.969	1500	1	N (4°)	31
Paso Tromen	TRO	Western	39°35′00.0″S	71°27′36.7″W	20.526	1215	1	E (90°)	23

[A]For Rahue, the coordinates correspond to a midpoint between the centroids of the two sub-sites sampled on the area.
[B]In Ñorquinco and Minchén, 14 samples (at each site) were taken in 1997 by T. Kitzberger (unpubl. data).

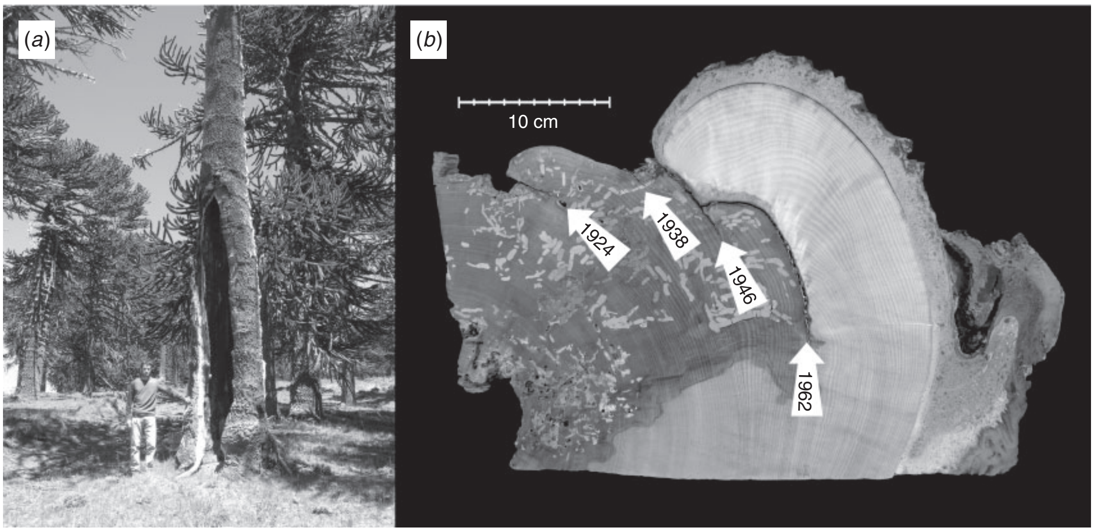

Fig. 2. Fire scars in *Araucaria*: (*a*) a multiple fire-scarred tree in Rahue site and (*b*) its scar pattern in a processed partial cross-section. Arrows indicate fire dates.

interval (WMPI) were determined (Grissino-Mayer 1999, 2001). The WMPI describes the fire interval associated with the 50th percentile of the fitted distribution in which half of the fire intervals will exceed and half will be shorter than the WMPI (Grissino-Mayer 1995). The composite fire intervals were calculated for the periods in which there were at least four recorder series and two scars in the first event. Kolmogorov–Smirnov goodness-of-fit tests were used to evaluate the fits of fire interval distributions to normal distributions (Grissino-Mayer 1995).

We analysed fire intervals based on the occurrence of any fire in the study area (≥1 trees scarred), and fire years in which at least 10% of the recorder trees (i.e. fire-scar susceptible trees that have been scarred previously or during the fire year of interest, *sensu* Romme 1980) were scarred. Site records were aggregated into western and eastern groups and all together into a regional composite. In each case, two composites were calculated according to the following filters: (1) all events and (2) fire scars recorded on two or more trees and on at least 10% of the recorder trees.

To analyse whether there were changes in the recurrence of regional fires before and after the Euro-Argentinean settlement (*c*. 1880) and before and after the establishment of Lanín National Park in 1937, fire parameters were compared in three 57-year equal-length sub-periods: pre-Euro-Argentinean settlement, 1823–1879; Euro-Argentinean settlement, 1880–1936; and the National Park period, 1937–1993. Fire intervals in these three periods were compared first by a non-parametric Kruskal–Wallis test and then, in case of differences, by paired comparison by Mann–Whitney *U* tests.

Analyses of climatic influences on fire occurrence

Superposed Epoch Analysis (SEA) (Grissino-Mayer 1995) was used to relate fire years with interannual climatic variation, the El Niño Southern Oscillation (ENSO), the Pacific Decadal

Table 2. Summary information of fire chronologies
Diameter at breast height (DBH) and Scar height are mean ± standard error

Site	DBH (cm)	Scar height (m)	Number of dated samples	Fires dated		Years with fire scars
				First	Last	
Caviahue	95 ± 8	2.22 ± 0.45	7	1824	1993	12
Paso del Arco	101 ± 7	2.07 ± 0.33	17	1710	2005	19
Remeco	97 ± 6	2.80 ± 0.37	19	1822	1986	18
Ñorquinco	89 ± 4	3.44 ± 0.33	31	1802	1998	27
Ruka Choroy	89 ± 4	3.65 ± 0.38	19	1836	1940	10
Minchén	98 ± 3	2.67 ± 0.23	27	1831	1935	23
Pinalada Redonda	86 ± 7	1.81 ± 0.26	14	1841	1967	10
Rahue	92 ± 4	3.00 ± 0.44	19	1811	2003	16
Nahuel Mapi	98 ± 5	3.40 ± 0.65	24	1441	1999	45
Paso Tromen	90 ± 7	1.54 ± 0.24	16	1762	1995	21

Oscillation (PDO) and the Southern Annular mode (SAM). SEA determines the relationship between fire events and climatic data (or climatically sensitive tree-ring chronologies) in the years before, during and after fire years. Mean values of these data were calculated for 4-year windows, including the year of the fire event. Mean values of climatic parameters during the fire-event years were compared with variations in the complete record by performing 1000 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. Using SEA, we compared the proxy records and climate indexes against widespread regional fires (i.e. fire dates recorded on at least 10% recorder trees in at least two sites).

On the basis of the absence of long and reliable temperature and precipitation instrumental records in the region and on the proven *Araucaria* tree-ring growth response to these variables, we used a residual *Araucaria* regional tree-ring chronology as a climate proxy record over the period 1140–2006 (Mundo *et al.* 2012) to investigate relationships between fire occurrence and climate over long periods. Regional *Araucaria* growth is strongly negatively related to temperatures during summer and autumn in the previous growing season and spring in the current growing season. A positive association of tree growth with precipitation is recorded during spring in the current growing season. To determine the relationship between fire occurrence and climate forcings, three records were used: (1) annual (January–December) Niño 3.4 index (1871–2007) derived from Trenberth and Stepaniak (2001), (2) annual PDO index reconstructed from tree rings (1700–1979) from D'Arrigo *et al.* (2001) and (3) annual SAM over the period 1887–2005 (Visbeck 2009). SEA was conducted using the program EVENT ver. 6.02P (http://www.ltrr.arizona.edu/software.html, accessed November 2011). In all analyses, significant differences were considered for $\alpha = 0.05$.

To evaluate the effect of PDO × ENSO and SAM × ENSO interactions, we calculated the proportion of widespread regional fires that occurred during each of the four PDO × Niño 3.4 index (SAM × Niño 3.4 index) phase combinations, and compared this to the proportion of years that fell within each phase combination during the complete 1871–1979 (1887–2005) period to determine whether fires occurred disproportionately during a particular phase combination (*sensu* Schoennagel *et al.* 2005). We used Chi-square tests to assess departure from expected frequency.

Results

Site chronologies

In all, 78% of the 246 collected samples were successfully dated (Table 2, Fig. 3). Groups of extremely narrow rings, advance wood decay, or ambiguous fire-scar tips were the major limitations for dating the remaining samples (22%). The oldest fire was dated to the year 1441 in the Nahuel Mapi sampling site. This site also showed the most frequent fire pattern in comparison to other sites. The most recent fire was dated to the year 2005 at the Paso del Arco site.

Taking into account the number of scars in each sample, approximately half of the samples were classified as single-scarred type (95) whereas the remaining 50% as multiple-scarred type. Most of the multiple-scarred samples show two fire scars (63 samples). The maximum number of fire scars dated on a single sample was 9 (sample TRO17 in the Tromen site).

Fire-scars were oriented upslope in almost every site, except for the Pinalada Redonda and Rahue sites. Fire seasonality was not clearly established in most scars (~70% of the scars were classified as undefined). For those samples where the position of the scar within the ring could be established, most fires were classified in the categories of early season (63%) followed by mid-season fires (29%). Only eight scars (7%) were classified as late-season fires and only two scars were produced during the dormant season at the Minchén site.

The composite MFI of all fire years varied between 5 and 16.3 years among sites (Table 3). For years of widespread fires (i.e. ≥10% recorder trees scarred), the MFI varied between 8.9 and 32 years among sites. In all sites, fire-interval distributions were described better by the Weibull than by the normal distribution as determined by the Kolmogorov–Smirnov goodness-of-fit test. The composite WMPI was always less than the MFI. As was expected, the maximum and minimum intervals for consecutive fires were generally greater for widespread fires

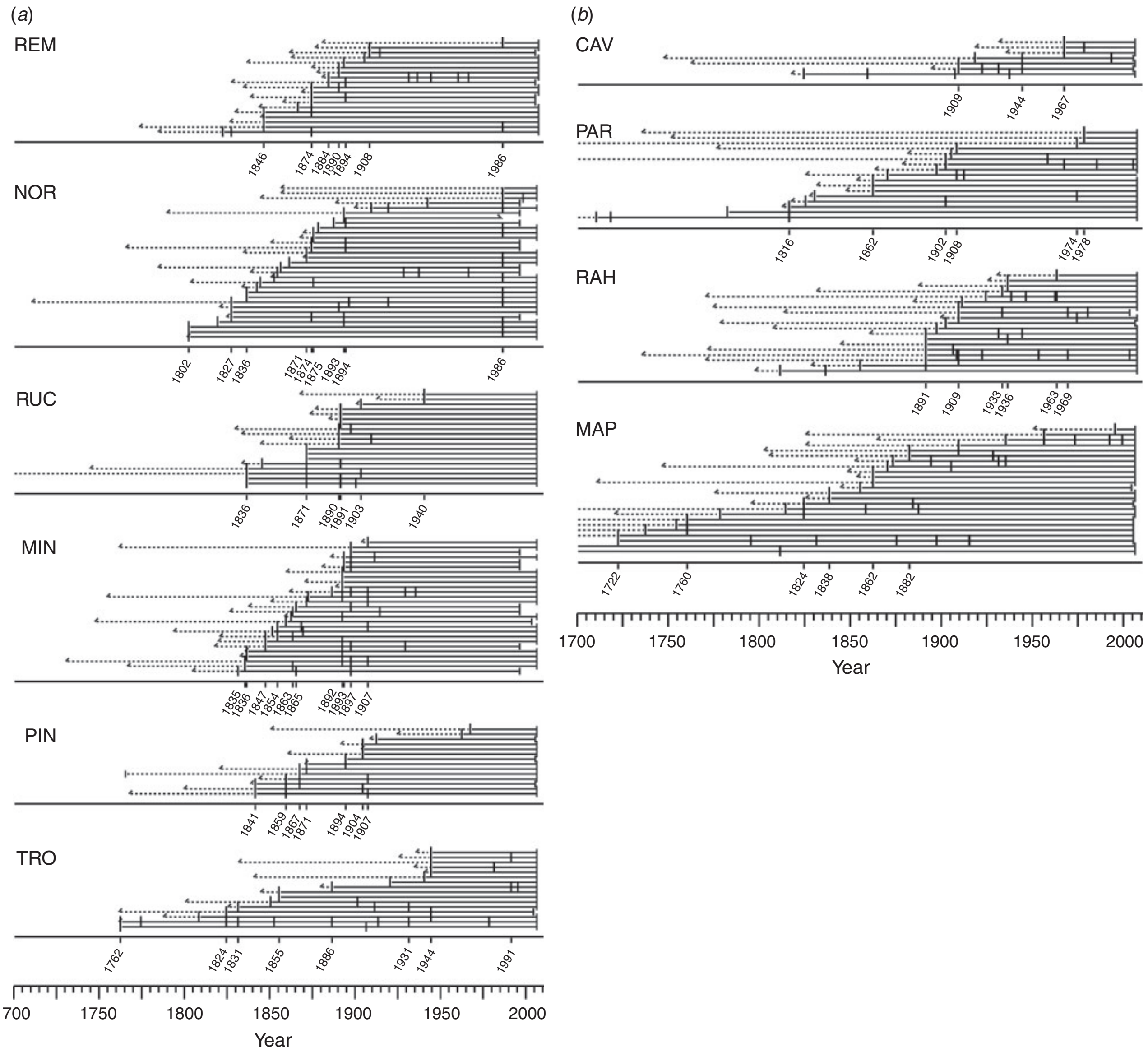

Fig. 3. Records of fire scars on individual trees and composite fire chronologies for each of the 10 sample areas for (*a*) western and (*b*) eastern sites. Each horizontal line represents a different tree on which dates of fire scars are indicated by short vertical lines. At the bottom of each chart, vertical lines drawn to the *x*-axis indicate occurrence of fire scars on at least one tree in the sample area (i.e. the composite chronology). For individual trees, pith dates and bark dates are respectively indicated by vertical lines at the beginning and at the end of the series and dates of innermost and outermost rings are indicated by half arrows at the beginning and at the end of the series. Dashed lines indicate years before the occurrence of the first scar on that tree. See Table 1 for code definitions.

than for all fire years. However, at the Pinalada Redonda site, widespread fires occurred more frequently. The recurrence of fire for an individual tree (i.e. only multiple-scarred trees) was generally greater than those registered for all trees at a single site (Table 4).

For the common period 1867–2006, the MFI and WMPI for all fire years range from 5.6 to 14.3 and from 4.4 to 9.9 years. For years of widespread fires (i.e. 10% recorder trees scarred), the MFI and WMPI for the common period range from 5.0 to 35 years and from 4.1 to 34.2. The lowest values of MFI and WMPI were found in the Minchén site, whereas the highest values for all fire years and widespread fires were respectively recorded at the Pinalada Redonda and Tromen sites. Only in the Minchén and Pinalada Redonda sites were the MFI and WMPI for widespread fires smaller than those for all fire years.

At Paso del Arco, Remeco, Pinalada Redonda, Nahuel Mapi and Tromen, fires were more frequent during the Euro-Argentinean settlement (1880–1936) than in the pre-settlement period (1823–1879). The opposite trend was observed at Ñorquinco and Minchén. All sites, where intervals allowed for comparisons, show an increase in MFI (although this variable was not estimated at each site due to scarce number of scars)

Table 3. Composite fire interval statistics for all fire events for the three 57-year sub-periods during the 1823–1993 interval

Sub-periods: 1823–1879, pre-settlement; 1880–1936, Euro-Argentinean settlement; 1937–93, after the establishment of Lanín National Park. Different lower-case superscript letters indicate statistical significance ($P < 0.05$). WMPI, Weibull median probability interval; MFI, composite mean fire interval; s.d., standard deviation of the mean fire interval (FI); n.a., insufficient intervals to perform the analyses

Site or group	Sub-period	WMPI (years)	MFI (years)	s.d.	Number of FI	Maximum FI (years)	Minimum FI (years)
Caviahue	1823–1879	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	1880–1936	5.69	6.00	3.56	4	9	2
	1937–1993	13.74	14.00	6.83	4	23	7
Paso del Arco	1823–1879	12.36	15.00	14.8	3	32	5
	1880–1936	3.79	3.75	0.96	4	5	3
	1937–1993	6.85	6.75	2.06	4	9	4
Remeco	1823–1879	15.80	15.67	6.66	3	20	8
	1880–1936	5.52	6.50	5.18	8	17	1
	1937–1993	13.80	14.00	7.21	3	20	6
Ñorquinco	1823–1879	4.13	4.64	3.17	11	10	1
	1880–1936	4.85	5.86	4.71	7	13	1
	1937–1993	15.45	16.33	10.02	3	24	5
Ruka Choroy	1823–1879	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	1880–1936	3.59	3.80	2.17	5	6	1
	1937–1993	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Minchén	1823–1879	2.67	3.15	2.7	13	11	1
	1880–1936	5.38	6.13	4.45	8	15	1
	1937–1993	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pinalada Redonda	1823–1879	9.25	10.00	7.21	3	18	4
	1880–1936	5.78	6.00	3.61	3	10	3
	1937–1993	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rahue	1823–1879	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	1880–1936	3.62	4.09	2.98	11	11	1
	1937–1993	5.01	5.25	2.60	8	9	1
Nahuel Mapi	1823–1879	5.64	6.38	4.84	8	17	2
	1880–1936	4.92	5.30	3.33	10	13	2
	1937–1993	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Paso Tromen	1823–1879	6.11	7.75	7.8	4	19	2
	1880–1936	6.94	7.50	4.72	6	15	2
	1937–1993	9.28	12.75	14.5	4	34	3
Regional (all sites)	1823–1879	1.42	1.50[a]	0.81	36	4	1
	1880–1936	1.40	1.50[a]	0.77	36	4	1
	1937–2006	2.16	2.34[b]	1.45	29	7	1
Eastern	1823–1879	3.26	4.25[a]	4.52	12	17	1
	1880–1936	2.37	2.45[a]	1.18	22	5	1
	1937–2006	3.01	3.24[a]	1.89	21	7	1
Western	1823–1879	1.66	1.80[a]	1.13	30	5	1
	1880–1936	1.54	1.79[a]	1.57	29	8	1
	1937–2006	3.92	4.69[b]	4.2	13	16	1

after the establishment of Lanín National Park. However, differences in MFI between the 57-year periods at site level were not significant due to the high MFI variability between periods.

Temporal patterns of fire regimes

Temporal patterns of fire occurrence exhibit regional consistencies as well as important inter-site differences (Figs 3, 4). Considering all fire years, seven fire events (1836, 1871, 1894, 1897, 1909, 1931 and 1944) were recorded in more than four sites. The temporal synchrony of fires over extensive areas (Figs 5, 6) suggests that fire occurrence is influenced by climatic variability. For example, at five sites fires were recorded in the years 1897, 1909 and 1931, which corresponds to 50% of the recorder sites for those dates (Fig. 6).

The high frequency of fires during the 19th century is the most obvious regional pattern (Fig. 4). Fire frequency during the 19th century was higher than in the 20th century at regional, sub-regional (groups) and local scales. The incidence of fires in the study area declined during the 20th century, a distinguishable pattern also for widespread fires. Regionally, fire interval comparison for all fire years between the three 57-year sub-periods show significant differences ($H = 8.63$, $P = 0.01$). Although the pre-settlement (1823–1879) and the Euro-Argentinean settlement periods (1880–1936) did not differ between them ($U = 638$, $P = 0.89$) (Table 3), fire intervals significantly increased after the establishment of Lanín National

Table 4. Point fire interval statistics for all fire events

WMPI, Weibull median probability interval; MFI, mean fire interval; s.d., standard deviation of the mean fire interval (FI)

Site	Period	WMPI (years)	MFI (years)	s.d.	Number of FI	Maximum FI	Minimum FI
Caviahue	1747–2006	12.1	15.4	14.4	11	48	2
Paso del Arco	1534–2007	15.9	22.7	26.7	13	98	4
Remeco	1773–2007	10.4	10.9	6.0	15	20	4
Ñorquinco	1700–2006	7.4	8.9	6.8	22	29	1
Ruka Choroy	1632–2006	6.9	9.1	8.8	8	26	1
Minchén	1700–2006	4.0	4.9	4.3	21	15	1
Pinalada Redonda	1765–2006	9.8	11.0	8.0	6	23	3
Rahue	1735–2007	6.5	9.1	5.8	21	23	1
Nahuel Mapi	1441–2006	10.2	19.2	41.5	29	228	1
Paso Tromen	1760–2006	11.1	13.7	11.1	17	34	2

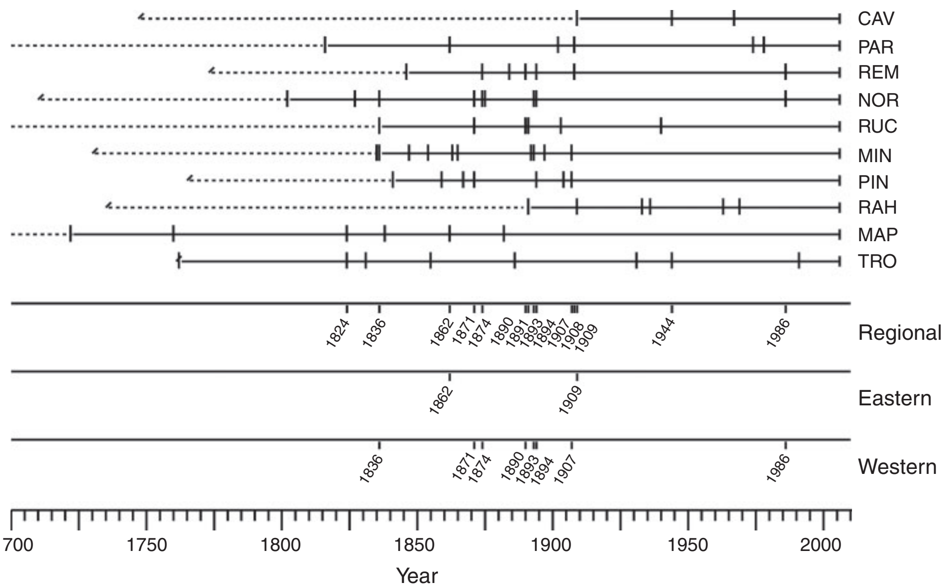

Fig. 4. Composite fire chronologies of each of the sample areas for widespread fires (i.e. fire scars recorded on two or more trees and on at least 10% of the recorder trees). At the bottom of each chart, vertical lines drawn to the *x*-axis indicate occurrence of fire scars for at least two sites for all 10 sample areas combined (i.e. regional composite) or by groups (eastern and western composites). Eastern sites: CAV, PAR, RAH and MAP. Western sites: REM, NOR, RUC, MIN, PIN and TRO. See Table 1 for code definitions.

Park (1937–2006) ($U = 279$, $P = 0.01$). The western sites show a frequent recurrence of widespread fire between 1825 and 1910, and consequently both the earlier periods recorded shorter fire intervals than did the 1937–2007 period ($H = 13.23$, $P = 0.001$). In contrast, a homogeneous fire regime throughout the 19th and 20th centuries was recorded in the eastern sites with no significant differences in MFI during the three sub-periods considered ($H = 1.52$, $P = 0.47$).

Climate influence on fire occurrence

Superposed Epoch Analysis indicates that the growth of *Araucaria* was below the long-term mean during years of widespread regional fires (Fig. 7*a*), reflecting dry conditions, especially during summer (Mundo *et al.* 2012). Over the period 1871–1987, years of widespread fire and the years before fire

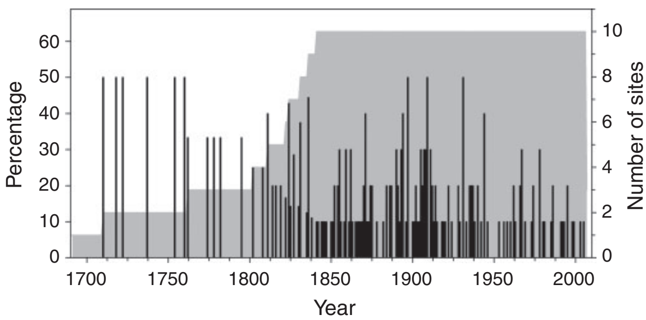

Fig. 5. Records, based on all 10 sites, showing percentage of sites with scars per year. Sample depth lines give the number of sites with recorder trees alive in each year.

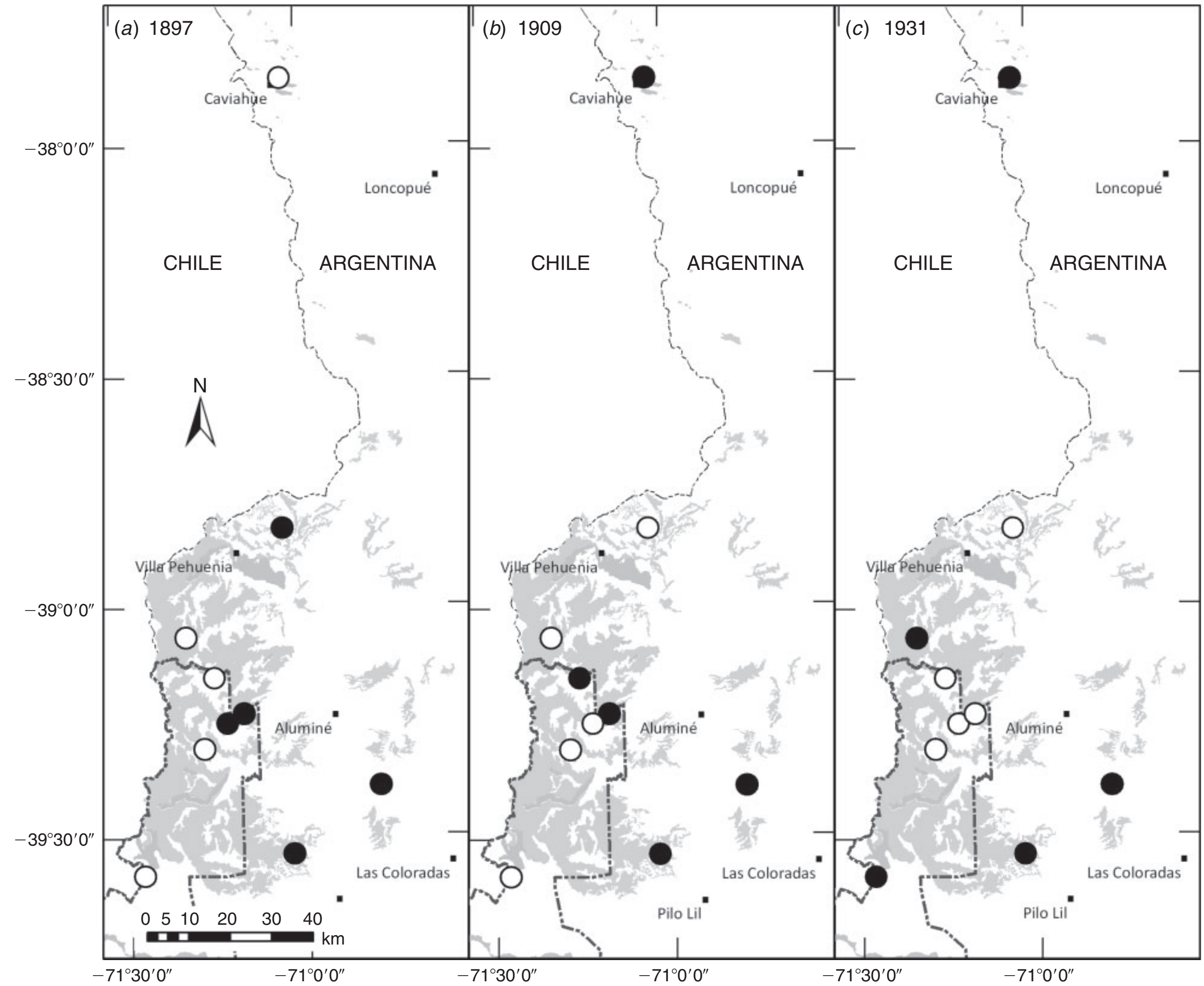

Fig. 6. Maps showing sites (solid symbols) that recorded fire (*a*) in 1897, (*b*) in 1909 and (*c*) in 1931. Open symbols are sites that had recorder trees at the date of the respective fire events but did not record fire.

occurrence were, on average, years of significant negative departures for the Niño 3.4 index, indicating La Niña conditions across the tropical Pacific (Fig. 7*b*). Similarly, the annual PDO index was significantly negative during widespread fires over the period 1822–1945 (Fig. 7*c*). Annual SAM indices were above average during the prior year and the fire year, reaching statistical significance only during the previous year (Fig. 7*d*).

Widespread fire occurrence in the *Araucaria* forests was also influenced by the combined phases of PDO and ENSO (Fig. 8*a*). Widespread fires in these forests occurred more frequently (70%) during years of negative PDO–negative Niño 3.4 (La Niña), although these phases co-occurred only 31% of the time during the 1871–1979 period ($\chi^2 = 7.162$, $P = 0.007$). In the case of SAM and ENSO combinations (Fig. 8*b*), widespread fires tend to occur more frequently (56%) during years of positive SAM–negative Niño 3.4 in the 1887–2005 period ($\chi^2 = 5.003$, $P = 0.025$). However, these results should be considered with caution given the low number of regional widespread fire events recorded in the interval 1887–2005.

Discussion

Human influences

According to the recurrence of events reconstructed since 1700, fires have been a major disturbance in the *Araucaria* forests of Argentina. The composite MFI for (a) the complete record, (b) the common period and (c) the point records, shows great variability among sites. The highest fire frequency observed in the Minchén (MFI for common period: 5 years) might be associated with its location in the Calfiquitra valley bottom near to the Ruka-Choroy lake. This site has been heavily used by the native Mapuche groups for cattle grazing due to its easy access and the abundance of grasses. The long-term human presence might be the principal cause for the comparatively higher fire frequency in this area. In contrast, the relatively low fire frequency observed in the Pinalada Redonda site reflects its location far from the influence of native populations. Located in the Malalco valley, the Pinalada Redonda sampling was conducted in a dense sapling forest near a basaltic cliff. Although a native

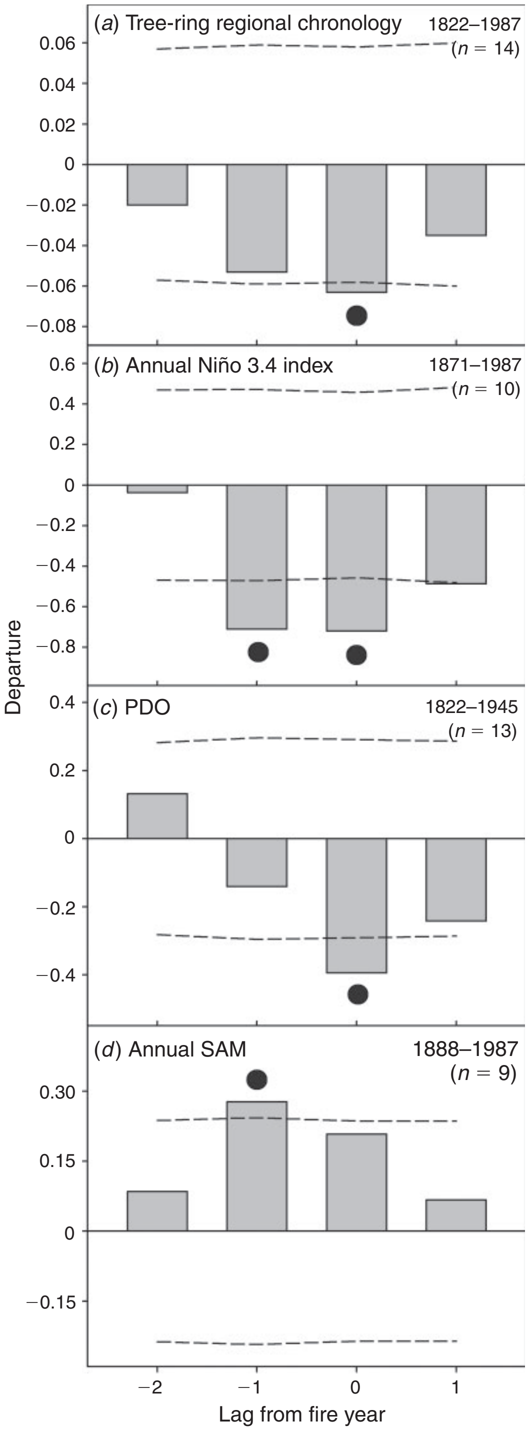

Fig. 7. Departure (standard deviations) from mean values for: (*a*) residual regional tree-ring chronology of *Araucaria* over the period 1140–2006 (Mundo *et al.* 2012), (*b*) annual Niño 3.4 index (1871–2007) derived from Trenberth and Stepaniak (2001) monthly index, (*c*) annual Pacific Decadal Oscillation (PDO) index reconstruction (1700–1979) from D'Arrigo *et al.* (2001) and (*d*) annual Southern Annular Mode (SAM) index over the period 1887–2005 (Visbeck 2009) for years before, during and after fire years (0) for regional widespread fires (i.e. years recording fire scars on at least 10% of recorders and a minimum of two scars on at least two sites). Bars capped with dots indicate statistically significant differences ($P < 0.05$). Dashed lines represent the 95% confidence limits.

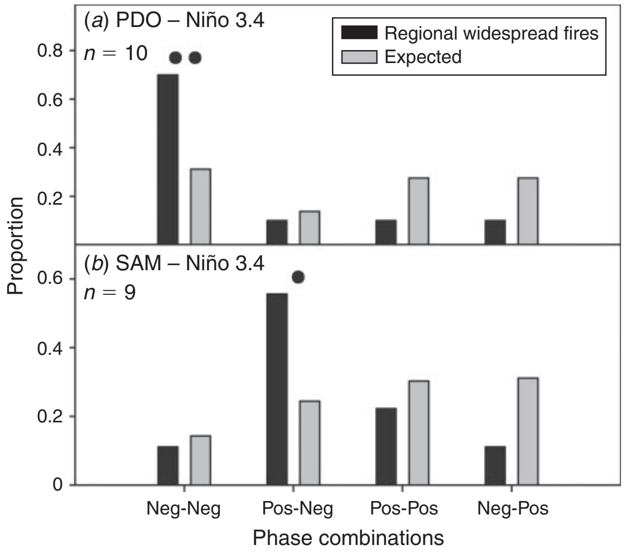

Fig. 8. Proportion of observed regional widespread fires (i.e. 10% recorder trees in at least two fire scars and in a minimum of two sites) in *Araucaria* forests relative to the expected total proportion of years during the period 1871–1979 (grey bars) in each (*a*) PDO–ENSO and (*b*) SAM–ENSO phase combination. PDO reconstruction (1700–1979) from D'Arrigo *et al.* (2001), annual Niño 3.4 index (1871–2007) derived from Trenberth and Stepaniak (2001) monthly reconstruction (updated record available at: http://www.cgd.ucar.edu/cas/catalog/climind/TNI_N34/index.html, accessed November 2011) and Southern Annular Mode index (SAM) annual reconstruction over the period 1887–2005 (Visbeck 2009). Paired bars capped with dots indicate statistically significant differences (two dots, $P < 0.05$; one dot, $P < 0.1$).

Mapuche population established along the Quillén Lake coast very close to the Malalco valley many centuries ago, it is possible that the Pinalada Redonda area was not frequently visited in the past due to its difficult access. The shorter MFI in the Pinalada Redonda for widepread fires in comparison to the complete record is related to the higher number of recurrent large fire events concentrated at the beginning of the record. The composite MFI at a site level shows similar values to those recorded in Chile (González *et al.* 2005; Quezada 2008).

At a regional scale, the establishment of Lanín National Park, the changes in cultural patterns, and the fire-control policy had a strong effect on the fire history of these forests. Consistent with the pattern detected at the site level as well as in the Lake Region of northern Patagonia (~41°S), a strong decrease in regional fire occurrence was observed since the beginning of the 20th century. In dry environments, this decrease in fire frequency might be associated with the displacement and extermination of native populations, who previously set fires mainly for hunting and warfare (Veblen *et al.* 2003). In contrast, the decrease in fire frequency in the mesic areas appears to be related to the cessation of frequent burning following the Euro-Argentinean settlement period of extensive fires to clear forests (Willis 1914). The high livestock pressure starting in 1900 may have also reduced the abundance of fine fuel and therefore fire activity. A similar and synchronous pattern of fire reduction since early 20th century has been observed for the *Austrocedrus* woodlands in northern Patagonia (Kitzberger and Veblen 1997).

In our study, differences in fire frequency trends between site groups (western and eastern) might be related to the fire-enforcement practices of most western sites (except Remeco) within Lanín National Park. In contrast, in the eastern sites in areas not protected by National Parks, neither the Euro-Argentinean colonisation nor the fire-control policy enforced since the 1930s substantially modified fire frequency.

The local and regional temporal patterns of fires recorded in our study differs from the increasing fire frequency trend observed in the *Araucaria* forests of Chile since 1883 (González *et al.* 2005; Quezada 2008). In Quillelhue, Villarrica National Park, fire frequency during the 20th was double that of the two previous centuries (18th and 19th). This remarkable increase in fire frequency coincided with the arrival of the Euro-Chilean settlers to the region after 1883, coincident with the incorporation of the Araucanía Region into the national territory (González and Veblen 2007). The lower fire frequency since 1960 coincides with the more effective control and prevention of fires after the establishment of Villarrica and Tolhuaca National Parks (González and Veblen 2007).

Fire frequencies since the arrival of the European settlers on sides of the northern Patagonian Andes show opposite patterns. In Argentina, the cutting and burning of the forests for land conversion to agriculture and livestock raising was restricted to one or three decades (1890–20). In contrast, fires were a common practice in Chile until the 1950–60s. In addition, the more recent establishment of protected areas in Chile compared with Argentina partly explains the differences in fire regimes recorded in both countries.

Climatic influences

Annual synchrony of widespread fires in the *Araucaria* forests of Argentina reflects the influence of interannual climatic variability. For example, fires in 1944 were recorded at four sites: Caviahue, Remeco, Rahue and Tromen. Severe forest fires in 1944 burnt 44 855 ha in the four National Parks in northern Patagonia (Veblen *et al.* 2003, 2008). In Quillelhue, Villarrica National Park (Chile), there was a severe fire in 1944, concurrent with the massive flowering and death of the bamboo *Chusquea culeou* at a regional level (González *et al.* 2005). Tortorelli (1947) described the quick spread of fires in the *Araucaria* forests during January 1943 in 3500 ha located in the north of Lanín National Park. These fires were also favoured by the massive flowering and withering of the bamboo *C. culeou*. During the period 1940–45, severe droughts fostered the development of large fires in the region (Veblen *et al.* 2003; González *et al.* 2005). The spring and summer of 1942–43 were extremely dry, and the period November 1943 to February 1944 was the second driest in the entire 20th century. Instrumental records since 1905 do not record another 2-year period with similar drought severity in spring–summer (Veblen *et al.* 2003, 2008).

On the basis of the relationship between climate and *Araucaria* growth (Mundo *et al.* 2012), the association between fire years and reduced radial growth suggests that fire occurrence is related to above-mean summer temperatures during the previous and current growing seasons concurrent with low rainfall in current spring. Large-scale climate modes influence the occurrence of fires in these forests. The cool phase of ENSO (i.e. La Niña) is the major driver of fires. The PDO–ENSO and SAM–ENSO phase combinations are also strongly associated with fire occurrence. ENSO is the primary source of variation in the intensity and location of the high-pressure cell in the south-east Pacific, which influences weather and consequently fire occurrence in the Patagonian forests. During La Niña events, the high-pressure cell intensifies and displaces farther south in winter (Aceituno 1988). Consequently, below-average precipitation during winter and spring (May through November) is recorded along western South America (Aceituno 1988; Kiladis and Díaz 1989; Villalba and Veblen 1998). Years of extreme fire occurrence in the *Austrocedrus* woodlands and the *F. cupressoides* rainforests were associated both with dry winter–springs during La Niña events and with warm summers following El Niño events (Veblen *et al.* 1999). In the Chilean *Araucaria* forests, years of high fire activity coincide with warm and dry summers following El Niño events (González and Veblen 2006).

The contingent analysis of PDO and ENSO clearly revealed their combined effect on fire occurrence in the *Araucaria* forests. Gershunov and Barnett (1998) define *constructive* (same-sign) phases of the PDO and ENSO when both oscillations are simultaneously in the cool phase (negative PDO, La Niña) or the warm phase (positive PDO, El Niño), whereas *destructive* (opposite-sign) phases occur when warm (cool) PDO and cool (warm) ENSO phases co-occur. Research in North America indicates that the phases of the PDO might strengthen or weaken ENSO teleconnections (Gershunov and Barnett 1998; McCabe and Dettinger 1999; Gray *et al.* 2003) with consequences for regional and subcontinental climate and fire occurrence (Schoennagel *et al.* 2005; Kitzberger *et al.* 2007). For example, Westerling and Swetnam (2003) found that the area burned in Arizona, Nevada, Utah, Colorado and Wyoming was larger during La Niña years enhanced by a cool (negative) PDO phase. Similarly, fires in north-eastern California were more widespread during El Niño years concurrent with a positive PDO phase (Norman and Taylor 2003).

In the present study, we recorded that years of widespread fire in the *Araucaria* forests were preceded by 2 years of persistent above-average SAM. The positive SAM phase is associated with negative rainfall anomalies in northern Patagonia (Aravena and Luckman 2009; Mundo *et al.* 2012). During the positive phase of the SAM, the westerlies shift southwards and, consequently, precipitation is reduced in northern Patagonia. Thus, increased fire activity associated with positive SAM may reflect either a lagged or a 2-year effect of reduced precipitation promoting fuel desiccation. Increased fire activity is also associated with positive SAM indices in southern Chile rainforests ($\sim$42–48°S) and in the *Austrocedrus* forests in northern Patagonia (Veblen *et al.* 1999; Holz and Veblen 2011*b*). In the current study, the coincidence of increased fire activity in the *Araucaria* forests with positive SAM lasting for one to 2 years suggests that fuel desiccation rather than build-up of fine fuels is the primary constraint on fire activity, consistent with similar findings in nearby the *Araucaria* forests in Chile (González and Veblen 2006).

In our study, positive SAM conditions combined with La Niña events are associated with a higher number of fire events than expected. Dry spring conditions are associated with both a positive SAM phase and La Niña conditions. A combined effect of SAM $\times$ ENSO on fire occurrence has also been reported for *Pilgerodendron* forests of Aysén and Chiloé in Chile (Holz and

Veblen 2012). These results are consistent with Fogt and Bromwich (2006) and Fogt *et al.* (2011), who show that the magnitude of the ENSO teleconnections increase when positive SAM occurs in phase with La Niña events.

In conclusion, the fire history in *Araucaria* forests has been strongly influenced by changes in cultural patterns and climate variations during the past two centuries. An increase in fire frequency after ~1850 coincides with increased human-induced fires in the region. Following the fire exclusion imposed by the creation of Lanín National Park and by national and provincial fire-control policies since the 1930s, fires decreased. In addition, our results underscore the influences of climatic variability at interannual scales on fire occurrence. Although there have been important changes in human-set fires over the past several centuries, fire occurrence is also highly influenced by ENSO interannual variability and its interactions with high-latitude circulation modes such as the SAM.

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