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Fire history in Andean *Araucaria–Nothofagus* forests: coupled influences of past human land-use and climate on fire regimes in north-west Patagonia

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Abstract. Historical fire regimes are critical for understanding the potential effects of changing climate and human land-use on forest landscapes. Fire is a major disturbance process affecting the Andean *Araucaria* forest landscape in north-west Patagonia. The main goals of this study were to reconstruct the fire history of the Andean *Araucaria–Nothofagus* forests and to evaluate the coupled influences of climate and humans on fire regimes. Reconstructions of past fires indicated that the *Araucaria* forest landscape has been shaped by widespread, stand-replacing fires favoured by regional interannual climate variability related to major tropical and extratropical climate drivers in the southern hemisphere. Summer precipitation and streamflow reconstructions tended to be below average during fire years. Fire events were significantly related to positive phases of the Southern Annular Mode and to warm and dry summers following El Niño events. Although Euro-Chilean settlement (1883–1960) resulted in widespread burning, cattle ranching by Pehuenche Native Americans during the 18th and 19th centuries also appears to have changed the fire regime. In the context of climate change, two recent widespread wildfires (2002 and 2015) affecting *Araucaria* forests appear to be novel and an early indication of a climate change driven shift in fire regimes in north-west Patagonia.

Additional keywords: climate variability, dendroecology, El Niño Southern Oscillation, Native Americans, Southern Annular Mode, tree-rings.

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Introduction

Historical fire regimes, characterised by aggregate properties such as frequency, duration, intensity, severity, seasonality and area affected, are critical for understanding the potential effects of changing climate and human land-use on the forest landscape (Falk *et al.* 2007; Swetnam *et al.* 2016; Coogan *et al.* 2019). In temperate South and North America, fire history studies have revealed the coupled influence of past land-use practices and climate on fire regimes, often with striking influences of Native American and European settlement land-use practices, including forest clearing and ranching activities (Kitzberger and Veblen 1997; Kitzberger and Veblen 2003; Veblen *et al.* 1999, 2003, 2008; Allen 2002; González *et al.* 2005; Taylor *et al.* 2016; Swetnam *et al.* 2016; Rozas *et al.* 2018).

Fire is a major disturbance process influencing the Andean *Araucaria* forest landscape in north-west Patagonia (González *et al.* 2005; Mundo *et al.* 2012). This ecosystem has evolved with fire and some plant species, such as *Araucaria araucana* (Molina) K. Koch, have developed distinct strategies to cope with wildfire (Veblen *et al.* 1995; González *et al.* 2013). In the case of *Araucaria* trees, thick bark insulates against the intense heat of fire. Nonetheless, high-intensity fires can create basal fire-scar cavities, which are recorded in the tree-rings. The fire regime of fire-adapted *Araucaria* forests is described as mixed severity, including patches of unburned, low, moderate, and severe (> 75% overstory tree kill) fire effects (González *et al.* 2005; González *et al.* 2010). Low-severity surface fires can occur at relatively short intervals and are generally associated with human ignitions at more open sites dominated by *Araucaria* mixed with *Nothofagus antarctica* (G. Forster) Oerst. woodlands. Stand-replacing fires are more common in more productive mesic mixed species stands of *Araucaria–N. pumilio* (Poep. et Endl) Krasser or *Araucaria–N. dombeyi* (Mirb.) Oerst., where emergent, thick-barked *Araucaria* trees frequently survive (Burns 1991; González *et al.* 2010).

Natural and human-caused fires have shaped the Araucarian landscape for the past several millennia as indicated by radiocarbon-dated records of charcoal in quaternary deposits (Heusser *et al.* 1988). Prior to the arrival of Spanish settlers in the eastern foothills of the Andes, nomadic Pehuenche Native Americans used fire as means of communication, to herd and corral endemic camelids (*Lama guanicoe* called guanacos) and to hunt rheas (*Rhea pennata pennata* called ñandu, a large flightless bird) (Musters 1871; Veblen and Lorenz 1988; Villalobos 1989). However, indigenous use of fire was likely altered by the profound socioeconomic changes that resulted from the introduction of livestock to the region by Spanish settlers in the mid-1500s (Villalobos 1989; Bengoa 2000, 2003; Torrejón 2001). At the beginning of the 18th century the Pehuenche already had small herds of cattle and horses and this pastoral activity intensified significantly after the 1750s, reaching its peak at the beginning of the 1800s (Villalobos 1989; Torrejón 2001). Thus, it is likely that these changes in land-use practices by indigenous groups altered the fire regimes in the Araucarian forest landscape even before widespread Euro-Chilean settlement of the region (~1883), when fire was widely used to clear forests to expand areas for livestock grazing (González *et al.* 2005).

Although human ignitions have played a key role in fire activity, weather conditions also exert a significant effect on fire occurrence and spread. Several studies in northern Patagonia illustrate that temporal patterns of fire are to some extent linked to both interannual climate variability (e.g. drought) and interdecadal climate patterns such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Southern Annular Mode (SAM) (Kitzberger *et al.* 1997; Kitzberger and Veblen 1997; Veblen *et al.* 1999; González and Veblen 2006; Mundo *et al.* 2012; Holz *et al.* 2012; Urrutia-Jalabert *et al.* 2018). Specifically, years of widespread fires are associated with annual variations in extremes of both precipitation and temperature that are clearly linked to large-scale atmospheric circulation features in the Pacific Ocean (González and Veblen 2006; Holz *et al.* 2017).

Since 2000, the region has experienced frequent severe droughts (Garreaud *et al.* 2017; Fernández *et al.* 2018) that have resulted in widespread, severe wildfires burning threatened temperate ecosystems, including *Araucaria* forests (González and Lara 2015; González *et al.* 2018; Bowman *et al.* 2019). Furthermore, recent (since 2000) declining snowpack in the region associated with decreased precipitation and increased temperatures (Saavedra *et al.* 2017) could be contributing indirectly to more extreme wildfire seasons as a result of earlier snowmelt such as in western and boreal North America (Kitzberger *et al.* 2017). In addition to the shift toward more frequent weather conditions conducive to wildfire occurrence, an increase in summer storms with lightning has been reported in nearby northern Patagonia (Veblen *et al.* 2008), which is in line with projected increases in lightning associated with climate warming (Romps *et al.* 2014; Hanes *et al.* 2019). Given the general abundance of forest fuels in these forest ecosystems, the combination of more frequent severe drought conditions and increased lighting strikes has the potential to initiate a shift in fire regime characteristics outside of historic conditions.

In the context of projected warmer and drier conditions in the *Araucaria* Andean forest region (Magrin *et al.* 2014), understanding past and recent temporal variations in fire activity is a research priority for land management and biodiversity conservation. Few tree ring-based fire history studies have been completed in the north-western Patagonia forests of Chile and even fewer studies have addressed fire–climate relationships (Mundo *et al.* 2017). Because of considerable differences in physical geography and land-use history between the eastern and western sides of the Andes, it is unlikely that studies from north-eastern Patagonia in Argentina accurately reflect the influences of climate and land-use in shaping fire and landscapes on the wetter Chilean side of the range. Consequently, the main objectives of this study were to: (1) reconstruct the fire history of Andean *Araucaria–Nothofagus* forests; (2) assess the influence of human land-use shifts on fire regimes; and (3) determine the relationships of climate variability and large-scale climate forcings (SAM, ENSO) on fire occurrence. The findings should expand our knowledge about the human and climatic influences on fire regimes and place recent patterns of wildfire in a larger context to address critical ecosystems management questions of Andean *Araucaria–Nothofagus* forest ecosystems.

Methods

Study area

Our study area to address these questions was Tolhuaca National Park (TNP; 38°10′ to 38°15′S and 71°40′ to 71°51′W; Fig. 1) located in the western windward slopes of the Andean Araucarian region in north-west Patagonia (Fig. 1*a*). The region is characterised by a west coast, maritime climate with a mild Mediterranean influence, reflected in a winter-maximum precipitation distribution and relatively dry summer months (December–March; Miller 1976). The Laguna Malleco meteorological station, located in TNP at 890 m.a.s.l. (38°13′S; 71°48′W), records mean annual precipitation of 2819 mm with 60% occurring in winter (between May and September), mostly as snow (years 1975–2016). Mean annual temperature is 8.8°C, with a mean monthly minimum and maximum of 3.4°C (July) and 14.6°C (February), respectively, for 1980–2011. Seasonal and annual variation in climatic conditions are affected by changes in the intensity and latitudinal position of the south-eastern Pacific anticyclone, which affects the westerly storm tracks (Schwerdtfeger 1976). Rain events are mainly associated with cold and warm fronts, which affect the narrow territory between the Pacific coast and the Andes range (Garreaud 2007). The Andes generally prevents the intrusion of Atlantic air-masses, creating a gradient from a wetter zone on the windward western slope to a drier region on the eastern (leeward) side of the Andes. Annual precipitation declines from ~1200–3000 mm on the Chilean side to less than 250 mm 40 km east of the Andes (Miller 1976).

On the interannual time-scale, regional climate is modulated by the Antarctic Oscillation or SAM and to a lesser extent ENSO

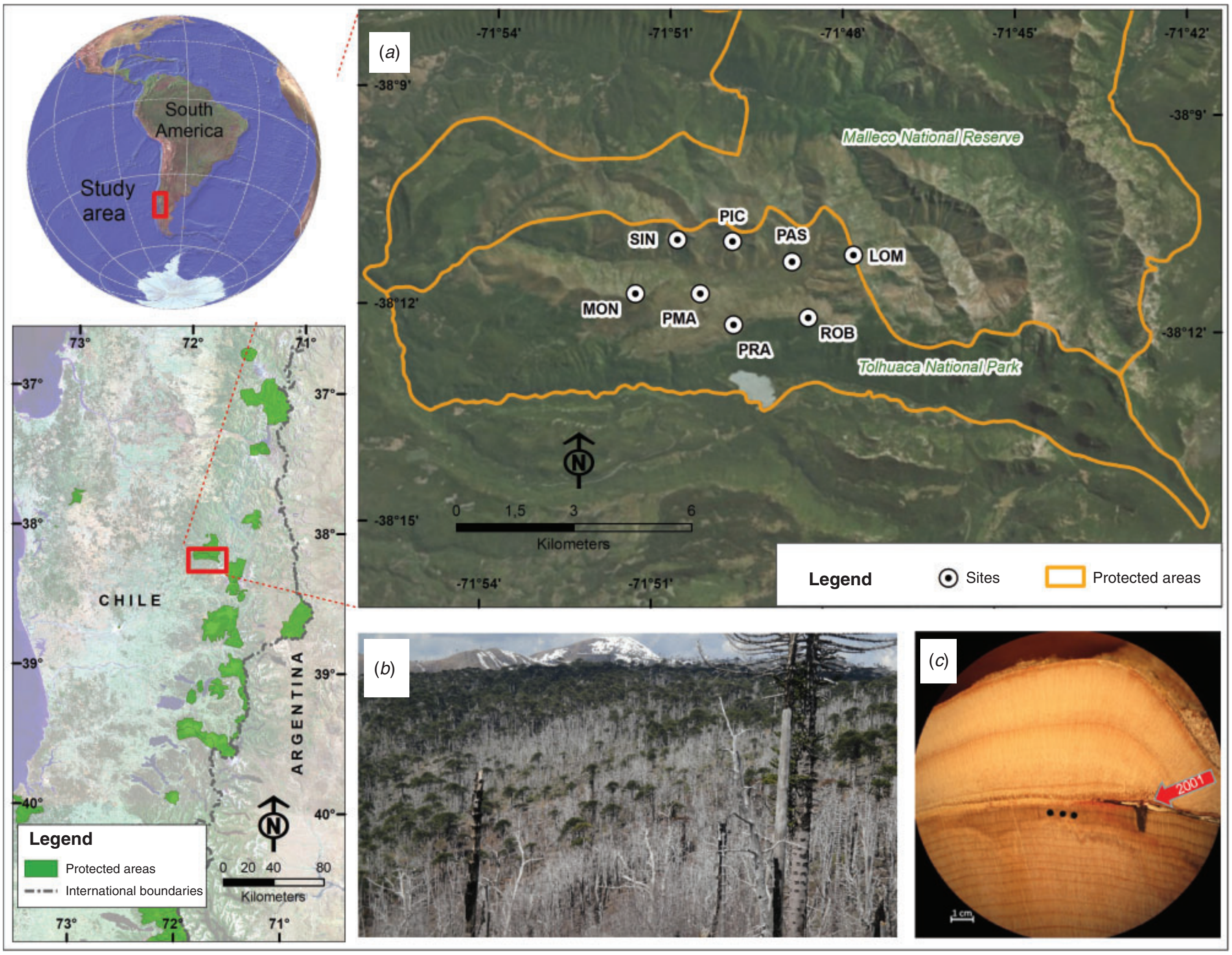

Fig. 1. Geographical location of Tolhuaca National Park (TNP) in the Andes range, north-west Patagonia. (*a*) Map of the eight sampling sites in TNP; (*b*) surviving *Araucaria* trees after a high-intensity fire in February 2002 (dendrochronological year 2001); and (*c*) fire-scars in an *Araucaria* cross-section showing the late season (summer) scar in 2001 (arrow).

(Garreaud *et al.* 2009; Christie *et al.* 2011). The SAM is the principal mode of variability of the atmospheric circulation in the southern hemisphere extratropics (Thompson and Wallace 2000). Positive SAM values are associated with decreased geopotential height over Antarctica, increased geopotential height over the mid-latitudes, a poleward shift of the storm track and a strengthening of the polar vortex, resulting in warmer and drier conditions over the study region during summer (Christie *et al.* 2011). The opposite conditions occur during negative SAM phases (Thompson and Wallace 2000; Fyfe 2003). El Niño (La Niña) events are associated with positive (negative) precipitation anomalies during late spring (Montecinos and Aceituno 2003).

In the study area, *Araucaria* exists in mixed species stands with a variety of *Nothofagus* species at elevations between 1100 and 1600 m.a.s.l. Above 1200 m, the most common forest type is *Araucaria* mixed with the deciduous *N. pumilio*, although mesic sites at these elevations often include *N. dombeyi*. In subalpine bottom valleys, subject to cold air drainage and drier summer conditions, sparse *Araucaria* trees are associated with *N. antarctica*, conforming to an open forest woodland. Also, small patches dominated by *N. obliqua* are found on the edge of these subalpine valleys. At lower elevation (< 1100 m), more mesic sites and sites with more developed soils, second and old-growth *N. nervosa–N. dombeyi* forests occurs as mixed stands. Below the *Araucaria–Nothofagus* forests, 2–4 m bamboo (*Chusquea culeou*) forms the common dense undergrowth, together with other shrub species (e.g. *Gaultheria phillyreifolia*, *Ribes magellanica*, *Drimys andina*), particularly on more mesic sites. Soils in the region are derived from recently deposited volcanic ashes that overlie Pleistocene glacial topography and vary from poorly developed, coarsely textured soils, with relatively shallow organic horizons to deep, fine-textured and well-drained soils (Casertano 1963).

TNP, initially part of the Malleco National Reserve, was established in 1935 with a total area of 6474 ha (Fig. 1*a*). According to historical accounts, TNP was used seasonally by Pehuenche for hunting, *Araucaria* seed collection and trade with Mapuche Native Americans during the summer seasons (Villalobos 1989). After the Euro-Chilean settlement of the area

(~1883), and particularly between 1907 and 1960, cattle grazing and logging were allowed inside the protected area, which promoted frequent and occasionally extensive fires. Settlers engaged in cattle ranching often burned high-altitude valleys occupied by open woodlands of *N. antarctica* to maintain productive summer pastures (veranadas) (Echegoyen 1915; Montaldo 1974; Neira 2004). Fire suppression was not considered effective until about the 1960s.

Field sampling

Fire history sampling in *Araucaria* forests was conducted at eight sites within TNP (Fig. 1*a*; see Table S1 in Supplementary Material online). Most sampling sites corresponded to subalpine *A. araucana*–*N. pumilio* forests and *N. antarctica* woodlands containing sparse or grouped individuals of *Araucaria*. Each sampling site was intensively searched for fire-scarred *Araucaria* trees and, whenever possible, samples were collected in clusters of several trees (including *Nothofagus* if present) to improve the chances of obtaining the most complete fire record possible and increase the likelihood of precisely dating the fires (Arno and Sneck 1977). Our sampling strategy maximised the completeness of an inventory of fire dates within the study area over the longest time period possible. Well-preserved paleo-fire scars from *Araucaria* are scarce and patchy and we opportunistically sampled these trees when encountered (Farris *et al.* 2013).

Partial cross-sections were cut with a chainsaw from both fire-scarred snags (killed in a high-severity fire in February 2002; Fig. 1*b*) and live trees with visible fire scars within the eight sampling sites (Fig. 1*c*). Information recorded for each sampled tree included: species, diameter at breast height (DBH), number of visible fire scars, scar height and the scar face azimuth. Location (Universal Transverse Mercator (UTM) coordinates) of each sampled tree was recorded using a hand-held global positioning unit.

Dating of fire-scar samples

Processing of fire scars followed standard dendrochronological procedures (Speer 2010). Fire scars were identified by the characteristic formation of a lesion caused by cambial death and healing patterns of radial tree ring growth (Smith *et al.* 2016). A regional tree-ring chronology, including samples from TNP and three other *Araucaria* sites (Muñoz *et al.* 2014), was used to verify the cross-dating of fire scar samples using the program COFECHA (Holmes 1983). This software statistically compares ring-width series from the cross-section with a master tree-ring chronology. Fire dating followed Schulman's (1956) convention, where in the southern hemisphere calendar, years of annual rings are assigned to the year in which ring formation begins even though the growing season may extend from September to March. Thus, a fire that occurred in February 2002 (summer) is assigned to 2001 according to this dating convention. Fire seasonality was assessed based on the position of the scar within the ring (Speer 2010). Five seasonal categories for fire scars were established: 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 formed from October to November, M from December to January, L from February to March and D from April to September.

Spatial and temporal analyses of fire

We used the computer program fhx2 (Grissino-Mayer 1995) to calculate standard fire statistics, including composite mean fire interval (CFI: mean time between successive fires in a specified search area) and point fire interval (PFI: recurrence of fire for an individual tree). We also calculated the Weibull median probability interval (WMPI) (Grissino-Mayer 1995). The WMPI describes the fire interval associated with 50% exceedance probability, in which half of the fire intervals will exceed and half will be shorter than the WMPI. Kolmogorov–Smirnov goodness-of-fit tests were used to evaluate the fit of fire interval distributions to normal and Weibull distributions. Student's *t*-test was used to test for changes in the mean fire interval or the number of trees being scarred (Grissino-Mayer 1995). High percentages of spatially dispersed trees recording the same fire event in the study area implied more widespread fires (Grissino-Mayer 1995; Kitzberger and Veblen 1997).

We analysed fire intervals based on the occurrence of any fire in the study area (≥ 1 fire-scarred tree), fire years in which ≥ 2 or ≥ 3 trees were scarred and fire years in which at least 10% or 15% of the recorder trees (i.e. fire-scar susceptible trees that had been scarred previously or during the fire year of interest) were scarred. The fire history record was analysed for three different periods: (1) the recent Native American period (1750–1882); (2) the Euro-Chilean settlement period (1883–1960); and (3) the Modern suppression period (1961–2005). The fire interval analysis, both for the CFI and PFI, began in 1759, when at least four scarred-trees present recorded a fire (i.e. the period of reliability *sensu* (Grissino-Mayer 1995)). To determine the recurrence rate of fires, we estimated fire probability using a Gaussian kernel technique with a 15-year bandwidth (Mudelsee *et al.* 2003). The kernel functions estimate the probability of occurrence of one specific event (fire) in a moving window, allowing the detection of non-monotonic trends. Confidence bands at the 95% level were obtained from 1000 bootstrap resampling steps. This routine was run in the R-project platform (R Development Core Team 2019) using the package 'Paleofire' (Blarquez *et al.* 2014).

Fire–climate relationships

We assessed the effect of regional hydroclimate and large-scale climate forcings (SAM and ENSO) on fire occurrence using Superposed Epoch Analysis (SEA; Mooney and Duval 1993) following Rao *et al.* (2019) in the R-project platform. We used a streamflow reconstruction from the Imperial river (1709–2005), which is in the same geographical area as our study area (Fernández *et al.* 2018), and a precipitation reconstruction for the region (1600–1987; Villalba *et al.* 1998). The Imperial river reconstruction represented summer (January–February) streamflow and the precipitation reconstruction reflected late-spring to early-summer (November–December) rainfall. Both reconstructions were completely independent in terms of the tree-ring series used in each. Specifically, *A. araucana* was used for the streamflow reconstruction and *Austrocedrus chilensis* for the precipitation reconstruction. For large-scale climate forcings

Table 1. Summary information of fire chronologies (diameter at breast height (DBH) and scar height are mean ± standard deviation)

Site	Code	DBH (cm)	Scar height (cm)	No. of dated samples	Fires dated		Years with fire scars
					First	Last	
Mirador Roble	ROB	95 ± 33	1.42 ± 1.10	18	1575	1987	13
Sendero del Indio	SIN	72 ± 28	0.76 ± 0.27	20	1632	1950	14
Picada del Indio	PIC	65 ± 18	1.66 ± 1.17	12	1691	2001	10
Pichimalleco	PMA	65 ± 28	1.02 ± 0.55	12	1802	1959	5
Loma Atravesada	LOM	77 ± 28	1.86 ± 0.66	16	1519	2001	10
Paso Niblinto	PAS	123 ± 66	1.03 ± 0.37	6	1759	2001	6
Prado Mesacura	PRA	37 ± 12	2.60 ± 2.12	8	1923	2001	8
Cerro La Mona	MON	71 ± 27	2.05 ± 1.19	10	1830	1956	6

(SAM and ENSO), we used the SAM (1409–2006; Villalba *et al.* 2012) and ENSO (1301–2005; Niño 3.4 Sea Surface Temperature; Li *et al.* 2013) reconstructions to compare against our fire record. SEA analysis compares the climatic reconstruction time series with a list of annually resolved fire events, considering only those fires recorded from a minimum of two fire-scarred trees. Fire years recorded at different sites were also used as a filter to determine the climate influence. For each fire event, a 7-year climatic window was considered, which included the 5 years previous to the fire event, the event year and 1 year after the event. The 7-year windows for all fire events were superimposed and averaged to obtain the mean pattern of climate variability associated with fires. Confidence limits were calculated using 1000 Monte Carlo simulations.

To examine the recent influence of tropospheric circulation anomalies on extreme moisture variations that are associated with wildfires in north-west Patagonia we used the 2.5° × 2.5° gridded monthly mean 500-hPa geopotential height dataset (1948 to present) from the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kistler *et al.* 2001). We calculated mean late-spring and summer (November–February) geopotential height anomalies for the 1961 to 1990 reference period to compare with mean late-spring and summer geopotential height anomalies of the fire years.

Results

Fire history of Araucaria–Nothofagus *forests*

We reconstructed the fire history in TNP from 102 cross-dated samples (from a total of ~144 samples collected), based on eight sampling sites (Table 1; Table S1). The number of fire-scar samples for *Araucaria* and *Nothofagus* spp. was 91 and 11, respectively, recording 148 fire scars and 42 fire years (Fig. 2). Most fire-scar samples (66%) recorded one fire-scar (single-scarred), but one-third (33%) recorded 2–3 fire-scars. The maximum number of fire scars dated on a single sample was four (in the Prado Mesacura site).

The fire chronology developed in TNP spanned ~500 years. The oldest fire was dated in 1519 and the most recent in 2001 (Fig. 2; Table 1). During the period 1500–1750, considering a minimum of two fire-scarred trees, only two fire years were dated compared with 26 fire years dated for the period 1750–2005 (Fig. 2). For the latter fire period (1750–2005; ≥ 2 fire-scarred trees), the WMPI and CFI were 8.2 and 9.7 years, respectively (Table 2). The PFI to the same tree for this fire period (1750–2005) was 55 years (see Table S2 in Supplementary Material online).

The spatial extent of fires ranged from small fires to those that likely burned a large portion of the study area (e.g. 2001 fire event burned > 60% of TNP). Of the 42 total fire years in the fire record, 14 (33%) were recorded by only one tree, most likely representing small fires that burned limited areas (Fig. 2). Fire scars on *Araucaria* trees in similar high-biomass mixed *Araucaria–Nothofagus* forests have been demonstrated to represent stand-replacing fires for *Nothofagus* species (González *et al.* 2005, 2010). Based on this understanding, widespread high-severity wildfires, represented by relatively numerous fire-scarred *Araucaria* trees in at least three sampled sites, occurred during the years 1759, 1896, 1912 and 2001 (Figs 2, 3). These widespread fires had a mean return interval of 81 years (Table 2; Fig. 3), with a maximum fire interval of 137 years and a minimum of 16 years. Although the 2001 high-severity fire affected all sampling sites, resulting in high tree mortality, just four sites of the eight recorded this fire event in the tree-ring record (sites PIC, LOM, PAS and PRA). During the 1900s, *Nothofagus* fire scars (site PRA) recorded mostly frequent low-severity fires associated with the burning of grasslands and open *A. araucana–N. antarctica* woodlands. In this site (PRA), a single *Nothofagus* tree recorded four fire scars. Fire seasonality, for samples that were possible to determine the position of the scar within the ring (47%; $n = 48$), all recorded late season fires (February–March).

Human land-use influence on fire regimes

Fire activity (≥ 1 fire-scarred tree) during the Native American period (1750–1882) was lower than during the Euro-Chilean settlement period (1883–1960), although the CFI was not significantly different between periods (7.8 *v.* 5.7 years; Table 2). Furthermore, the fire record of the Modern suppression period (1961–2005; ≥ 1 fire-scarred tree) showed significantly larger fire intervals compared with the Euro-Chilean period (10 *v.* 5.7 years), but it was also not statistically different from the Native American period (10 *v.* 7.8 years). However, when considering a filter ≥ 2 fire-scarred trees, the CFI during the Native American period was double that of the Euro-Chilean settlement period (12.6 *v.* 6.8 years). The same temporal fire pattern between both periods is illustrated by the PFI (41 *v.* 25 years; Table S2). Similar to the findings obtained from the fire interval analyses,

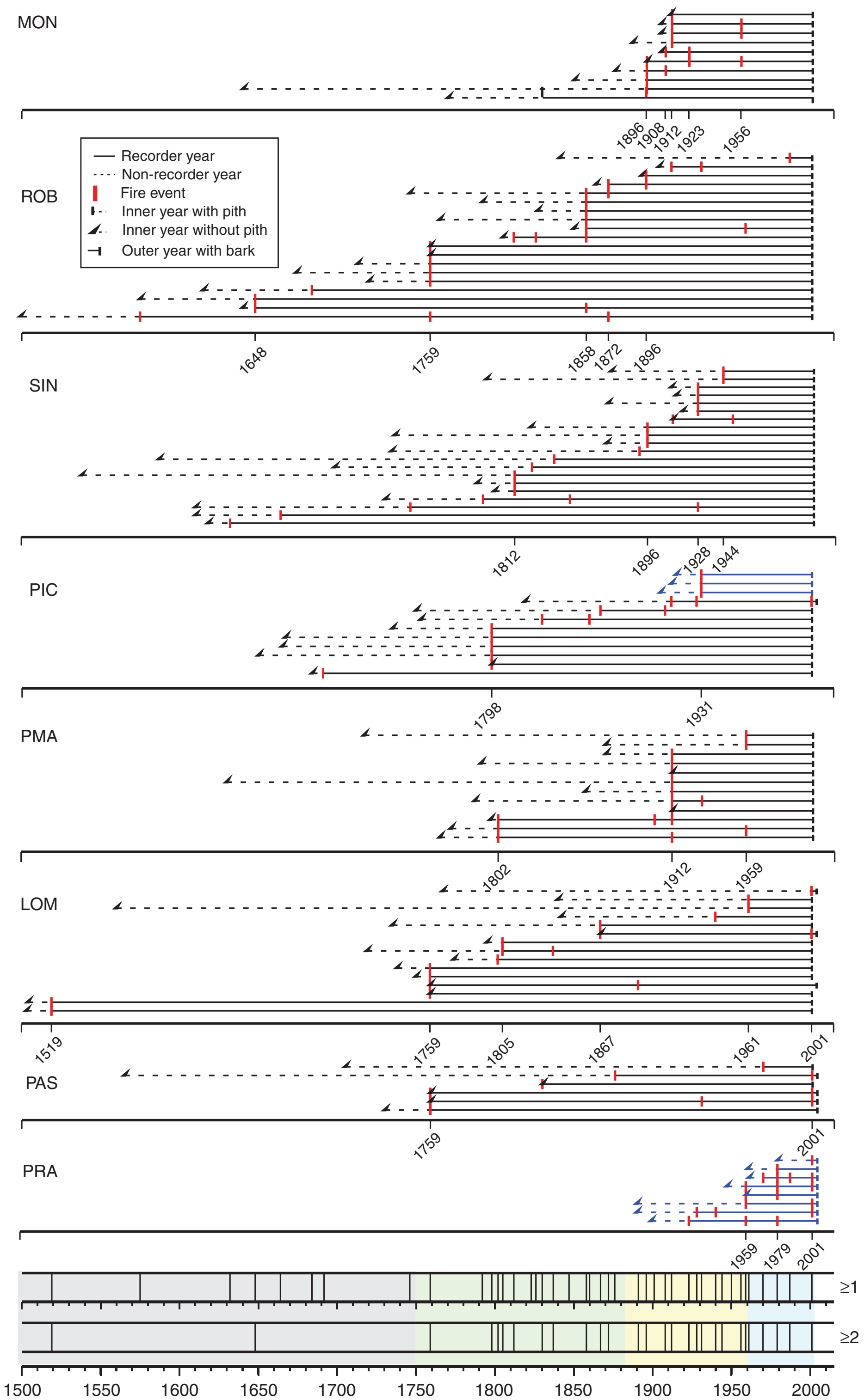

Fig. 2. Fire-scar chronologies from eight sites in Tolhuaca National Park. Horizontal lines represent individual trees (black and blue represent *Araucaria* and *Nothofagus* species, respectively) and fire-scar events are shown by short vertical lines. Fire dates (≥ 2 fire-scarred trees) are indicated below each site. Vertical lines extending to the *x*-axis indicate fire events (≥ 1 or ≥ 2 fire-scarred trees). Colour bands in the composite bar at the bottom correspond to the historical periods displayed in Fig. 4 (grey: Native Americans; light-green: adoption of cattle by Native Americans; light-yellow: Euro-Chilean settlement; light-blue: fire suppression).

Table 2. Composite fire interval statistics for the fire records over the complete study period from 1750 to 2005, the Native American period (1750–1882), the Euro-Chilean settlement period (1883–1960) and the Modern suppression period (1961–2005)

Different letters (a, b, c) indicate statistical significance ($P < 0.05$). MSS, minimum sampled scarred; WMPI, Weibull median probability interval; CFI, composite fire interval (mean); s.d., standard deviation of the CFI; Max. F. I., maximum fire interval; Min. F. I., minimum fire interval; +, too few intervals to perform the analyses

Time period	MSS or % scarred	No. intervals (years)	WMPI (years)	CFI (years)	s.d.	Max. F.I. (years)	Min. F.I. (years)
1750–1882	≥1 (All)	15	6.5	7.8^{ac}	7.5	33	2
	≥2	9	10.2	12.6	11.7	39	3
	≥3	7	13.7	16.1	13.1	39	4
	≥10%	4	19.8	24.8	20.8	46	4
1883–1960	≥1 (All)	12	5.6	5.7^{a}	2.4	11	3
	≥2	10	6.5	6.8	3.8	12	3
	≥3	7	7.5	9.0	8.0	25	3
	≥10%	+	+	+	+	+	+
1961–2005	≥1 (All)	4	10.1	10^{bc}	2.7	14	8
	≥2	4	10.1	10	2.7	14	8
	≥3	+	+	+	+	+	+
	≥10%	+	+	+	+	+	+
1750–2005	≥1 (All)	33	6.5	7.33	5.7	33	2
	≥2	25	8.2	9.7	8.0	39	2
	≥3	17	12.1	14.2	10.7	39	3
	≥10%	7	27.9	34.6	28.9	89	4
	≥15%	5	+	48.4	27.5	89	16
	≥15%[A]	3	+	80.7	60.9	137	16

[A]≥3 sites scarred for a particular fire.

fire occurrence during the Native American period showed a rising trend that peaked during the Euro-Chilean period and then decreased during the Modern suppression period (Fig. 4).

Climate influences on fire occurrence

Widespread fires were significantly related to extreme regional dry conditions as indicated by the SEA analysis between fire events and the independent hydroclimatic records of precipitation and streamflow from north-west Patagonia (Fig. 5*a*, *b*). Early summer precipitation, and especially the summer streamflow reconstructions, tended to be below average during fire years (Fig. 5*a*, *b*). Furthermore, the results demonstrate that regional fire events were associated with tropical and high-latitude forcings. Specifically, fire years were significantly related to years of positive phases of the SAM and also to El Niño event years (Fig. 5*c*, *d*). The climate conditions before fire events were not especially important for fire occurrence. Only the Imperial river streamflow and ENSO reconstructions were significantly related 3 years prior to the fire occurrence (Fig. 5*b*, *c*). In both cases the SEA analyses indicated that wet climate conditions associated with La Niña years, and also expressed in high flows of the Imperial river, showed significant relationships with fire occurrence.

In the context of atmospheric circulation patterns associated with fire events, our results from the 500-hPa height anomaly maps show a strong association during late-spring and summer hydroclimate variability in northern Patagonia and large-scale tropospheric circulation in the mid- to high-latitudes of the south-eastern Pacific Ocean (see Fig. S1 in Supplementary Material online). These negative (positive) height anomalies over Antarctic latitudes produce the southward (northward) migration of the westerly storm track, resulting in anomalously dry (wet) conditions over the study region that favour fire occurrence. For example, in years when fire events were recorded (i.e. 1956, 1961 and 2001), we observed a clear negative anomaly pattern over high latitudes in terms of the 500-hPa, with positive anomalies over the mid-latitudes (Fig. S1). Moreover, we identified a strong dipole during 2001 (Fig. S1c), revealing severe, dry conditions over Patagonia.

Discussion

Fire regime of Andean Araucaria–Nothofagus *forests*

Widespread stand-replacing fires have been an important ecological process shaping the *Araucaria–Nothofagus* forests over the past 500 years (González *et al.* 2005, 2010). The abundance and location of fire-scarred trees suggested that extensive fires in 1759 and 2001 each affected a large portion of the study area. Furthermore, the 1759 fire not only burned extensive areas of the *Araucaria–Nothofagus* forests in TNP, it also affected the adjacent Malleco National Reserve (unpubl. data, ME González). Similarly, the large-scale lightning-caused fire of 2001 affected both protected areas, with a total of ~12 000 ha burned (Assal *et al.* 2018).

Extensive fire events, such as those of 1759, 1896 and 1912, were only recorded by fire-resistant *Araucaria* trees. Based on previous research in similar high-biomass mixed *Araucaria–Nothofagus* forests in the region (González *et al.* 2005), scar formation only on *Araucaria* trees suggests that fire intensity was high enough to kill fire-sensitive *Nothofagus* species. This

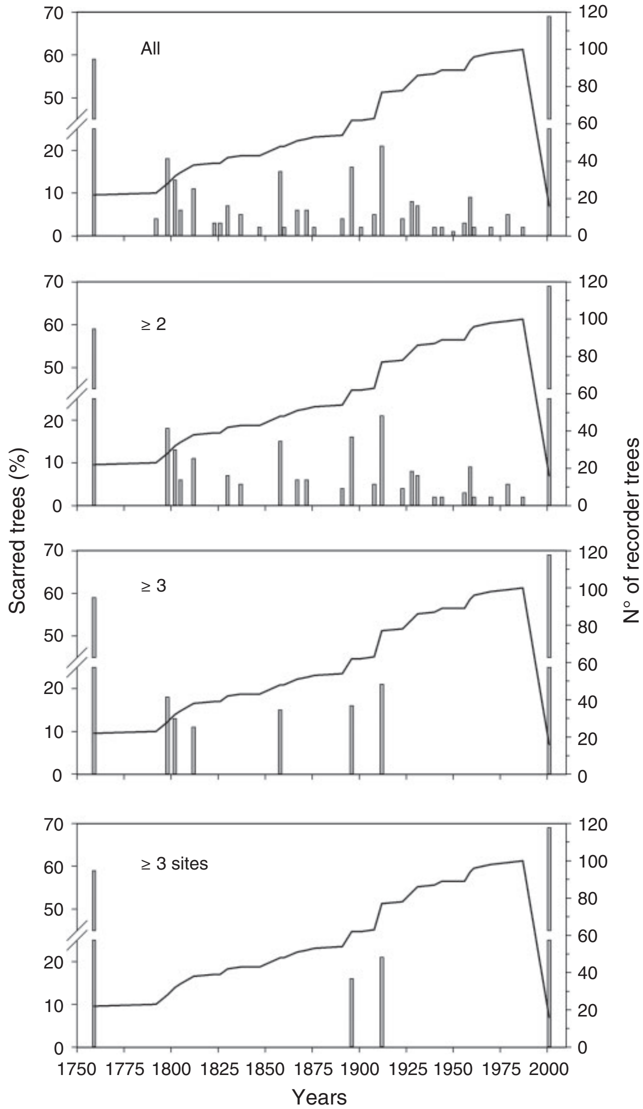

Fig. 3. Percentage of fire-scarred trees for the fire records based on 'All' samples (years in which ≥ 1 scarred trees recorded a fire date), ≥ 2 scarred trees, and ≥ 3 scarred trees (with fire dates recorded by at least 10% of the fire-scarred trees) and ≥ 3 sites (with fire dates recorded by at least 15% of the fire-scarred trees). The sample depth (horizontal line) is the cumulative number of recorder trees over the same time period.

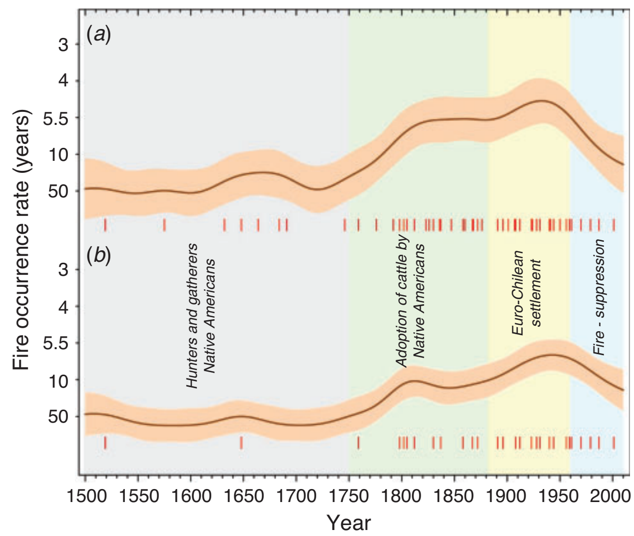

Fig. 4. Occurrence rate (years) of fire events for (*a*) all recorded fires and for fires that occurred in (*b*) ≥ 2 sites in Tolhuaca National Park, north-west Patagonia for the 1500–2002 period using a Gaussian kernel technique with 95% confidence interval (shaded) from 1000 bootstrap simulations.

result confirms both the ability of *Araucaria* to survive fires that are stand-replacing for *Nothofagus*, as well as its distinctiveness in recording older fire events and fire events that are stand-replacing for other species (Fig. 1*b*; González *et al.* 2005; Mundo *et al.* 2012). The seasonality of fires determined from the tree-ring record indicated that fire events occur typically during the summer. Fire statistics from the Chilean Forest Service covering the past 40 years, and documentary records for the past century, indicate that most large fires occur between January and March (Urrutia and Lanza 1993; González *et al.* 2018), which corresponds to the drier period of the temperate southern hemisphere summer. The last two large-scale fire events affecting TNP in February 2002 (lighting-ignited fire) and March 2015 (human-ignited fire) were also summer season fires (González and Lara 2015).

Influence of human land-use shifts on fire regimes

Land-use by both Native Americans and Euro-Chileans settlers is closely related to the temporal patterns of fire occurrence. For several thousand years this Andean region was inhabited by the Pehuenche ethnic group who used the area seasonally (transitory camps) to take advantage of seasonally available food (Villalobos 1989; Torrejón 2001; Goicovich 2005). The adoption of livestock by Native Americans changed their lifestyles and their land-use practices, especially in the territories inhabited by indigenous people lacking intensive productive activities, including the Pehuenche in the TNP area (Torrejón 2001). Trade between Pehuenche and Spanish settlers became more prevalent after the 1750s, which achieved an important exchange network of livestock and salt products between the pampas and the western valleys of the Andes (Zapater 1978; León 1991; Villalobos 1995). The resulting increased trade of cattle may have favoured clearing travel corridors and a more intensive use of high-altitude woodlands and meadows (veranadas) interspersed in the Andean *Araucaria* forest landscape (Poeppig 1960; Villalobos 1989; Torrejón 2001; León 2005). Given the increase in fire activity coincident with the adoption of cattle by Native Americans, a plausible historical fire regime for the Native American period (without livestock effect) in TNP would be from 1519 to 1750, when the CFI was 30 years for all fires (≥ 1 fire-scarred; Fig. 2).

With the expansion of Euro-Chilean settlers in the Araucarian region, the number of human-caused fires increased dramatically (González *et al.* 2005). During Euro-Chilean settlement (1883–1960), montane and subalpine forests were deliberately burned to increase pasture for cattle ranching. According to records for Reserva Malleco, which began in 1907, settlers entered this area

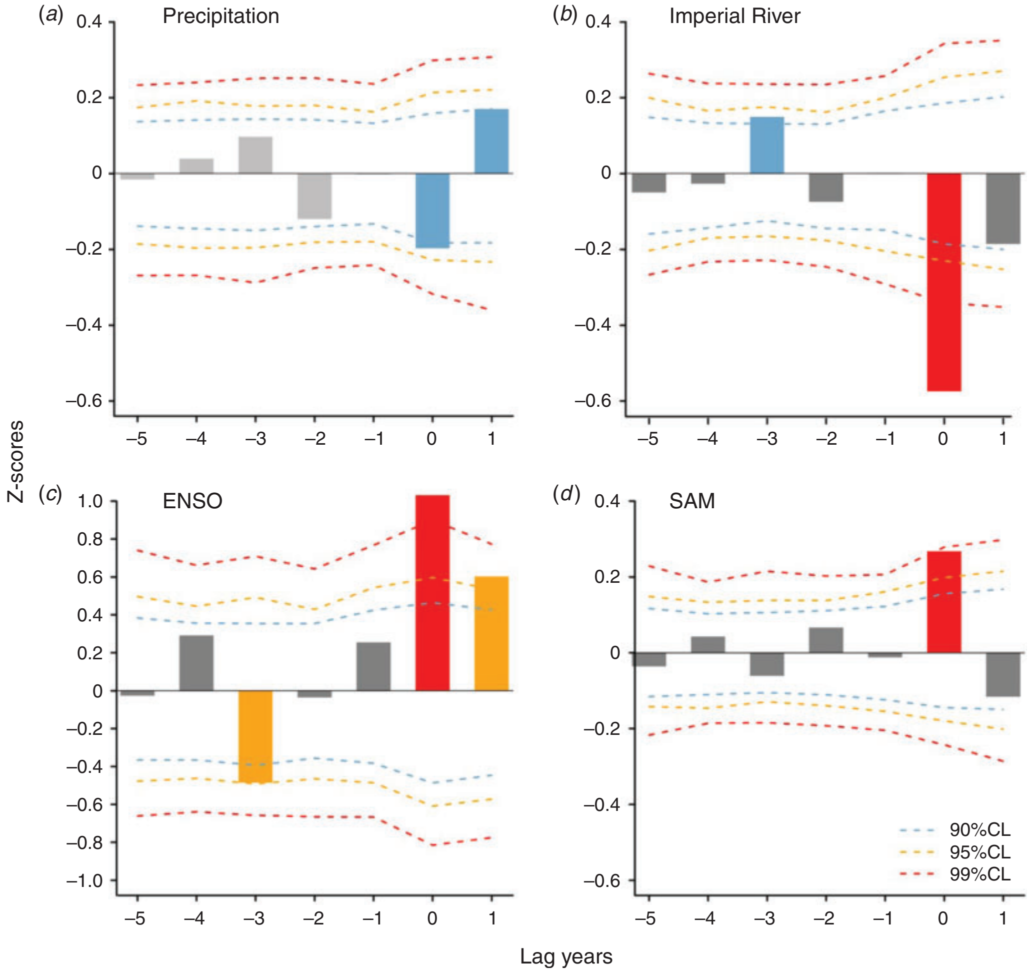

Fig. 5. Superposed Epoch Analysis (SEA) exhibiting the relationships between fire events in Tolhuaca National Park and regional hydroclimate and broad-scale climatic modes and proxies, where (*a*) corresponds to a precipitation reconstruction for northern Patagonia (Villalba *et al.* 1998), (*b*) is a streamflow summer reconstruction of the Imperial River, (*c*) the El Niño 3.4 sea surface temperature reconstruction is an indicator of ENSO (El Niño Southern Oscillation) variability (Li *et al.* 2013), where positive (negative) values indicate El Niño (La Niña) years, and (*d*) is the Southern Annular Mode (SAM; Villalba *et al.* 2012). Analyses were computed for fire years recorded in at least two trees in all cases. Precipitation and streamflow reconstructions used 21 and 18 fires. ENSO and SAM variability were computed in the SEA with fire years recorded in at least two sites ($n = 11$).

immediately after the Chilean government took control of the territory in 1882. To control the new lands, Chile leased pastures within the Reserva Malleco in 1889, which included the land that eventually became TNP in 1935. Thus, the 1896 and 1912 widespread fires are related to this early Euro-Chilean land use. Moreover, in 1914 Chile also leased large tracts of forest in the Reserve to private logging companies (Stein 1952). Extensive logging operations lasted until the mid-1960s (~mid-1940s in TNP) and during this time, burning of recently logged areas and high-altitude woodlands and meadows, to increase pasture for cattle, was a common practice (Neira 2004).

Fire activity decreased significantly in TNP during the Modern suppression period (1961–2005). At the beginning of the 1960s, the forest administration established more effective measures and regulations to prevent and control wildfires (Johnson 1970; Neira 2004). Livestock and logging activities were banned in the protected area, although cattle ranching was still informally and illegally carried out inside the Park by settlers during the 1960s (Johnson 1970). Thus, the intentional burning of *N. antarctica* woodlands in high-altitude valleys (e.g. sites PMA, PRA) seems to have continued after fire suppression was enacted. Overall, the increase of fire activity associated with livestock, forest clearing and logging emerges as a hallmark of human effects on *Araucaria* forests and fire regimes over the past 300 years.

Climate–fire relationships

Hydroclimatic variability is a major regional climatic driver promoting the occurrence of fires in the *Araucaria* ecosystems. Independent hydroclimate reconstructions (i.e. early summer precipitation and summer streamflow) exhibit extreme dry conditions during fire events, confirming that the occurrence of fires in our study area is controlled by regional-scale summer drought conditions across northern Patagonia. Drought conditions are favoured by large-scale tropical and high-latitude climate drivers in the southern hemisphere including ENSO and the SAM. Fire events are significantly related to years of positive phases of the SAM and warm and dry summers following El Niño years (González and Veblen 2006). ENSO and SAM are also related to fire occurrence on the eastern side of the Andes (Argentina), although fire events are associated with the opposite (La Niña) phase of ENSO (Mundo *et al.* 2012, 2017). Although these last authors reported large fires associated with dry years during La Niña conditions, in TNP, on the western side of the Andes, fires were related to El Niño years. These differences can be explained by the relative importance of fine fuels (i.e. grass cover) to fire occurrence and spread on the eastern side of the Andes. In other words, fire occurrence on the eastern slopes of the Andes is fuel-limited and thus dependent on wet antecedent climatic conditions for the development of fine fuels necessary for fire occurrence and spread (Kitzberger and Veblen 2003; Veblen *et al.* 2008; Holz *et al.* 2012). Antecedent climatic influences were less important in our study area located on the wetter, western side of the Andes and were only observed 3 years before fire events, in two of the four climate proxies used in this study. Given that the *Araucaria–Nothofagus* forests of north-west Patagonia are not fuel-limited, it is likely that the wet antecedent climate conditions are an artefact of the 2–3-year frequency of the ENSO phase change in contrast to the need to develop fuels to help fire occurrence and spread. Furthermore, the SAM has a relatively greater influence than ENSO in shaping moisture variability (Christie *et al.* 2011; Muñoz *et al.* 2016) and snowpack conditions (Saavedra *et al.* 2017) in this region; therefore, it is not surprising that positive phases of the SAM promote widespread fires on both sides of the Andes (Holz *et al.* 2012, 2017). Since the 1950s, a positive trend in the SAM has been related to regional scale decreases in precipitation (Villalba *et al.* 2012; Holz *et al.* 2017) and also with low summer flows in the Imperial River (Fernández *et al.* 2018), which is in the same drainage basin of TNP. Moreover, the influence of large-scale atmospheric pressure patterns associated with severe drought years (Fig. S1) is consistent with the atmospheric conditions that are created by the fire-climate relationships with ENSO and the SAM that we identified here (Holz *et al.* 2017).

Fire seasons since 2000 have included extensive wildfires and large total areas burned in south-central Chile, which are strongly related to severe drought years (González *et al.* 2018; Urrutia-Jalabert *et al.* 2018; Bowman *et al.* 2019). Andean *Araucaria–Nothofagus* forests have been one of the primary forest types affected by these recent natural and human fires. For instance, TNP has been burned by two extensive (>60% of protected area burned), high-severity fires in a short timespan (2002, 2015) (González *et al.* 2005; González and Lara 2015). Similar extreme wildfire events and reburns after short intervals globally have been attributed to climate trends and land-use practices. Understanding how wildfire alters the potential for subsequent wildfire and favours transition to more fire-prone landscapes through fire-driven positive feedback are key research topics for the management and conservation of *Araucaria* forests in the Araucanía region.

Conflicts of interest

The authors declare no conflicts of interest.

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