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Fire history in southern Patagonia: human and climate influences on fire activity in *Nothofagus pumilio* forests

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Abstract. Fire is a major disturbance affecting forests worldwide with significant economic, social, and ecological impacts. The southernmost forests on Earth extend continuously along the Andes from mid- to subantarctic latitudes in South America. In this region, warming and drying trends since the mid-20th century have been linked to a positive trend in the Southern Annual Mode (SAM), the leading mode of extratropical climate variability in the Southern Hemisphere. Due to the scarcity of documentary fire records and the lack of tree-ring fire histories, little is known about how wildfire activity responds to shifts in the westerly circulation pattern and associated climatic variability in the Andean region south of ~44° S. For the first time, we applied dendrochronological techniques to reconstruct fire history from the angiosperm *Nothofagus pumilio* at 16 sites distributed from ~44° to 50° S to determine relationships between fire occurrence and the two primary drivers of wildfire activity: climate variability and human activities. Partial cross-sections with fire scars were collected from 363 trees in Argentina and Chile. Chronologies of annually resolved fire-scar dates start in 1791 and show a pattern of higher fire frequency during the 20th century, concurrent with the human occupation and colonization processes in southern Patagonia. Years of widespread fire occurring synchronously in two or more disjunct sites are associated with broad-scale climatic anomalies. Intense droughts inferred from extreme departures in temperature, precipitation, and the Standardized Precipitation-Evapotranspiration Index (SPEI) during the growing seasons of 1944 and 1962 are consistent with the two most severe fires at northern sites. Extended droughts, reflected by the association of fire occurrence with six-month cumulative precipitation and SPEI, create conditions for widespread fires at the southern sites (south of ~46° S). Regional fires were concurrent with significant positive departures of SAM during the austral spring–summer. This tree-ring fire record reveals the influences of both climate variability and human activities on fire in the *N. pumilio* forests across the Andes, and also establishes the feasibility of using this tree species as a natural archive of fire history.

Key words: dendrochronology; fire-scars; *Nothofagus pumilio;* Southern Annular Mode; southern Patagonia.

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Introduction

Fire is the most important disturbance affecting forests worldwide. Humans and climate are the major drivers in determining wildfire activity, which in turn through the release of carbon to the atmosphere can produce positive feedbacks on the climatic factors controlling future fire activity (Bowman et al. 2009). Both climate and humans have strong influences on ignition sources and fuel characteristics (fuel type, structure accumulation, and moisture content), but their effects can be distinguished at different spatial scales. For example, over large areas of homogeneous regional climate, annual or quasi-annual synchrony of peaks in wildfire activity is clear evidence of short-term climatic controls on fire. In contrast, human influences on fire activity, either through increased ignitions or through exclusion of natural fires, are more likely to be reflected in local variability of human population sizes and land-use practices, especially when interannual variability in fire activity is examined. Particularly, at longer than annual timescales, the roles of both humans and climate must be considered to understand broad-scale changes in patterns of wildfire activity (Veblen et al. 1999).

Recent surges in wildfire activity on all forested continents derived from relatively short-term satellite observations imply that current climate trends are driving global shifts in fire activity (Flannigan et al. 2009, Jolly et al. 2015, Abatzoglou and Williams 2016), but these short-term trends of wildfire activity need to be evaluated in the context of longer fire records through the use of tree-ring evidence of past fires (Falk et al. 2011). Direct and indirect impacts of climate change on ecosystems processes are expected to be strongest at high latitudes (Randerson et al. 2006, Moritz et al. 2012). Indeed, occurrence of boreal forest fires has increased during recent decades inducing large-scale changes in fire frequency and biomass burning of global significance (Kelly et al. 2013, 2016). In contrast to the many decades of research on centennial-scale fire activity based on tree-ring fire records across North America and Eurasia, tree-ring-based research on fire history in the Southern Hemisphere is much more recent and limited only to southern South America (Kitzberger and Veblen 1997, Veblen et al. 1999, Grau and Veblen 2000, Holz and Veblen 2011*a*).

South America is the only continent in the Southern Hemisphere that stretches continuously from temperate to subantarctic climates, a key latitudinal gradient where changes in circumpolar atmospheric circulation and ecological impacts are occurring under climate change (Garreaud et al. 2009, Veblen et al. 2011, van Leeuwen et al. 2013). The Patagonian Andean region (~36°–55° S) in South America is the only area in the Southern Hemisphere for which there is the potential to create a latitudinally extensive network of tree-ring fire history records. The Patagonian Andes are a major barrier to the Southern Hemisphere westerlies inducing a steep climate and vegetation gradient from temperate rainforests west of the Andes to a narrow strip of mesic to xeric *Nothofagus* forests in the rain shadow east of the Andes.

Fire, as documented by both sedimentary charcoal and dendrochronological records, has long been a major forest disturbance in the Andean Patagonian region throughout the Holocene period (Huber et al. 2004, Whitlock et al. 2007, Holz et al. 2012, Jara and Moreno 2012, Méndez et al. 2016). Sedimentary charcoal records indicate infrequent occurrence of natural fires as early as 44,000 yr BP associated with either volcanic eruptions or lightning (Heusser 1994). Following the arrival of humans in Patagonia (~12,000 yr ago), fires set by Native Americans for hunting and other purposes have been an important source of ignitions, and since European colonization mostly in the 19th century, modern humans have had an increasingly pervasive influence on wildfire activity in most of the region (Veblen and Lorenz 1988, Huber et al. 2004, Holz and Veblen 2011*a*, Iglesias and Whitlock 2014). However, centennial and millennial-scale records of fire are largely limited to forests and woodlands east of the Andes in northern Patagonia (37°–44° S; Kitzberger et al. 1997, Veblen et al. 1999, Mundo et al. 2013, Iglesias and Whitlock 2014), and in fact, there are no tree-ring fire history records available for the climatically sensitive forest–steppe ecotone south of 44° S.

Previous research in northern Patagonia has demonstrated that climate variability plays a major role in driving fire activity on which human influences on fire ignitions are superimposed. The intensity and latitudinal position of the subtropical high-pressure cell on the southeast Pacific modulates annual-scale droughts, and consequently, fire activity in the *Austrocedrus chilensis* woodlands along the forest–steppe ecotone at ~39°–41° S (Kitzberger et al. 1997). The El Niño–Southern Oscillation (ENSO) is an important factor modulating interannual variability in fire activity in northern Patagonia. Fires in this region have been linked to the negative or cool phase of ENSO (i.e., La Niña years) associated with variations in the intensity and latitudinal position of the southeast Pacific pressure cell (Veblen et al. 1999, Holz and Veblen 2012, Mundo et al. 2013). Recently, northern Patagonian wildfire activity has been linked with positive anomalies of the Southern Annular Mode (SAM), which in turn is associated with warmer and drier conditions throughout Patagonia (Holz and Veblen 2011*b*, 2012, Mundo et al. 2013). Southern Annular Mode is the leading extratropical driver of climate variability in the Southern Hemisphere and is defined by the seesaw pattern of synchronous zonal sea-level pressure anomalies between Antarctica and a circumpolar band at 40° S (Thompson et al. 2011). The positive phase of SAM indicates lower surface pressure over Antarctica and a poleward shift of the westerlies, which in turn correlates with warmer temperatures and lower precipitation at mid-latitudes (Garreaud et al. 2009). Since c. 1950, SAM has exhibited an upward trend consistent with the modeled effects of reduced stratospheric ozone concentrations, and models driven by greenhouse gas concentrations project the continued rise in SAM and warming throughout the 21st century (Thompson et al. 2011).

In contrast to the relative abundance of charcoal and tree-ring fire history studies in northern Patagonia linking changes in wildfire activity to ENSO activity, variability in the intensity and position of the westerlies and to human activities (e.g., Veblen et al. 1999, Whitlock et al. 2007, Mundo et al. 2013, Iglesias and Whitlock 2014), data on fire history south of 44° S are sparse. At a multi-millennial timescale, sedimentary charcoal records indicate that increased aridity appears to have favored fire occurrence near the eastern limit of the deciduous forest zone at 52° S between c. 11,700 and 5500 cal yr BP (Huber and Markgraf 2003). There has been only a single tree-ring-based fire history study conducted in southern Patagonia and it was limited to coastal rainforests at ~42°–48° S (Holz and Veblen 2012). That study, based on tree-ring fire scars on the conifer *Pilgerodendron uviferum*, documented a strong fire-enhancing influence of positive departures of SAM associated with warmer and drier conditions in the coastal rainforest environment (Holz and Veblen 2012). Along the climatically sensitive forest–steppe ecotone between deciduous forests and the Patagonian steppe south of 44° S, there have been no previous tree-ring-based studies of fire history. Consequently, the aim of the current study was to develop a network of tree-ring fire history records at these southerly latitudes near the forest to steppe ecotone to examine the influences of broad-scale climate drivers as well as humans on wildfire activity.

In the current study, we examined the fire-recording potential of the deciduous angiosperm *Nothofagus pumilio*, which is distributed in the Andean region from 35°35′ to 55° S (Tortorelli 1956, Donoso 1981). Its extensive north–south distribution as well as its occurrence at the forest–steppe ecotone implies that it could be highly useful in documenting variability in fire activity. *Nothofagus pumilio* has long been used in dendroclimatic studies because of the sensitivity of its growth to annual variability in temperature and moisture availability in habitats ranging from the forest–steppe ecotone to Andean upper treelines (Boninsegna et al. 1989, Villalba et al. 1997, 2003, Lara et al. 2001, 2005, Massaccesi et al. 2008, Srur et al. 2008, Álvarez et al. 2015, Lavergne et al. 2015, Rodríguez-Catón et al. 2015). In addition to the use of this species for developing reconstructions of past climatic conditions (Lara et al. 2001, Villalba et al. 2003), it has been used to date geomorphic processes (Mundo et al. 2007, Casteller et al. 2009, Masiokas et al. 2009) and insect defoliation events (Paritsis et al. 2009, Paritsis and Veblen 2011). Although fire scars from *N. pumilio* previously have been used in one study in northern Patagonia to complement records derived from the conifer *Araucaria araucana* (González et al. 2005), there have been no previous attempts to develop a multi-site network of fire records solely based on *N. pumilio*. Previous experience with the dating of *N. pumilio* fire scars (González et al. 2005) revealed the high susceptibility of its wood to decay once injured by fire so that it has been regarded as having a less potential as a fire history recorder in comparison with conifer species. However, conifers are absent along the dry gradient from forest to steppe at latitudes south of 44° S, making *N. pumilio* the only possible fire recorder over an extensive area from 44° to 55° S.

The specific objectives of this study were to use dendrochronological techniques to (1) assess the potential of *N. pumilio* to develop annually resolved fire-scar chronologies; (2) reconstruct fire history in *N. pumilio* forests over a wide latitudinal range from ~43° to 50° S in southern Patagonia; (3) examine the relationships between fire activity and climate variability driven by variability of SAM and ENSO; and (4) relate variability in fire activity to the history of human presence and activities in the region. Based on previous findings in northern Patagonia (i.e., north of 44° S), we hypothesized that for southern Patagonia, the early to mid-20th-century period of colonization and forest conversion to pasture should be reflected by an increase in fire frequency compared to the 19th century. Furthermore, we hypothesized that given the high-latitude location of the study area, variability in SAM would be the primary driver of climatic conditions modulating fuel moisture and/or fine fuel build-up, which in turn determines the potential for fire ignition and spread. Since most sampled sites are located near the xeric limit of *N. pumilio* distribution, we expected lagged increases in fire activity following wetter years favorable to the growth of grasses and other fine fuels as well as widespread fire synchronous with regional below-average moisture conditions, analogous to findings for the northern Patagonian forest–steppe ecotone (Kitzberger et al. 1997, Veblen et al. 1999).

Methods

Study area

Sample sites are located in the eastern Andes and foothills from 43°48′ to 50°28′ S mostly in the Argentine Provinces of Chubut and Santa Cruz (Fig. 1, Table 1). The pronounced rainshadow effect of the Andes is reflected by a decline in total annual precipitation from 3000 to 6000 mm near the continental divide to 600–800 mm in the eastern foothills (Barros et al. 1983, Villalba et al. 2003). Rainfall is concentrated over the colder period of the year (April–September) in the northern sector, but is more uniformly distributed in the southern Patagonian Andes. In both regions, summer (December–February) represents the driest season. Mean annual temperature declines from north to south, but the decreasing effect of continentality buffers temperature extremes at the higher latitudes. *Nothofagus pumilio* forests occur in an elevational zone along the Patagonian Andes defined by mean annual temperatures of 6.5–7°C and 3.5–4°C at the lower and upper limits, respectively (Schlatter 1994). Soils of these Andean forests are mainly derived from postglacial volcanic ash deposits (Casertano 1963). Sites sampled for fire scars included locations in national parks as well as large privately owned properties; all sites were remote from roads and fire-fighting infrastructure and it is unlikely that active fire suppression would have affected fire frequency in the sampled areas.

Field sampling

Sampling in the *N. pumilio* forests was conducted at 16 sites (Table 1, Fig. 2) from February 2009 to February 2012. Only two sites were sampled in Chile (sites MON and SLC). Initially, all areas were intensively searched to sample at least 20 fire-scarred trees in a targeted sampling design. However, this target number of samples was attained only for eight sites. In the remaining eight sites, the lack of fire-scarred trees or lack of well-preserved scars limited the availability of trees for sampling. Partial cross-sections from fire-scarred trees were extracted to determine exact fire dates (Arno and Sneck 1977, McBride 1983; Fig. 2b). Information recorded for each sampled tree included diameter at breast height (dbh), number of visible fire scars, and the scar-face azimuth. Location (geographical coordinates) of each fire-scarred tree sampled was recorded using a Global Positioning System (GPS) unit. Maximum height above the ground for each fire scar was also estimated. The absence of well-preserved stumps did not allow us to obtain datable material. Although we tried to get material from some stumps, the extracted partial cross-sections were completely rotten and fire scars were not visible.

Standard dendrochronological procedures (Stokes and Smiley 1968, Arno and Sneck 1977,

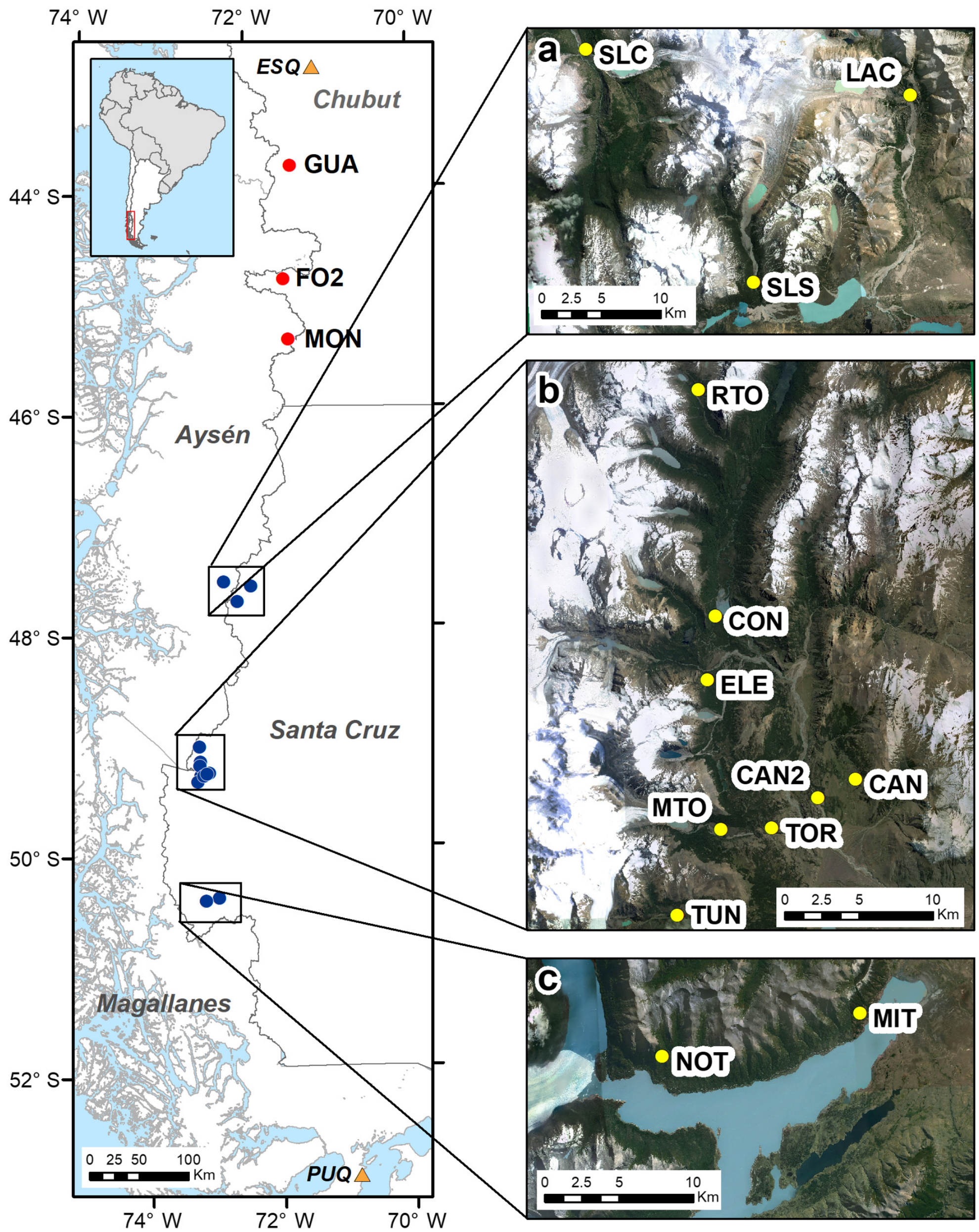

Fig. 1. Location of the 16 *Nothofagus pumilio* forests sampled for developing the fire histories in the Patagonian Andes (see Table 1 for site code definition). Red dots correspond to the northern sites, while blue dots correspond to the southern sites. The three sub-regions intensively sampled (with squares in the map; left panel) are magnified in true-color satellite imagery to the right, (a) San Lorenzo Mount, (b) Río de las Vueltas valley, and (c) Lago Argentino-Brazo Rico. Orange triangles correspond to the two most representative meteorological stations (Esquel and Punta Arenas).

McBride 1983) were followed to process all the partial cross-sections. Samples were air-dried and sanded to allow the identification of the annual rings under the stereomicroscope (10×–50×). Dates of rings containing fire scars were determined by counting backward from the outermost ring and visually verified by cross-dating against marker rings in reference chronologies from

Table 1. Site characteristics of areas sampled for *N. pumilio* fire histories in Southern Patagonia.

Site	Code	Group	Latitude†	Longitude†	Area (ha)	Elevation (m a.s.l.)‡	Slope (°)	Aspect	Number of samples
lago Guacho	GUA	Northern	43°48′40.0″ S	71°27′48.6″ W	9.960	1182	16	SW (218°)	18
lago Fontana II	FO2	Northern	44°50′28.4″ S	71°35′10.5″ W	10.300	992	13	S (168°)	10
Punta del Monte	MON	Northern	45°23′25.6″ S	71°33′03.7″ W	5.000	1139	9	E (101°)	12
San Lorenzo	SLC	Southern	47°34′41.3″ S	72°31′14.2″ W	4.890	417	13	W (249°)	10
Río Lacteo	LAC	Southern	47°37′23.3″ S	72°09′33.1″ W	1.896	1067	9	SW (220°)	26
San Lorenzo Sur§	SLS	Southern	47°45′36.6″ S	72°20′38.7″ W	1.359	878	2	SW (231°)	42
Ea Río Toro	RTO	Southern	49°03′54.4″ S	72°57′31.2″ W	8.314	705	3	S (198°)	51
Laguna Cóndor	CON	Southern	49°12′08.8″ S	72°57′12.7″ W	33.074	454	12	E (92°)	31
C° Eléctrico	ELE	Southern	49°14′26.8″ S	72°57′51.2″ W	0.882	536	18	NE (49°)	19
Ea. Canigó E	CAN	Southern	49°18′20.5″ S	72°49′54.2″ W	44.898	694	10	SW (245°)	27
Ea. Canigó W	CAN2	Southern	49°18′56.7″ S	72°52′02.8″ W	2.370	536	18	E (84°)	16
Morena Torre	MTO	Southern	49°19′55.0″ S	72°57′32.3″ W	0.485	597	3	S (174°)	21
Sendero Laguna Torre	TOR	Southern	49°19′56.8″ S	72°54′42.0″ W	7.390	565	8	S (159°)	11
Valle del Río Túnel	TUN	Southern	49°22′56.3″ S	73°00′13.0″ W	7.479	615	3	SW (244°)	32
Desembocadura Río Mitre	MIT	Southern	50°26′50.6″ S	72°46′51.4″ W	1.522	311	13	SE (134°)	15
Brazo Rico - Faldeo Los Notros	NOT	Southern	50°28′02.5″ S	72°58′13.8″ W	1.229	627	21	S (179°)	22

† The latitude and longitude coordinates correspond to the centroids of the polygons defined by the sampled trees and calculated by the convex hull method.
‡ Elevations from SRTM Digital Elevation Model (DEM).
§ For San Lorenzo Sur, the coordinates correspond to a midpoint between the centroids of the two sub-sites sampled on the area.

nearby sites (Srur et al. 2008). Fire scars from suppressed trees were cross-dated quantitatively by measuring the ring widths (to the nearest 0.001 mm with a Velmex Unislide measuring system) and using the computer program COFECHA (Holmes 1983). We followed the Schulman's convention (1956) for the Southern Hemisphere, which assigns to each annual ring the calendar year in which ring formation begins. Determination of the fire seasonality was based on the position of the scar within the ring (Dieterich and Swetnam 1984).

Temporal analyses of fire frequency

The program FHAES (Brewer et al. 2016) was used to calculate standard fire statistics, including composite mean fire interval (MFI; mean time between successive fires in a specified search area) and to create the fire history charts. Composite fire intervals were calculated for the periods in which there were at least two recorder series and two scars in the first event.

We analyzed fire intervals based on (1) the occurrence of any fire in the study area (≥2 trees scarred) and (2) fire years in which at least 20% of the recorder trees were scarred (i.e., fire scar-susceptible trees that have been scarred previously or during the fire year of interest; *sensu* Romme 1980). Site records were aggregated into northern and southern groups and all together into a regional composite. In each case, composites were calculated based on fire scars recorded on two or more trees and on at least 20% of the recorder trees. To analyze temporal trends in fire intervals, no *a priori* periods of interest were defined. Instead, following Kitzberger and Veblen (1997), moving 25-yr sums of the number of fire event years were computed and assigned to the last year of the period.

Analyses of climatic influences on fire occurrence

Superposed epoch analysis (SEA; Grissino-Mayer 1995) was used to relate fire years to monthly temperature and precipitation, September through February indices of ENSO and SAM. Superposed epoch analysis determines the relationship between fire events and climatic data (or climate proxies) in the years prior to, during, and succeeding fire years. Mean values of these climatic data were calculated for four-year windows, including the fire event year. Mean values of climatic parameters during the fire event years were compared to variations in the complete record by performing 1000 Monte Carlo

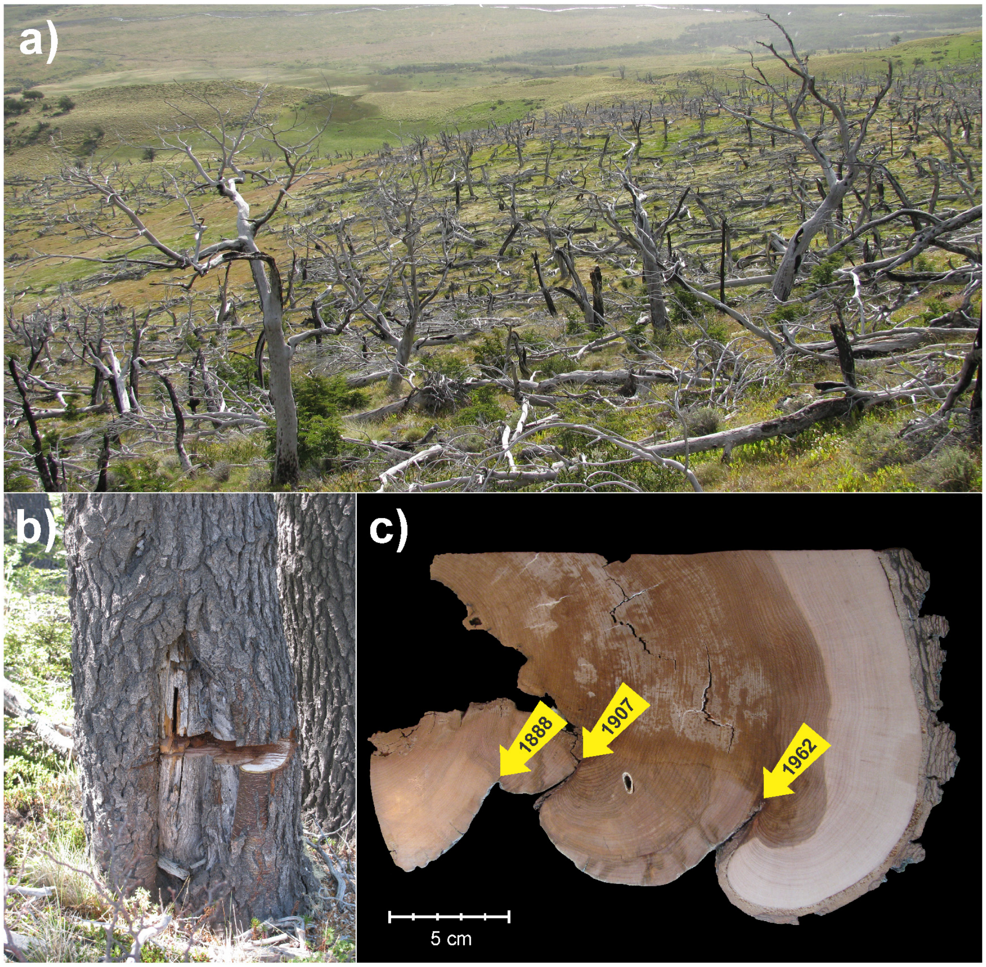

Fig. 2. Fires in *Nothofagus pumilio* forests: (a) high-severity fire at CAN, Santa Cruz, Argentina; (b) a multiple fire-scarred tree at LAC, Parque Nacional Perito Moreno, Santa Cruz, Argentina; and (c) its respective fire-scar dates on the partial cross-section.

simulations (randomly selecting years) to calculate expected means and estimate 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 mean values of the proxy records and climate indices against the means for years of widespread regional fires (i.e., fire dates recorded on at least 20% recorder trees in at least two sites). Superposed epoch analysis was conducted using the program EVENT version 6.02P (http://www.ltrr.arizona.edu/software.html).

Climatic records longer than 40 yr with <30% of missing values were compiled from 14 stations along the Patagonian Andes (Table 2). Most of these data are from Koninklijk Nederlands Meteorologisch Instituut of Netherlands (KNMI) Climate Explorer (https://climexp.knmi.nl/), a web-based research tool for investigating climate (Trouet and Van Oldenborgh 2013). Only those records that passed homogeneity screening (Alexandersson 1986, Menne and Williams 2009) were used in this study. The precipitation and temperature records from KNMI Climate Explorer were supplemented with information provided by the Dirección de General de Aguas of Chile, the Dirección Meteorológica de Chile, the Servicio Meteorológico Nacional of Argentina, and Subsecretaría de Recursos Hídricos of

Table 2. Meteorological records used for comparing fire dates in *Nothofagus pumilio* forests with climate variations.

Station	Code	Latitude (S)	Longitude (W)	Elevation (m a.s.l.)	Parameter	Record period	Source
Esquel	ESQ	42°55′00.0″	71°09′00.0″	785	P	1896–2015	KNMI
					T	1931–2015	
Futaleufú Aeródromo	FUT	43°11′20.0″	71°51′09.0″	347	P	1961–2014	DMC
					T	1963–2015	
Lago Rosario	ROS	43°14′08.2″	71°21′41.6″	720	P	1956–2015	SRH
Alto Palena Aeródromo	PAL	43°36′44.3″	71°48′08.8″	252	P	1961–2014	DMC
					T	1964–2014	
Puyuhuapi	PUY	44°19′30.0″	72°33′30.0″	11	P	1936–2012	DMC
Puerto Cisnes	CIS	44°45′00.0″	72°42′00.0″	10	P	1955–2008	DGA
Puerto Aysén	AYS	45°24′00.0″	72°42′00.0″	11	P	1931–2014	KNMI
					T	1932–2014	
Coyhaique	COY	45°35′44.0″	72°06′40.0″	304	P	1961–2014	DMC
					T	1943–2015	
Balmaceda	BAL	45°55′00.0″	71°41′00.0″	520	P	1958–2014	DMC
					T	1959–2014	
Chile Chico Aeródromo	CHC	46°34′52.0″	71°41′33.0″	306	T	1963–2015	DMC
Cochrane Aeródromo	COC	47°14′39.0″	72°35′07.0″	205	P	1964–2012	DMC
Lago Argentino/El Calafate	LAR	50°20′15.0″	72°14′44.0″	220	T	1956–2000	SMN
Punta Arenas/Chabunco	PUQ	53°00′18.0″	70°50′37.0″	38	P	1888–2015	KNMI
					T	1888–2015	
Observatorio Met. Monseñor Fagnano	MFA	53°09′43.2″	70°54′39.2″	18	P	1919–2007	DMC

Note: P, precipitation; T, temperature; DGA, Dirección General de Aguas of Chile; DMC, Dirección Meteorológica de Chile; KNMI, Koninklijk Nederlands Meteorologisch Instituut of Netherlands; SMN, Servicio Meteorológico Nacional, Argentina; SRH, Subsecretaría de Recursos Hídricos, Argentina.

Argentina. Following Aravena and Luckman (2009), for each individual station with missing data (candidate series), a reference file was created using those stations best correlated with the candidate (correlation coefficient >0.5; usually the closest stations). The mean of the reference series was calculated and missing values estimated from the value in the mean reference series multiplied by the ratio between mean monthly averages from the candidate and the reference series (Alexandersson 1986, Stepanek 2006).

Spatial and temporal patterns of climatic variability were examined using principal component analyses (PCA) for both monthly temperature and precipitation records over their common periods. Principal component analyses has been widely used to identify dominant patterns of climate variability and to reduce the dimensionality of climate data (Lorenz 1956, White et al. 1991) and particularly for temperature and precipitation in Patagonia (Aravena and Luckman 2009). The longest and most representative (based on PCA) record from each sub-region was selected for SEA and for inferring climate influences on fire occurrence in each sub-region (results of the PCA are in Appendix S1).

Additionally, the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010), for different scales ranging from 1 to 12 months, was downloaded from the Global SPEI database for representative stations within each region (http://sac.csic.es/spei/database.html). Standardized Precipitation-Evapotranspiration Index is a drought index based on precipitation and potential evapotranspiration. It combines the sensitivity of the Palmer Drought Severity Index to changes in evaporation demand (caused by temperature fluctuations and trends) with a multi-scale character (i.e., it is calculated for different temporal scales: 1, 3, 4, 6, 8, 12, 16, 24, 36, and 48 months; Vicente-Serrano et al. 2010). For example, December SPEI6 refers to precipitation and climatic water balance accumulated over the preceding six months (July–December). Following Kingston et al. (2014) and van Loon and van Lanen (2012), a six-month accumulation period (SPEI6) was selected to reflect both summer rainfall and winter snowfall deficits, following comparison with other accumulation periods (1, 3, 9, and 12 months).

Relationships between fire occurrence and climate forcings were determined using austral spring–summer (six-month period) of (1) Niño 3.4 SST anomalies (1870–2016; available at: NOAA: http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/) calculated by Rayner et al. (2003) and (2) observed SAM (hereafter Marshall's observational SAM index; available at the British Antarctic Survey: https://legacy.bas.ac.uk/met/gjma/sam.html) over the instrumental AD 1957–2015 period (Marshall 2003). Finally, spatial field correlations between ENSO and SAM indexes and climate variables were performed using KNMI Climate Explorer (https://climexp.knmi.nl/) and then imported into GIS to verify the spatial association between variables.

Results

Site chronologies, groupings, and temporal trends of fire occurrence

Seventy-two percentage of the total 363 collected samples were successfully cross-dated and yielded annually resolved fire dates (Table 3, Fig. 3). Dating fire scars in *N. pumilio* is a very difficult task due to the presence of extremely narrow rings, rotten wood, and indistinct fire-scar tips. Consequently, assessment of fire seasonality was not possible for most scars (92% of the 396 scars were classified as seasonally undefined). For those samples where the position of the scar within the ring was established (33 scars), most fires were classified as the early-season fires (29 scars).

The earliest fire event was dated to the year 1791 at LAC; however, the earliest widespread fire (≥2 trees scarred in at least 20% of the recorder trees) was dated to 1843 at RTO. This site also showed the largest number of recorded fire events (13). The most recent fires were dated to the year 2003 at both MTO and TUN. This fire event at MTO was used for validation against the documentary fire record from Parque Nacional Los Glaciares (4 November 2003; ~25 ha of forest burned).

Based on the number of scars per sample, half of the samples were classified as single scars (136), whereas the remaining 50% were multiple-scarred trees. Most of the multiple-scarred samples show two fire scars (63 samples). The maximum number of fire scars dated on a single sample was 7 (samples MON04 and CAN21 at MON and CAN, respectively).

Table 3. Summary of fire chronologies and composite fire interval statistics.

			Fire dates‡			Scarred/recorders filter							
						All				≥20% scarred/rec.			
Site code	N	Period†	First	Last	No. of events	FI	MFI	SD	Range	FI	MFI	SD	Range
GUA	16 (89%)	1858–2010	1914	1975	7	6	10.2	5.2	4–18	6	10.2	5.2	4–18
FO2	7 (70%)	1902–2010	1915	2000	5	4	21.3	11.5	8–34	4	21.3	11.5	8–34
MON	10 (83%)	1854–2010	1944	2002	6	5	11.6	8.0	5–25	5	11.6	8.0	5–25
SLC	9 (90%)	1955–2010	1962	1988	4	3	8.7	4.7	5–14	3	8.7	4.7	5–14
LAC	22 (85%)	1765–2011	1907	1991	10	9	9.3	6.1	3–21	4	13.8	6.9	6–21
SLS	32 (76%)	1761–2011	1928	1982	7	6	9.0	6.4	1–17	3	18.0	25.2	1–47
RTO	40 (78%)	1730–2011	1843	1994	13	12	12.6	13.5	2–35	4	29.5	16.6	6–45
CON	20 (65%)	1820–2010	1959	1988	6	5	5.8	3.8	2–11	2	4.5	3.5	2–7
ELE	15 (79%)	1866–2010	1965	1999	2	1	34.0	–	–	–	–	–	–
CAN	16 (59%)	1873–2010	1930	1986	5	4	14.0	12.0	3–31	1	14.0	12.0	3–31
CAN2	12 (75%)	1905–2010	1975	1983	2	1	8.0	–	–	–	–	–	–
MTO	17 (81%)	1860–2010	1912	2003	5	4	22.8	21.0	4–46	3	30.3	21.4	6–46
TOR	8 (73%)	1927–2010	1962	1995	4	3	11.0	7.2	5–19	3	11.0	7.2	5–19
TUN	16 (50%)	1702–2010	1938	2003	5	4	16.3	11.1	6–29	3	19.0	11.8	6–29
MIT	12 (80%)	1878–2011	1927	1974	2	1	47.0	–	–	–	–	–	–
NOT	20 (91%)	1881–2011	1959	1978	4	3	6.3	5.8	3–13	2	9.5	9.2	3–16

Note: FI, number of fire intervals; MFI, mean fire interval; SD, standard deviation; N, number of dated samples (% of sampled); –, too few intervals to perform the analyses.

† ≥2 samples.

‡ Recorded in at least two individual trees.

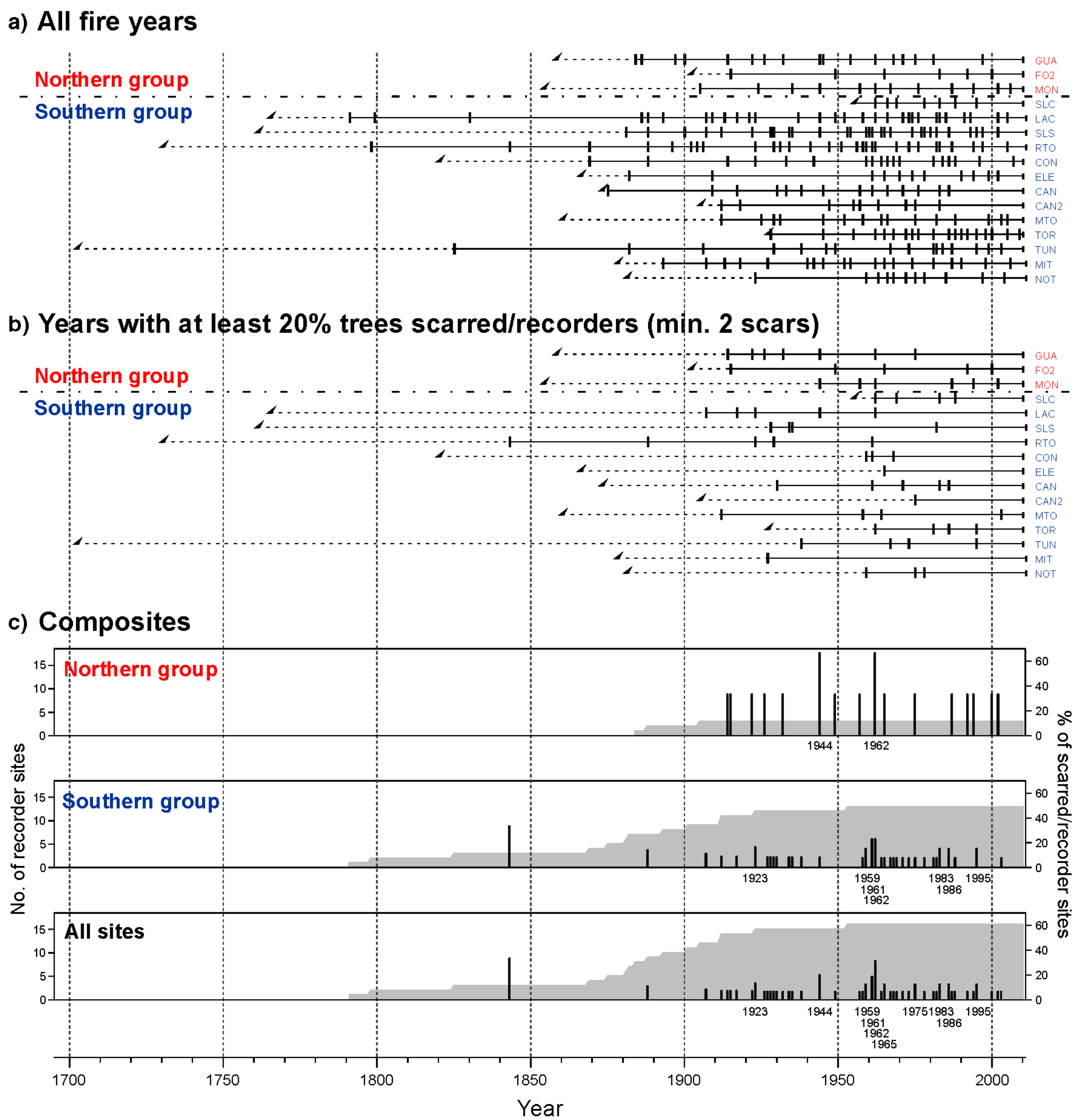

Fig. 3. Local fire chronologies at each sample area indicating (a) years of any fire occurrence, (b) years in which 20% of the recorder trees (minimum two scars) recorded fire, and (c) composite fire chronologies (based on filters in b) with fire scars for at least two sites for the northern and southern group and all sites combined. In (a) and (b), each horizontal line represents a different site (arranged from north to south), 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 site based on the corresponding filter. Northern sites: GUA, FO2, and MON. Southern sites: SLC, LAC, SLS, RTO, CON, ELE, CAN, CAN2, MTO, TOR, TUN, MIT, and NOT. In (c), sample size (number of recorder sites) is shown as the shaded gray areas and only those widespread fire events (based on filters in b) recorded in at least two sites in each group are labeled.

The composite MFI for all fire years recorded in at least two samples varied between 5.8 and 47 yr among sites (Table 2). For years of widespread fires (i.e., ≥20% recorder trees scarred), the MFI varied between 4.5 and 30.3 yr among sites. At a regional scale, considering all events, the MFI was 15.5 yr. Among the 16 sites, the highest percentage of trees recording a synchronous fire was 90% for the 1959 fire event at NOT, but the median percentage of maximum synchronous scars was 49%.

When 25-yr moving sums for years of widespread fires (i.e., >20% scarred class) were considered, differences in the temporal trends of fire occurrence over the 20th century were detected between the northern and southern groups (Fig. 4). Southern sites showed a first period with numerous fires during the first half of the 20th century and a second period, with even more fires, starting in mid-1970s. This temporal trend is coherent with the pattern of colonization in Chubut and Santa Cruz showing increments in fire activity coincident with periods of rapid growth of the human population (Fig. 4c). In contrast, changes in fire occurrence during the 20th century were not recorded in the northern sites. Two events (1944 and 1962) occurred simultaneously in at least two sites in the northern sector, whereas seven events were recorded in the southern sites (Fig. 3). Regionally, the most important fire was recorded at four sites in the year 1962.

Influences of interannual climatic variability on fire activity

Principal component analysis indicated that Esquel (ESQ) and Punta Arenas (PUQ) were representative of climatic variation in the northern and southern study areas, respectively, and consequently, the temperature and precipitation records from these two stations were compared with the years of widespread fire. The small number of widespread fires recorded for the northern group (only 1944 and 1962) did not allow the use of SEA to statistically validate climate–fire relationships. However, temperature and precipitation records from ESQ indicate that both events were coincident with short, but intense droughts in December of 1944 and 1962, respectively (Fig. 5a, c). Monthly precipitation, temperature, and SPEI1 records show that drought in December was preceded by relatively wet-warm winter and spring conditions. Consistent with these observations, the spatial patterns of December temperature and precipitation indicate that droughts were more severe in the northern Patagonian Andes (Fig. 5b, d).

In the southern sector, the seven years of widespread fire are associated with significant climatic anomalies that facilitate fire occurrence. These events were concurrent with significant negative departures from PUQ six-month accumulated precipitation ending in December, indicating persistent drought conditions from winter to early summer (Fig. 6a). Similarly, the mean SPEI6 for years of widespread fires from the gridded point associated with PUQ was significantly below the mean for the 1921–1996 period (Fig. 6c). The PUQ six-month (July–December) mean temperature during years of widespread fire was not significantly different from the longer-term mean. Monthly mean temperature anomalies show weak positive departures between October and March during widespread fire events (Fig. 6e). In contrast, negative anomalies of monthly total precipitation at PUQ and of SPEI1 from June to March were concurrent with widespread fires. Years of widespread fire coincided with dry conditions, whereas climatic conditions one to two years previous to fire were not anomalous (Fig. 6a, c).

Spatial field correlations were estimated between ENSO and SAM and regional climate during the fire season (austral spring–summer months of September–February; Fig. 7). No significant relationships between Niño 3.4 SST and fire-season precipitation or temperature were recorded over the area encompassed by our study sites (Fig. 7a). However, to the north of our study area, positive correlation between Niño 3.4 SST and precipitation during spring–early summer was observed consistent with previous studies (Montecinos and Aceituno 2003), indicating an association between ENSO and abundant precipitations during spring in the Pacific Coast north of 40° S.

In contrast to ENSO, consistent correlation patterns were observed between SAM, precipitation, temperatures, and SPEI during September through February over the entire southern Patagonian Andes (Fig. 7b). All the fire history sample sites are located in the region of negative

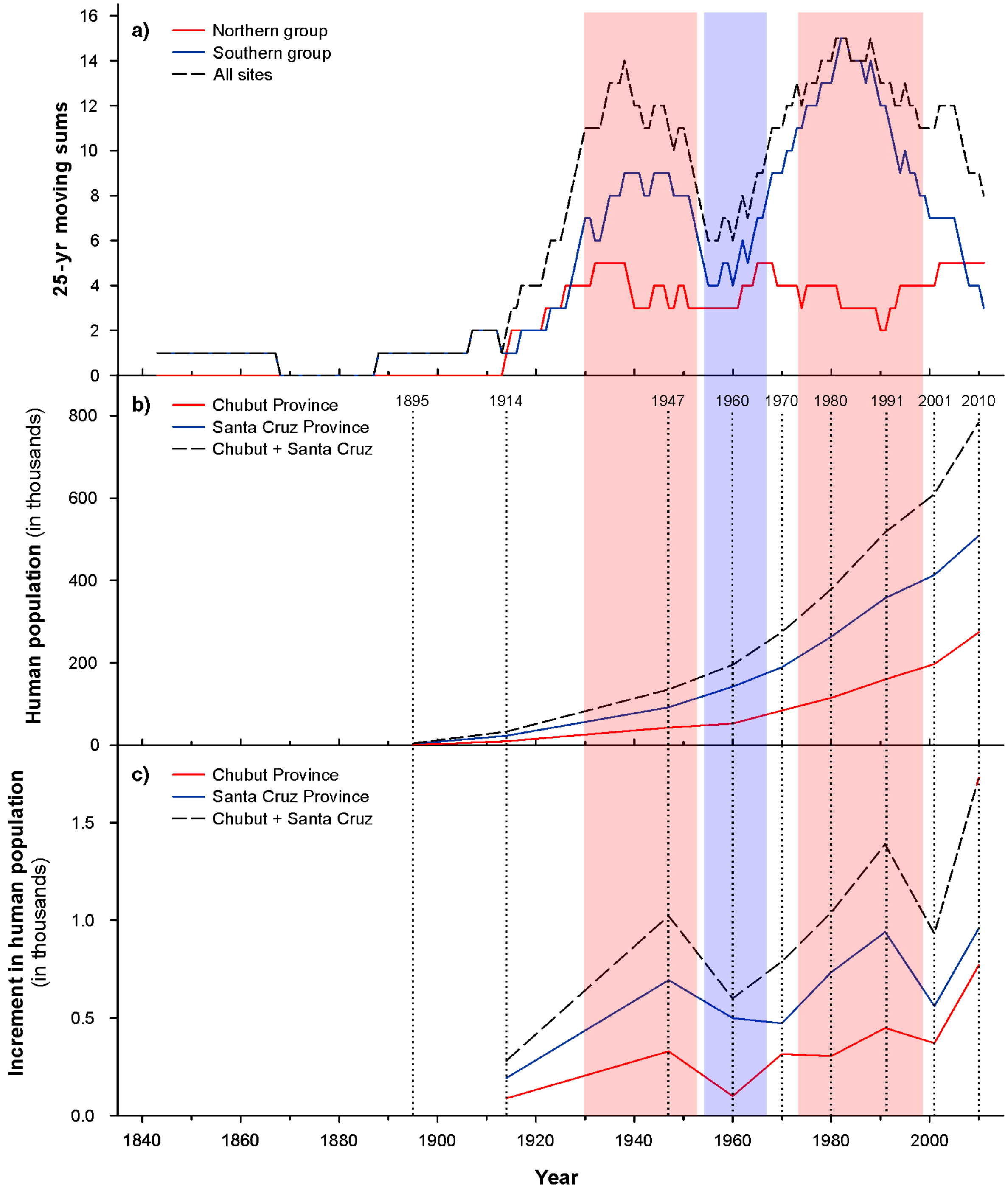

Fig. 4. Time series since the year of the first widespread fire in 1843 of (a) moving 25-year sums of widespread fire years (registered on >2 tree and 20% of recorder trees) for the northern and southern groups and all sites, (b) human population in Chubut and Santa Cruz provinces (corresponding to the northern and southern sample sites, respectively), and the aggregated population for both provinces, and (c) the increment in human population between consecutive censuses. Vertical dotted lines indicate census years. Vertical bars highlight coincident periods of increasing (light red) or decreasing (purple) population growth rate and number of fires.

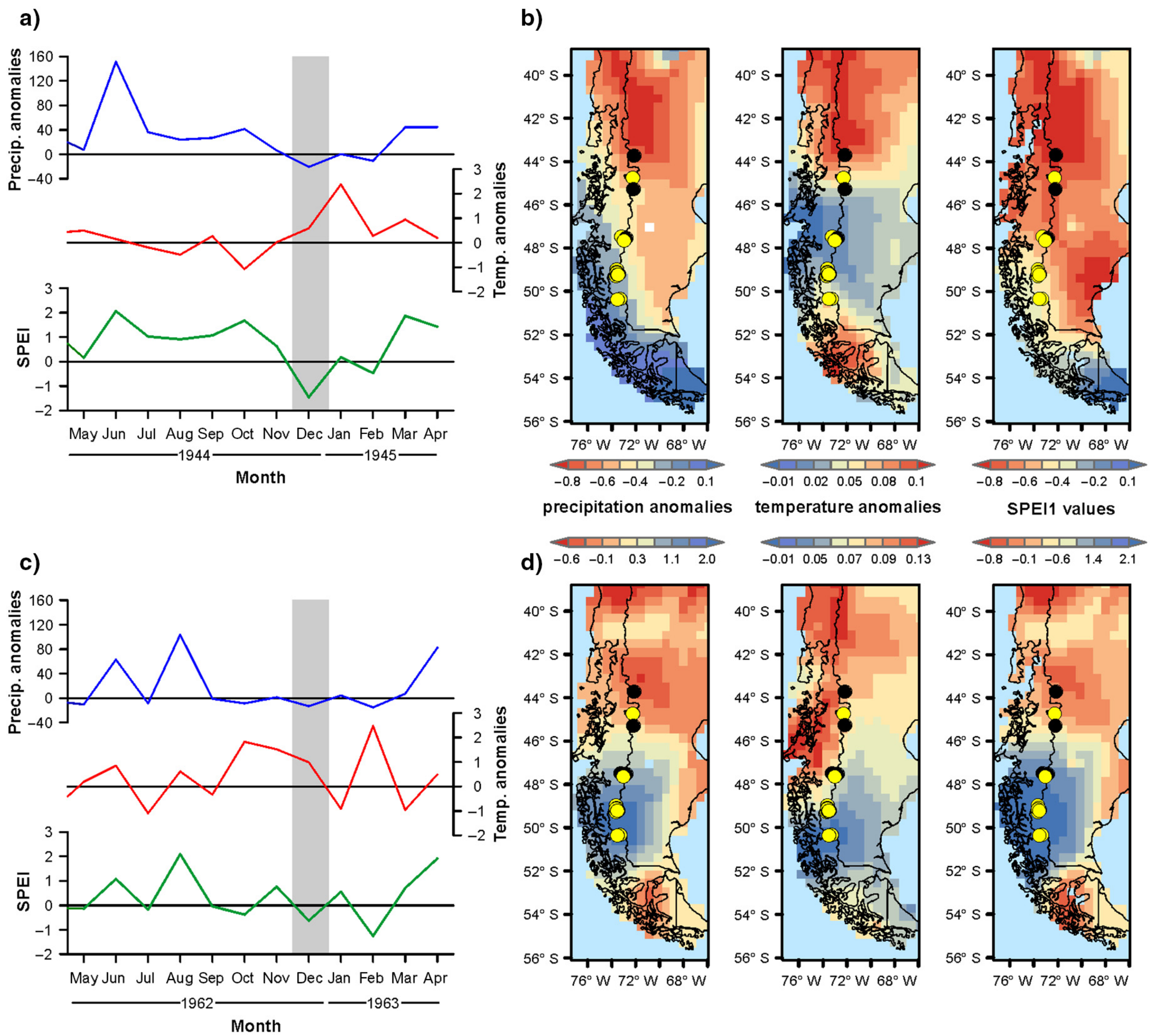

Fig. 5. Anomalies from monthly mean temperature and total precipitation from Esquel (ESQ) weather station and Standardized Precipitation-Evapotranspiration Index (SPEI1) 0.5° × 0.5° grid point centered at 70.75° S; 43.25° W for 1944–1945 (a) and 1962–1963 (c). Right panels display the spatial anomaly patterns for CRUTS 3.23 precipitation and temperature and for SPEI1 for December 1944 (b) and 1962 (d). ESQ monthly temperature and precipitation anomalies were calculated over the 1931–2014 and 1896–2014 periods, respectively. Spatial anomaly patterns from Koninklijk Nederlands Meteorologisch Instituut of Netherlands Climate Explorer (https://climexp.knmi.nl/). Vertical gray bars in panels (a) and (c) highlight December anomalies, the most likely month when fires could have occurred. Black dots in c and d correspond to burned sites on 1944 or 1962, respectively.

correlations between SAM and precipitation. In addition, SAM is positively associated with spring–summer temperatures enhancing drought severity in southern Patagonia as also indicated by the negative correlation between SAM and SPEI6. Consistent with these spatial correlation fields (Fig. 7), regional fires occurred in years with significant positive departures of the SAM index during austral spring–summer (six-month period ending in February), whereas there were no significant departures for the ENSO index (Fig. 8). It is noteworthy that there is no indication of lagged response between SAM and year of widespread fire.

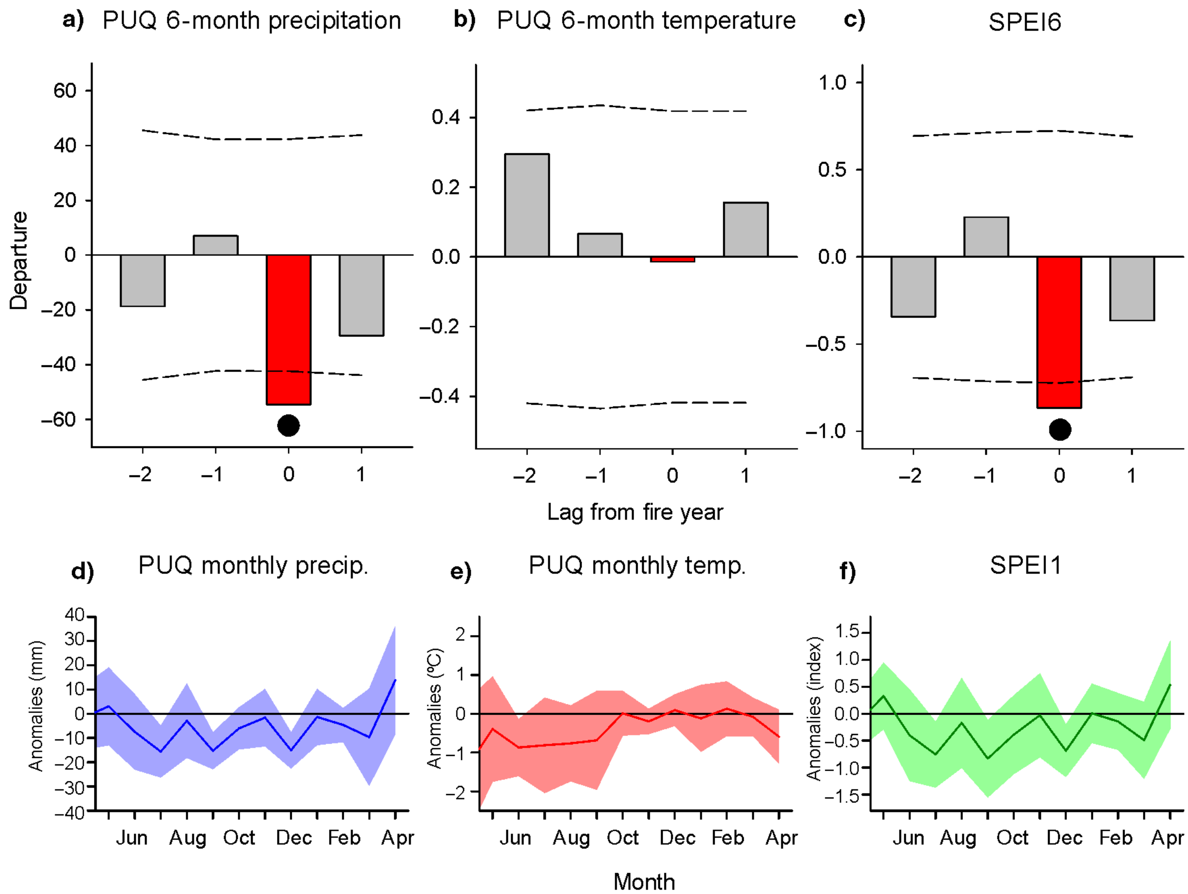

Fig. 6. Superposed epoch analyses (SEA) for six-month (July–December) mean and monthly mean anomalies of precipitation (a), temperature (b), and Standardized Precipitation-Evapotranspiration Index (SPEI6) (c) ending in December for the Punta Arenas (PUQ) weather station during widespread fire years in the southern Patagonian Andes (n = 7 over the window 1921–1996). In the upper panels, departures (standard deviations) are for mean six-month periods ending in December for PUQ accumulated precipitation, PUQ mean temperature, and SPEI 6 grid including PUQ (53.25° S; 71.25° W) for years before, during, and after widespread fire years (0). Bars capped with dots indicate statistically significant differences (P < 0.05). Dashed lines represent the 95% confidence limits. In the lower panels (d, e, and f), the lines represent the mean monthly anomalies during the seven widespread fire years and the shadowed area delimits the 95% confidence interval.

Discussion

Our study provides the first regional fire history based entirely on tree-ring fire scars from the deciduous angiosperm *Nothofagus pumilio* and represents the southernmost tree-ring-based reconstruction of fire history on Earth. As revealed by these new fire chronologies, fire is a relatively frequent disturbance in these high-latitude forests near the steppe in southern Patagonia. Temporal variations in this regional fire history reflect the combined effects of human and climate influences on fire occurrence. Low-frequency variations in fire recurrence are related to pulses of human population growth and settlement in southern Patagonia, whereas inter-annual variability in fire activity is strongly modulated by the Southern Annular Mode through its direct influence on regional climate and consequently on fuel desiccation.

All previous tree-ring fire histories in Patagonia have been based on native conifers located in

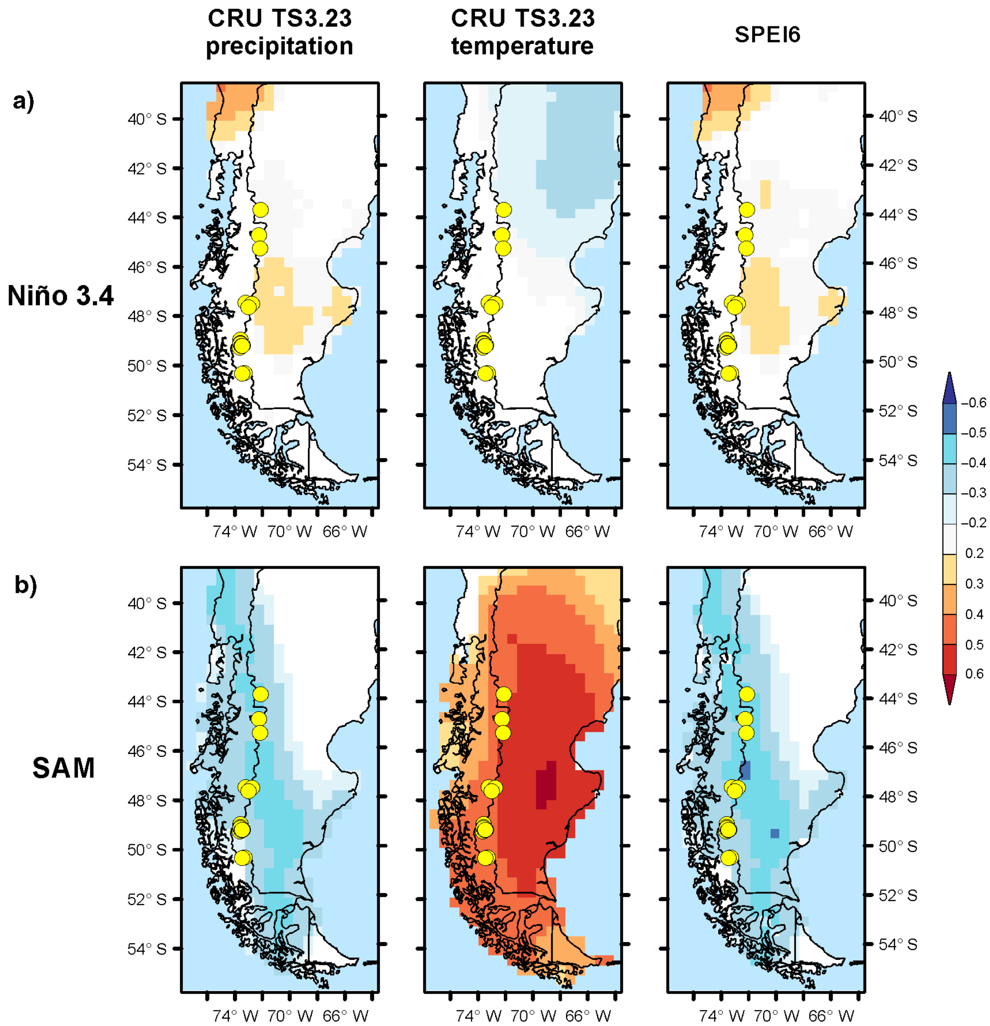

Fig. 7. Spatial field correlations between monthly detrended Niño 3.4 sea surface temperature (El Niño–Southern Oscillation; a) and the Southern Annular Mode index (SAM; b) and CRU TS3.23 precipitation, temperature, and Standardized Precipitation-Evapotranspiration Index (SPEI6) during the austral spring–summer (six-month period from September to February) over the period 1901–2014. Correlation coefficient values are shown on the right. Spatial field correlations estimated using the Koninklijk Nederlands Meteorologisch Instituut of Netherlands Climate Explorer (https://climexp.knmi.nl/). Only significant patterns are shown in color (n = 114, P < 0.05, r = |0.184|).

the northern Patagonian Andes (i.e., north of 44° S; Kitzberger et al. 1997, Lara et al. 1999, Veblen et al. 1999, González et al. 2005, Mundo et al. 2013) or the western Andean slopes in central-southern Patagonian rainforests (Holz and Veblen 2009, 2011*a*). Although *N. pumilio* fire scars have previously been used to complement the fire history for *Araucaria* forests in the Chilean sector of northern Patagonia (González et al. 2005), the development of fire chronologies based solely on this species has remained as a major challenge for reconstructing past disturbances in the southern Andes. Despite the advances presented in this study, 28% of the collected samples could not be dated due to wood decay, presence of extremely narrow rings, and indistinct fire-scar tips. In addition, as is the case for other fire-recording tree species, it was

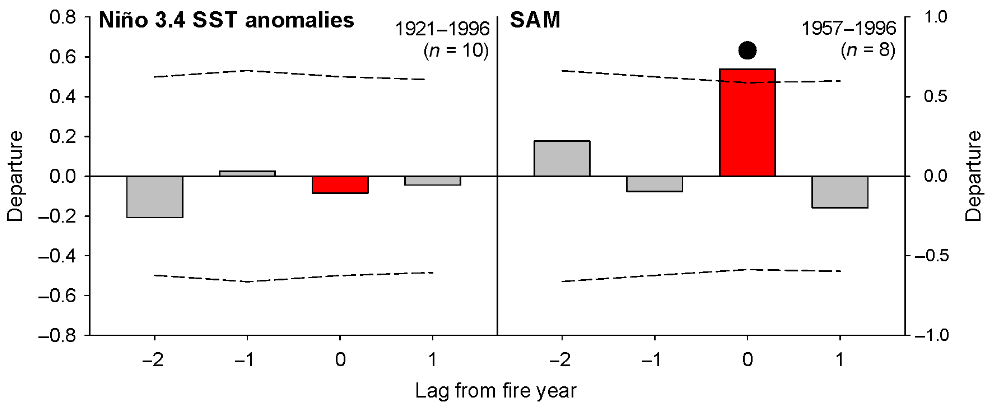

Fig. 8. Departures (standard deviations) from mean six-month periods ending in February for Niño 3.4 SST anomalies over the period 1870–2015 (http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/) and Marshall's observational SAM index over the period 1957–2014 (https://legacy.bas.ac.uk/met/gjma/sam.html/) for years before, during, and after regional (both groups combined) widespread fire years (0). Bar capped with dots indicate statistically significant differences ($P < 0.05$). Dashed lines represent the 95% confidence limits.

often challenging in the field to correctly distinguish fire scars from wounds caused by other agents such as mechanical damage from windthrow, snow, and rock falls. We also recorded some fire wounds showing non-typical triangular shapes (i.e., not classic "cat-face" shapes; Arno and Sneck 1977). In addition, heavy rains and strong winds in the area often remove charcoal from the scar face. Future studies in this forests need to consider these current challenges by collecting a larger number of samples than those used in traditional studies using fire-scar recording conifers. Future wood anatomical studies to clearly define *N. pumilio* traits associated with fire damage may prove helpful in identifying wood anatomical features in tree increment core samples to supplement dates determined on partial cross-section samples.

Fire type

Our results reveal differences in fire history among stands in distinct valleys or basins reflecting local environmental histories and, most importantly, variations in ignition sources. Although the occurrence of common fire years among sampled sites was observed, a high inter-site variability in fire histories was also detected. When filtering out the type of fires based on the percentage of scarred trees and number of scars, a mix of small to extensive fires is recorded at most sites. Although our research design was not aimed at determining fire severity and fire perimeters, the existence of many asynchronous fires within sites indicates small patchy fires. However, highly replicated fire-scar events, as those recorded in NOT in 1959, ELE in 1965, and CAN in 1983, demonstrate the existence of extensive fires, which based on field observation of high percentages of dead trees (e.g., Fig. 2a) clearly were high-severity fires. Other studies have also documented modern fires burning at high severity (i.e., killing most trees) across thousands of hectares of *N. pumilio* forest (Vidal and Reif 2011, Paritsis et al. 2013). Although the objective of this study was not to quantify and fully describe the range of fire regimes found in *N. pumilio* forests, the fire history data presented here in combination with field observations indicate that fires in this forest type range from small patchy events resulting in low numbers of fire-killed trees to large high-severity events killing most trees over thousands of hectares (i.e., a mixed-severity fire regime in space and time). However, in the absence of spatially explicit data collection on percentages of trees killed by fire, we did not try to characterize the severity of each fire event.

Trends over time in fire activity and human occupation

In contrast to years of widespread fire (i.e., >20% trees scarred of the recorders), trends in all fire years are likely to be reflective of changes over time in the number of ignitions by humans. Although the sample depth attained in this study is relatively short compared to fire history studies derived from conifers in northern Patagonia (e.g., Veblen et al. 1999, Mundo et al. 2013), all the site fire chronologies start prior to large-scale European settlement in the region in the early to mid-20th century and several chronologies start prior to 1850 during the period of solely Native American occupation. Inspection of individual site chronologies recording all fires indicates that the 20th century and in many cases the second half of the 20th century was a period of higher fire frequency. The sample depth for the northern group of sample sites is too short to contrast the frequency of 20th-century fires with 19th-century or earlier fires. However, for the southern group, the records of all sites start in the 19th century or earlier and in the aggregate show that fires became more frequent during the 20th century.

Fires at two sites (sites LAC and SLS) in the late 18th and at most sites during the 19th century indicate that fires were present in the *N. pumilio* forests prior to the European colonization in late 19th to early 20th century. Although our regional fire history is relatively short in time (the earliest widespread fire was dated to 1843 at RTO), many of our fire scars predated the Euro-Argentinean settlement and intensive grazing in the region. Ignition sources for specific fire events cannot be determined, and both lightning and humans must be considered as possible causes of these fires. During the course of our own fieldwork, we have observed lightning-ignited small fires in *N. pumilio* forests, but there are no modern data confirming the capacity of a lightning-ignited fire to spread to large areas. For example, Argentine National Park records for the period 1940–1993 covering a small part of our southern study area record 15 fires >1 ha, of which 13 were ignited by humans and two by unknown causes (Administración de Parques Nacionales, *unpublished records*). Likewise, all the recent fires in similar vegetation in nearby Torres del Paine National Park in Chile were ignited by humans (Vidal and Reif 2011). Thus, although lightning should not be ruled out as a source of ignition, we tentatively assume that most, if not all, of the fires recorded in our fire-scar record were ignited by humans. This is consistent with the known use of fire by the Patagonian Tehuelche Native Americans in hunting guanaco and other game (Musters 1871, Prieto et al. 2011). Archeological evidence from the forest–steppe ecotone of southern Patagonia (Chubut specifically) shows a clear correlation between periods of local occupation by hunter-gatherers and charcoal in sedimentary records (Méndez et al. 2016). It is likely that the fires recorded in our tree-ring fire records prior to the beginning of European settlement reflected burning by the Native American hunter-gather populations.

Despite the impossibility of ruling out the possibility of some fires being ignited by lightning, we assume that trends in the frequency of "all fires" in our study are more likely to reflect trends in human activities than in lightning activity. However, after considering the effects of interannual climatic variability on fire occurrence, we will return to the theme of possible influences of multi-decadal trends in climatic conditions on fire activity. Although the similar temporal trends in the growth of the modern human population in southern Patagonia and of fire activity are only correlative, the known land-use practices during colonization and the early phases of European settlement are consistent with a causal relationship. The first long-term period (1920–1950) of more abundant fires was concurrent with the establishment of sheep ranches in southern Patagonia (Barberia 1995). During the Patagonian sheep boom of the 1920s–1950, the Patagonian steppe was described as "pasture lands full of soft grasses" providing suitable conditions for sheep raising (Haberzettl et al. 2006). The first sheep company (Waldron & Wood, later administered by the Patagonian Sheep Farming) was established in 1885 in Estancia El Cóndor, in the southeastern extreme of Santa Cruz near the Atlantic Coast. However, sheep raising quickly expanded to the rest of Santa Cruz, and by 1940, most of the Patagonian steppe had been fully colonized for sheep raising (Bandieri 2005). During this colonization process, some settlers established near the ecotone between forests and the steppe, and forests were often burned to expand the area suitable for livestock use (Butland 1957, Martinic 2005).

The multi-decadal decline in wildfire activity at our southern sample sites centered on 1960 (Fig. 4) coincides with a period of slow human population growth in Santa Cruz Province and migration from rural to urban population centers. The wool industry collapsed in the 1950s due to reduced pasture productivity induced by overgrazing and soil erosion, which triggered migration of the rural population to urban centers on the Atlantic Coast (Soriano 1983, Pérez Álvarez 2015). Population growth accelerated in the 1970s and 1980s due to the establishment of industrial parks in the northeastern cities of Chubut Province (Pérez Álvarez 2015), the massive development of tourism activities in the region, and Chilean immigration into the region following the replacement of the democratic government in Chile by a military dictatorship in 1973 (Matossian 2012). The second peak in population growth involved the establishment of new towns near the forest–steppe ecotone. For example, the remote town of El Chaltén was transformed from a National Park administrative center with a population of only 1500 in 1985 to a major seasonal tourist destination hosting more than 40,000 visitors per year in the 2000s. The fire record from Los Glaciares National Park at the southern edge of our southern group of sample sites lists "fogón" (campfire) as the most common cause of wildfires.

Overall, our results show a strong temporal association of regional fire activity with the history of human settlement—including increases in fire activity coincidental with periods of likely accelerations in rural settlement and pioneer ranching activity. This finding is consistent with the general conceptual framework proposed by McWethy et al. (2013), suggesting that the impacts of anthropogenic burning are most detectable and impactful in temperate forest regions where natural fire was rare. Such regions are characterized by sufficient fuels and even by moderately frequent seasonal drought sufficient for fires to ignite and spread, but are apparently not characterized by high frequencies of lightning strikes that ignite fires. In southern as well as in northern Patagonia, numerous studies have documented pulses of increased burning associated with Euro-Argentinian colonization and pioneer activity (e.g., Veblen et al. 1999, Holz and Veblen 2011*a*, Mundo et al. 2013). While increases in sources of ignition resulting from Euro-Argentinian colonization and land-use practices are important in elevating wildfire activity, all these studies document a controlling influence on fire of interannual variability linked to broad-scale climate drivers such as the SAM.

Influences of interannual climatic variability on fire occurrence

By analyzing the climatic conditions suitable for occurrence of widespread fires (>20% trees scarred), we sought to identify the years in which fires could both ignite and spread over extensive areas. Although the number of widespread fires in the northern sites was too small for statistical analysis of the associated climatic conditions, the two widespread fire years (1944 and 1962) occurred during known spring and summer droughts across northern Patagonia (Fig. 5). In addition, recent work has identified a major summer heat wave in northern Patagonia during December 1962 that may have facilitated fire spread at these latitudes (Jacques-Coper et al. 2016). In the case of the southern Patagonia sample sites, years of widespread fire were abundant enough to perform SEA, which clearly showed the dependence of those fires on anomalously dry six-month periods prior to and extending into the fire season (Fig. 6).

A key finding of the current study was the absence of any evidence of fire years lagging by one- or two-year periods of above-average moisture availability (i.e., cooler temperatures, higher precipitation). Thus, there is no evidence that fires in *N. pumilio* forests along the forest–steppe ecotone are dependent on prior years of wetter conditions to enhance the abundance of grass or other fine fuels. In this environment, fine fuel quantity does not appear to limit fire occurrence, whereas fire is limited to anomalously dry fuel conditions. This is an important contrast from studies in northern Patagonia where fires in the *Austrocedrus* woodlands near the steppe ecotone are more frequent following years of wetter climatic conditions, indicating that fire spread is limited by fine fuel quantity (Kitzberger et al. 1997, Veblen et al. 1999). In contrast, in southern Patagonian *N. pumilio* forests, fires are dependent solely on extreme fuel desiccation due to drought.

Correlation climate fields show that climate in southern Patagonia is only weakly teleconnected to ENSO variability, which is consistent with the lack of an association of fire activity with ENSO variability. Weak relationships between Niño 3.4 SST with temperature and precipitation across southern Patagonia during spring–summer are consistent with previous research showing that strong regional climatic teleconnections in western South America only extend as far south as ~41°–42° S (Garreaud et al. 2009) where fire activity is also strongly influenced by ENSO variability (Kitzberger et al. 1997, Veblen et al. 1999, Mundo et al. 2013). For southern Patagonia, SAM is the major driver of droughts across the Patagonian Andes in spring and summer. Consistent with previous research (Garreaud et al. 2009), we documented warmer spring–summers associated with persistent positive SAM departures. In addition, reduced spring–summer precipitation across the Patagonian Andes is also related to a positive SAM index. Consistent with these climatic teleconnections, SEA showed that positive phases of SAM during austral spring and summer induce warmer and drier conditions conducive to fire activity in the *N. pumilio* forests of southern Patagonia.

The strong influences of interannual variability of regional climate and SAM on year-to-year variability in wildfire activity naturally lead to the hypothesis that the trend toward more fire activity in the second half of the 20th century is also due to long-term trends in these climatic variables. The upward trend in SAM documented since the inception of its measurement in c. 1950 is in fact associated with multi-decadal trends toward warmer and drier conditions in southern Patagonia (Garreaud et al. 2009). However, given the co-occurrence of significant increases in human presence in this landscape and by implication increased human-set fires, our research design did not permit resolution of that hypothesis. Developing research designs that can control for variable degrees of human control of the fire regime remains a challenge for future research. Nevertheless, given the upward trend in SAM since the mid-20th century and its strong modulation of climate variability across southern Patagonia, in combination with continued growth of tourism and therefore ignition sources, the next several decades will likely witness an increase in fire activity in the *N. pumilio* forests of southern Patagonia.

Acknowledgments

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