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ORIGINAL ARTICLE

Fire history of *Araucaria–Nothofagus* forests in Villarrica National Park, Chile

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ABSTRACT

Aim In this study we examine fire history (i.e. *c.* 500 yr BP to present) of *Araucaria–Nothofagus* forests in the Andes cordillera of Chile. This is the first fire history developed from tree rings for an *Araucaria–Nothofagus* forest landscape.

Location The fire history was determined for the Quillelhue watershed on the north side of Lanin volcano in Villarrica National Park, Chile. The long-lived *Araucaria araucana* was commonly associated with *Nothofagus pumilio* and *N. antarctica* in more mesic and drier sites respectively.

Methods Based on a combination of fire-scar proxy records and forest stand ages, we reconstructed fire frequency, severity, and the spatial extent of burned areas for an *c.* 4000 ha study area. We used a composite fire chronology for the purpose of determining centennial-scale changes in fire regimes and comparing the pre-settlement (pre-1883) and post-settlement fire regimes. In addition, we contrasted *Araucaria* and *Nothofagus* species as fire-scar recorders.

Results In the study area, we dated a total of 144 fire-scarred trees, representing 46 fire years from AD 1446 to the present. For the period from AD 1696 to 2000, using fire dates from *Araucaria* and *Nothofagus* species, the composite mean fire interval varied from 7 years for all fires to 62 years for widespread events (i.e. years in which ≥ 25% of recorder trees were scarred). Sensitivity to fire was different for *Araucaria* and *Nothofagus* species. More than 98% of the fires recorded by *Nothofagus* species occurred during the 1900s. The lack of evidence for older fire dates (pre-1900) in *Nothofagus* species was due to their shorter longevity and greater susceptibility to being killed by more severe fires. Whereas the thin-barked *N. pumilio* and *N. antarctica* are often destroyed in catastrophic fire events, large and thick-barked *Araucaria* trees typically survive. The spatial extent of fires ranged from small patchy events to those that burned more than 40% of the entire landscape (*c.* > 1500 ha).

Main conclusions Fire is the most important disturbance shaping the *Araucaria–Nothofagus* landscape in the Araucarian region. The forest landscape has been shaped by a mixed-severity fire regime that includes surface and crown fires. High-severity widespread events were relatively infrequent (e.g. 1827, 1909 and 1944) and primarily affected tall *Araucaria–N. pumilio* forests and woodlands dominated by *Araucaria–N. antarctica*. Although there is abundant evidence of the impact of Euro-Chilean settlers on the area, the relative influence of this settlement on the temporal pattern of fire could only be tentatively established due to the relatively small number of pre-1900 fire dates. An apparent increase in fire occurrence is evident in the fire record during Euro-Chilean settlement (post-1880s) compared with the Native American era, but it may also be the result of the destruction of evidence of older fires by more recent stand-devastating fires (e.g. 1909 and 1944). Overall, the severe and widespread fires that burned in

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Araucaria–Nothofagus forests of this region in 2002, previously interpreted as an ecological novelty, are within the range of the historic fire regimes that have shaped this forested landscape.

Keywords

***Araucaria*, bamboo, Chile, disturbance, fire history, fire scars, *Nothofagus*, stand dynamics, tree ring analysis.**

INTRODUCTION

Fire disturbance is recognized to be an important factor in shaping the forest mosaic of *Araucaria–Nothofagus* forests in the Andean Araucarian region of south-central Chile (Heusser *et al.*, 1988; Burns, 1991, 1993; Veblen *et al.*, 1995). Charcoal presence in pollen records spanning the last 44,000 yr BP (Heusser, 1994) suggests that natural fires played a significant role in this landscape prior to the arrival of Native American populations in *c.* 12,500 BP (Dillehay, 1997). Despite widespread recognition of the ubiquity of fire in these ecosystems there have been no quantitative studies regarding the relative importance of stand-replacing vs. surface fires in shaping landscapes characterized by *Araucaria araucana* (Molina) K. Koch (Araucariaceae), nor have there been any studies on temporal trends in fire frequency that could be attributed to either climatic variation or anthropogenic influences.

During the 2001–02 fire season, catastrophic fires burned nearly 20,000 ha of temperate forests in the Andean Araucarian region of Chile. Private forests as well as three National Parks and four National Reserves were affected, including Tolhuaca National Park and Malleco National Reserve, which each lost more than 50% of their forested area (CONAF, 2002). These wildfires prompted discussion of the role of fire in these forested ecosystems (CONAF-FORECOS, 2002) for three reasons: (1) the great cultural and ecological significance of *A. araucana*, which has the official status of a national monument; (2) the surprisingly great extent and severity of the fire events; and (3) the abundance of ignitions by lightning in contrast to the traditional public and resource managers' belief that fires in these forests are ignited by humans. Previously, fires in these forests were believed to originate solely as human-set fires, and were not believed to naturally affect areas as extensively or as severely as they did in 2002. Clearly, resource managers urgently need better information on the frequency and type (stand-replacing vs. surface fires) of past fires that shaped the present landscape of *Araucaria–Nothofagus* forests, and on how fire regimes may have been affected by humans. Furthermore, given that fire history studies are in their infancy in the temperate forests of South America, the reliability of fire history data obtained from different fire-recording tree species needs to be evaluated.

Variations in the frequency and severity of fire in forested landscapes have major influences on stand-level forest structure and species composition and on broad-scale landscape patterns (Pitcher, 1987; Turner *et al.*, 1994, 1997; Chappell & Agee, 1996; Brown *et al.*, 1999; Taylor, 2000). High-severity fires are commonly associated with longer intervals between fire events and result in greater mortality of canopy trees (Heinselman, 1981). Such stand-replacing events are often followed by a distinct regeneration pulse due to the sudden availability of resources. In contrast, low-severity fires are commonly associated with shorter time intervals and, although juvenile populations of tree species may be killed, result in no or little mortality of canopy trees and a little or no new tree establishment (Brown *et al.*, 1999). Between these two fire regime extremes are mixed-severity fires which span a continuum of fire effects and responses (Agee, 1993). Mixed-severity fires include a component of stand-replacing fire in addition to low-severity surface fire that results in little or no mortality of canopy trees and does not necessarily trigger new tree establishment. Field observations suggest that both stand-replacing fire events and non-lethal surface fires characterize the *Araucaria–Nothofagus* fire regime, but the spatial and temporal heterogeneity of fire severity in this landscape has not previously been investigated.

Centennial or decadal-scale trends in fire occurrence in *Araucaria* forests may reflect influences from climatic variation and/or humans, including native populations and Euro-Chilean settlers. Regardless of the cause (climatic, anthropogenic or both), resource managers need to understand whether the current fire regime is different from the historic fire regime, and if trajectories under current management policies (e.g. fire suppression) are consistent with the long-term historic range of variability of fire occurrence in these ecosystems. During the period of historic observation, fires in this region have been largely attributed to humans even though lightning and volcanism are known sources of ignition (Baquedano, 1914; Tortorelli, 1947; Montaldo, 1974; Bruno & Martin, 1982). Lack of awareness of the importance of ignition by lightning (Heusser, 1987; Heusser *et al.*, 1988; CONAF, 1995) in combination with the well-documented forest burning associated with Euro-Chilean settlement in the late nineteenth and early twentieth centuries (Baquedano, 1914; Montaldo, 1974; González, 1986) led to the general perception of fire as an unnatural disturbance agent in the dynamics of these southern temperate forests. Increases in burning during the 1900s, mainly associated with forest clearing, grazing and logging activities of new settlers, could have strongly affected *Araucaria* landscapes. Thus, an important question for managers of national parks in this region is whether or not human alterations to fire regimes and vegetation patterns following the settlement period (i.e. post-1883) have resulted in current *Araucaria–Nothofagus* forest structures that are outside their historic range of variability (*sensu* Morgan *et al.*, 1994). In the present study, we examine the recent fire history (i.e. *c.* 500 yr BP to present) of *Araucaria–Nothofagus* forests in the south-central Andes cordillera of Chile. Based on a combination of fire-scar proxy records and forest stand ages we reconstructed fire frequency, severity, and the spatial extent of burned areas for an *c.* 4000 ha study area. The specific objectives of this study are to: (1) compare the dominant species, *A. araucana*, and *Nothofagus pumilio* (Poeppig et Endlicher) Krasser (Fagaceae) and *N. antarctica* (G. Forster). Oersted, as fire-recording species for the purpose of determining centennial-scale changes in fire regimes; (2) generally describe the fire regime in terms of fire type (stand-replacing vs. surface fires), extent and frequency (and how they have shaped the extant *Araucaria–Nothofagus* forests); and (3) detect any major changes in fire regimes that might be associated with Euro-Chilean settlement (i.e. after 1883).

METHODS

Species and study area

Araucaria araucana is a long-lived conifer tree sometimes exceeding 1000 years in age and occasionally reaching 50 m in height and 2 m in diameter (Kozdon, 1958; Veblen *et al.*, 1995). Compared to *Nothofagus* species, this evergreen conifer can withstand fire due to its 15–20 cm thick bark (Kozdon, 1958; Montaldo, 1974; Veblen, 1982; Heusser *et al.*, 1988; Burns, 1991), whilst both *N. antarctica* and *N. pumilio* are thin-barked and not likely to survive intense fires (Veblen *et al.*, 1996). *Nothofagus antarctica* resprouts vigorously after fire, and under appropriate weather, micro-site and seed availability *N. pumilio* can establish abundantly after fire. Thus, stem ages of both *Nothofagus* species can be used to detect relatively even-aged post-fire cohorts. Whereas *Araucaria* often attains ages > 500 years, *N. antarctica* and *N. pumilio* rarely live more than 200 and 350 years, respectively (Veblen *et al.*, 1996).

The study area is the Quillelhue watershed (*c.* 4000 ha) on the north side of Lanin volcano in Villarrica National Park (39°35′ S and 71°31′ W; Fig. 1). The region is characterized 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). Seasonal and annual variation in these climate 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). The nearest climatic station is Puesco, located at 700 m a.s.l., 5 km north-west of the study area. At Puesco, mean annual precipitation is 3150 mm with 65% occurring in winter (between May and September), mostly as snow. Mean annual temperature is 9.3 °C, with a mean monthly minimum and maximum of 4.6 °C (July) and 13.9 °C (February), respectively. Throughout the region, most of the soils are derived from recently deposited volcanic ashes that overlie Pleistocene glacial topography (Casertano, 1963). The soils of the study area vary from poorly developed, coarsely textured soils, with relatively shallow organic horizons occupied by the drier *Araucaria–N. antarctica* forests, to deep, fine-textured and well-drained soils supporting mesic *Nothofagus* forests.

In the study area, *Araucaria* occurs in either pure stands or mixed species stands along with *Nothofagus* species at elevations between 1000 and 1600 m. In its most common forest type, *Araucaria* is mixed with the deciduous *N. pumilio*, typically on moderately dry sites located on the lower slopes of Lanin volcano. In the valley bottom of the Quillelhue watershed, subject to cold air drainage and drier conditions, *Araucaria* is commonly associated with *N. antarctica*. On southern aspects and more mesic sites associated with more developed soils, old-growth *N. pumilio* occurs as pure stands. Two- to four-meter-tall bamboo (*Chusquea culeou*) forms dense undergrowth particularly on more mesic sites.

The study area is an ancient pass across the Andes cordillera used by Native Americans and known by colonial Spaniards since the founding of Villa Rica in 1552 (González, 1986; Rosales, 1989). Similar to many mountain passes in the region, this pass was used to drive cattle from the pampas beginning in the early 1700s, with more intensive use in the 1800s as a consequence of increased trade between Native Americans and Euro-Chilean settlers (San Martin, 1940; Bengoa, 2000). Euro-Chilean settlement of the area started late in the nineteenth century (*c.* 1883), after the Chilean government took definitive control of the Araucarian region from the Native Americans (González, 1986). Following settlement, extensive fires associated with the creation of cattle pastures and logging activities impacted forests, particularly from *c.* 1910 to the 1940s (Echegoyen, 1915; Montaldo, 1974; von Buch, 1975; Gómez, 1986).

Geographic information system spatial data base: vegetation and disturbance history map

A geographic information system (GIS) data base containing spatial and descriptive data (e.g. hydrology, topography, roads) was developed from topographic maps (IGM, 1994) by CONAF-CONAMA (1995, 1997). Land-cover types (i.e. vegetation units and ground surface covers) were interpreted from aerial photographs taken in 1960 (flight CH 60; 1 : 60,000; CONAF-CONAMA, 1995). To improve the quality of this initial vegetation coverage, boundaries and structural homogeneity of each mapped forest patch were verified by using new aerial panoramic photos and by visiting and observing the patches from high viewpoints. This map was used to guide field sampling. Dates of, and areas affected by, individual fire events, as well as the GPS location of sample sites and fire-scarred trees, were digitized into the GIS data base for analysis.

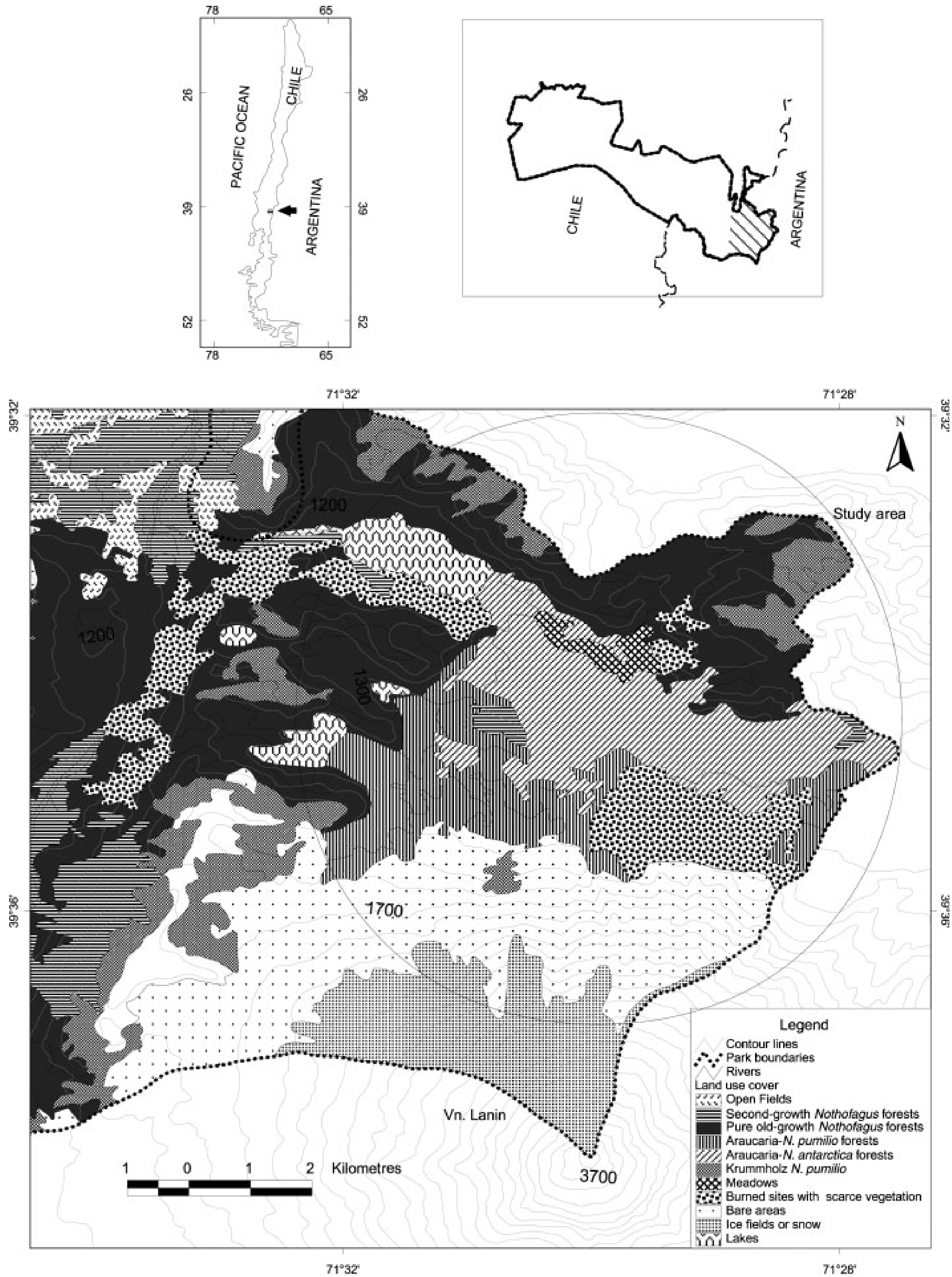

Figure 1 Cover types in the Quillelhue study area. Source: CONAF-CONAMA (1997).

Field sampling

For reconstructing fire history, vegetation units (i.e. forest patches of homogenous structure and composition) were sampled for fire-scar and tree-age data. The number of sampling sites was based on the size and complexity of the patch. Patch size varied from 9 to 573 ha, and the number of sites sampled per patch varied from 1 to 4. At each sample site, cores were taken from the 15 to 30 of the largest (and presumably oldest) live trees of the post-fire cohort, mainly from *N. antarctica* or *N. pumilio* species in order to obtain initial estimates of dates of regeneration-triggering fire events. If other distinct cohorts were present within the patch they were also sampled for tree ages (including a few old remnant trees). Trees were cored near the base and generally to the pith; some samples were slightly off the pith but ages were corrected as described below. For each tree sampled, the following information was recorded: core height, species, diameter at breast height (d.b.h.), and canopy position. General information recorded for each sampling site included: forest type and developmental stage, species composition, canopy cover and topographic characteristics (i.e. aspect, slope and elevation).

To determine the exact fire dates we cut partial cross-sections from fire-scarred trees (McBride, 1983). The patch and adjacent areas were intensively searched for fire-scarred trees, and whenever possible, samples were collected in clusters of several trees to improve chances of obtaining the most complete fire record possible (Arno & Sneck, 1977). Information recorded for each sampled tree included: species, d.b.h., number of visible fire scars and the scar face azimuth. Location (UTM coordinates) of each fire-scarred tree sampled was recorded using a hand-held global positioning unit. Fire scars were also sampled opportunistically when encountered *en route* to other patches.

Data analyses

Dendroecological analyses

Processing of tree cores and fire scars followed standard procedures (Arno & Sneck, 1977; McBride, 1983; Stokes & Smiley, 1996). *Nothofagus* tree-core samples were counted and dated to determine the earliest ring date and the initial growth patterns. For determining tree ages in cases where the pith was not intercepted, a maximum of 20 and 30 years were added for *Nothofagus* and *Araucaria*, respectively, based on Duncan's (1989) geometric procedure. Fire dates were determined by counting backwards from the outermost ring and were verified by visually crossdating against marker rings derived from master tree-ring chronologies developed in this study and in nearby studies (R. Villalba: Estancia Pulmari; V. La Marche: Lago Tromen; R. Holmes: Estancia Mamuil Malal; International Tree-Ring Data Bank, NOAA). Fire scars from trees with suppressed growth were crossdated by measuring ring widths and using the computer program COFECHA (Holmes, 1983). Fires dating from prior to 1700 could not be conclusively dated and should initially be considered as tentative fire years. According to Schulman's (1956) convention, in the Southern Hemisphere calendar, years of annual rings are assigned to the year in which ring formation begins even though the growing season extends from September to March. Thus, according to this dating convention a fire date assigned to 1944 may have occurred between September 1944 and March 1945.

Stand-age structures and tree-ring growth patterns were used to determine stand origin. A conspicuous pulse of tree regeneration with rapid initial growth indicated a post-fire cohort established under open conditions. Dates of past canopy disturbances were also determined by changes in growth patterns (i.e. growth releases) exhibited by *Araucaria* remnant trees that survived the disturbance. A growth release was defined by visually examining individual ring-width chronologies and identifying conspicuous positive changes (i.e. > 100% growth increase sustained for at least 5 years) in the tree-ring pattern. Tree-ring series used for interpreting disturbance were standardized using a horizontal straight line, which transforms ring widths into dimensionless index values (Fritts, 1976; Cook & Holmes, 1984; Cook & Kauriustis, 1990). This standardization procedure does not detrend the series but instead facilitates the detection of sudden sustained changes in tree growth such as those that occur after canopy disturbances (Veblen *et al.*, 1991).

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). Both means and the Weibull median probability interval (WMPI) were determined (Grissino-Mayer, 1999). The WMPI describes the fire interval associated with the 50% exceedance probability, in which half of the fire intervals will exceed and half will be shorter than the WMPI (Grissino-Mayer, 1995). Kolmogorov–Smirnov goodness-of-fit tests were used to evaluate the fits of fire interval distributions to normal and Weibull distributions (Grissino-Mayer, 1995). 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 imply more widespread fires (Grissino-Mayer, 1995; Kitzberger & Veblen, 1997).

We analysed fire intervals based on the occurrence of any fire in the study area (≥ 1 trees scarred), and fire years in which at least 10%, 20% and 25% of the recorder trees (i.e. fire-scar susceptible trees that have been scarred previously or during the fire year of interest; *sensu* Romme, 1980) were scarred. The fire history record was analysed for two different periods: (1) the recent Native American period (1696–1882); and (2) the Euro-Chilean settlement period (1883 to present). The fire interval analysis, both for the CFI and PFI, began in the year 1696, in which there were at least four scarred-trees present (i.e. the period of reliability *sensu* Grissino-Mayer, 1995). In addition to analysing the complete fire record, separate analyses were performed for the fire-recording species to detect possible differences in susceptibility to scarring between the thin-barked *N. pumilio* and/or *N. antarctica* species. The *Nothofagus* fire record includes both of these species and is contrasted with the fire record from the thick-barked *Araucaria*. Thus, fire interval statistics were computed from 1696 to 2000 for *Araucaria* and *Nothofagus* fire scars combined and for

Araucaria alone, and over the period 1909–2000 for the *Nothofagus* fire record alone.

The spatial extent of historical fires was reconstructed only for four major high-severity fire events (> 20% recorder trees scarred), represented by those fires that left sufficient evidence to allow confident mapping of their boundaries. The following criteria were used to map past fire perimeters (Arno & Sneck, 1977; Hemstrom & Franklin, 1982; Agee *et al.*, 1990; Goldblum & Veblen, 1992; Veblen *et al.*, 1994; Kipfmueller & Baker, 2001): (1) stand-age data from trees established after a fire event (post-fire stands as indicated by even-aged *Nothofagus* cohorts and rapid initial growth); (2) locations of fire-scarred trees; (3) locations of remnant trees with tree-ring series showing growth releases; (4) inference of fire spread based on topography and location of natural fire breaks, and (5) structural variation in vegetation patterns on aerial photos and maps available for 1960 and 1981.

RESULTS AND INTERPRETATION

Fire interval analysis: comparison of *Araucaria* and *Nothofagus* as fire-scar recorders

Fire history in the Quillelhue study area was reconstructed from 144 cross-section samples (from a total of *c.* 200 samples collected), representing 46 fire years. The number of fire-scar samples for *Araucaria*, *N. antarctica* and *N. pumilio* used was 59, 11 and 74, respectively. The earliest fire year recorded was AD *c.* 1446 and the most recent was 1990 (Fig. 2). Most of the multiple-scarred samples contained two fire dates (80%), and the maximum number of fire scars dated on a single sample was 18 (on *Araucaria*).

For the fire record based on all species (1696–2000), using fire dates from *Nothofagus* and *Araucaria* species, the WMPI and CFI for all fire years were 5.8 and 7.2 years, respectively (Table 1). For years of widespread fires (i.e. ≥ 25% recorder trees scarred), the WMPI and CFI were 56.7 and 62 years, respectively (Table 1; Fig. 3a). For the *Araucaria* record (1696–2000), the WMPI and CFI for all fire years were 7.2 and 8.4 years, respectively. Years of the most severe and widespread fires (i.e. > 25% scarred) had a return interval of *c.* 80 years (Table 1). The low minimum fire interval (2 years in the *Araucaria* record for ≥ 20% of the *Araucaria* recorder trees) implies that such extensive fire events did not overburn the same area because 2 years would be insufficient for fuel recovery. In fact, for the fire events 1942 and 1944, none of the sample sites recorded both fire episodes. For the *Nothofagus* record (1909–2002), the WMPI and CFI for all fire years were 4.5 and 5.1 years, respectively. These values were relatively comparable with those obtained for all species (i.e. all three

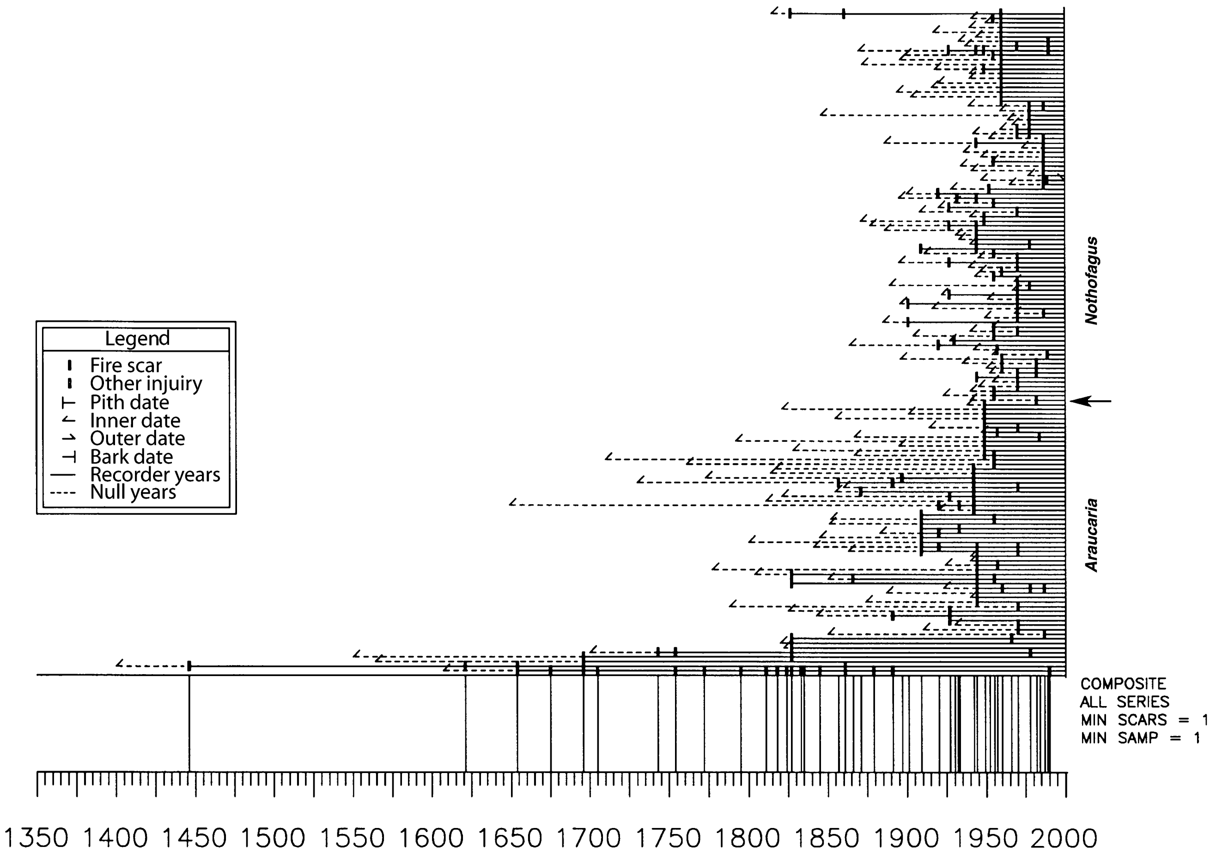

Figure 2 Composite fire-scar records for the complete record (n = 144), including all fire years and all species (i.e. *Araucaria*, *Nothofagus pumilio* and *N. antarctica*). Each horizontal line represents a different fire scar sample, where fire dates are indicated by short vertical lines. Dates and vertical lines at the bottom of charts indicate fire years.

Table 1 Composite fire interval statistics for the fire records from all species and for *Araucaria* and *Nothofagus* spp. separately. Fire statistics are shown over the complete period from 1696 to 2000, the Native American period (1696–1882), and the Euro-Chilean settlement period (1883 to present). For the *Nothofagus* spp. fire record, statistics are shown over the period from 1909 to 2000. Different letters indicate statistical significance ($P < 0.05$)

Fire record and time period	MSS or % scarred	No. of intervals (years)	WMPI (years)	CFI (years)	SD	Max. FI (years)	Min. FI (years)
All species							
1696–1882	All	17	9.1	10.8[a]	9.0	38	2
	≥ 20%*	3	55.7	55	19.7	73	34
1883–2000	All	23	3.9	4.3[b]	2.7	11	1
	≥ 20%	5	13.8	13.8	5.7	18	5
1696–2000	All	41	5.8	7.2	6.9	38	1
	≥ 20%	9	25.2	29.3	22.6	73	5
	≥ 25%†	4	56.7	62	46.4	131	34
Araucaria							
1696–1882	All	17	9.1	10.8[a]	9.0	38	2
	≥ 20%	+	+	+	+	+	+
1883–2000	All	17	5.6	5.8[b]	2.9	12	2
	≥ 20%	4	10.7	14.5	14.2	33	2
1696–2000	All	35	7.2	8.4	7.0	38	2
	≥ 20%	7	26.5	36.1	29.1	73	2
	≥ 25%	3	79.9	82.7	48	131	35
Nothofagus							
1909–2000	All	16	4.5	5.1	3.5	12	1
	≥ 20%	5	9.8	10	4.6	17	5
	≥ 25%	3	10.7	11	6	17	5

MSS, minimum sampled scarred; WMPI, Weibull median probability distribution; CFI, composite mean fire interval; SD, standard deviation of the CFI; Max. FI, maximum fire interval; Min. FI, minimum fire interval; +, too few intervals to perform the analyses.

*≥ 2 sampled scarred.

†≥ 3 sampled scarred.

species) and *Araucaria* fire records for the time period 1883–2000 (4.3 and 5.8 years; Table 1). Fire return intervals to the same tree showed similar PFIs (32.6 vs. 36) for all species and *Araucaria* fire records (Table 2).

The fire histories recorded by *Araucaria* and the two *Nothofagus* species differed in both length and frequency. The earliest fire recorded on *Araucaria* was in AD 1446 and by 1696 this species had recorded eight fire scars; in contrast the first fire scars dated on *N. antarctica* and *N. pumilio* were in 1944 and 1827, respectively. More than 98% of the fires recorded by *Nothofagus* species occurred during the 1900s, which is partially explained by the relatively short longevity of *N. antarctica* (Figs 2 & 3b). In addition, however, the lack of older fire dates in the thin-barked *Nothofagus* species can mostly be attributed to their inability to survive fires. In contrast, due to its thick bark, *Araucaria* is able to withstand catastrophic fires. During the 1900s, some low to moderate severity (i.e. mainly spotty surface fires) fire years were exclusively recorded by *Nothofagus* spp. (23%) or *Araucaria* (18%) species. However, most fire years during this period (> 50%) were recorded by both *Nothofagus* spp. and by *Araucaria*. Low- to moderate-severity fires consisting primarily of surface fires were typically only recorded by *Araucaria* if a more severe stand-replacing fire had previously scarred the tree, thus rendering it susceptible to scarring by a less intensive surface fire. Thus, low to moderate intensity surface fires are commonly recorded by *Nothofagus* spp. but are only recorded by *Araucaria* where it was previously scarred by a more intense fire, which usually included a stand-replacing component.

Pre- and post-settlement fire regimes

Fire frequency increased during the 1900s, particularly when considering all fire years (≥ 1 fire-scarred tree) in the composite fire record (Fig. 2). The fire records based on all species as well as the *Araucaria* record showed a trend towards shorter fire intervals after 1883, which is indicated by significant differences in the mean CFI (4.3 vs. 10.8 years, $t = 3.80$, $P = 0.0005$; and 5.8 vs. 10.8 years, $t = 2.17$, $P = 0.0374$; Table 1). That trend was also indicated by more severe fires (≥ 20% trees scarred) in the all species fire record (CFI of 13.8 vs. 55 years). Although the fire-scar evidence persisting in the landscape shows significantly fewer fires prior to 1883, overburning by more recent fires may have destroyed the fire evidence of earlier fires.

Spatial patterns and severity of past fires

The spatial extent of fires in the Quillelhue study area ranged from small fires that presumably burned just a few hectare to those that burned more than 40% of the entire forested watershed (*c.* 1600 ha; Fig. 4). All of the fires recorded in the study area affected almost exclusively the *Araucaria–N. pumilio* and *Araucaria–N. antarctica* forest types. More mesic and relatively pure old-growth *Nothofagus* (dominated mostly by *N. pumilio*) forests located on either southern aspects or areas of higher topographic complexity did not show recent evidence (i.e. last 200 years) of large-scale fire disturbances, although some sites showed evidence of spotty, low-severity fires. Twenty-eight of the forty-six total fire years in the fire record (Fig. 2) were recorded by only one or two trees, most likely representing small fires that burned over limited areas. During the 1900s, fire dates represented by groups of fire-scarred trees were separated by ≥ 3–6 km and there is a lack of evidence of burn continuity between scarred trees (e.g. 1920, 1927, 1942, 1955, 1978, 1982 and 1987; Fig. 4). This pattern may have resulted from either multiple ignitions or several episodes of burning during a single fire season in the landscape. The lack of distinct post-fire *Nothofagus* cohorts during all of these fire years (Fig. 5), and the high fire frequency, suggests that these events were mainly low–moderate-severity surface fires.

A few fire years, such as 1827, 1909 and 1944, were clearly widespread, high-severity fire events. These events were represented by relatively numerous fire-scarred trees widely dispersed across the landscape and coincided with post-fire cohort establishment (Figs 4 & 5). These fires were mainly

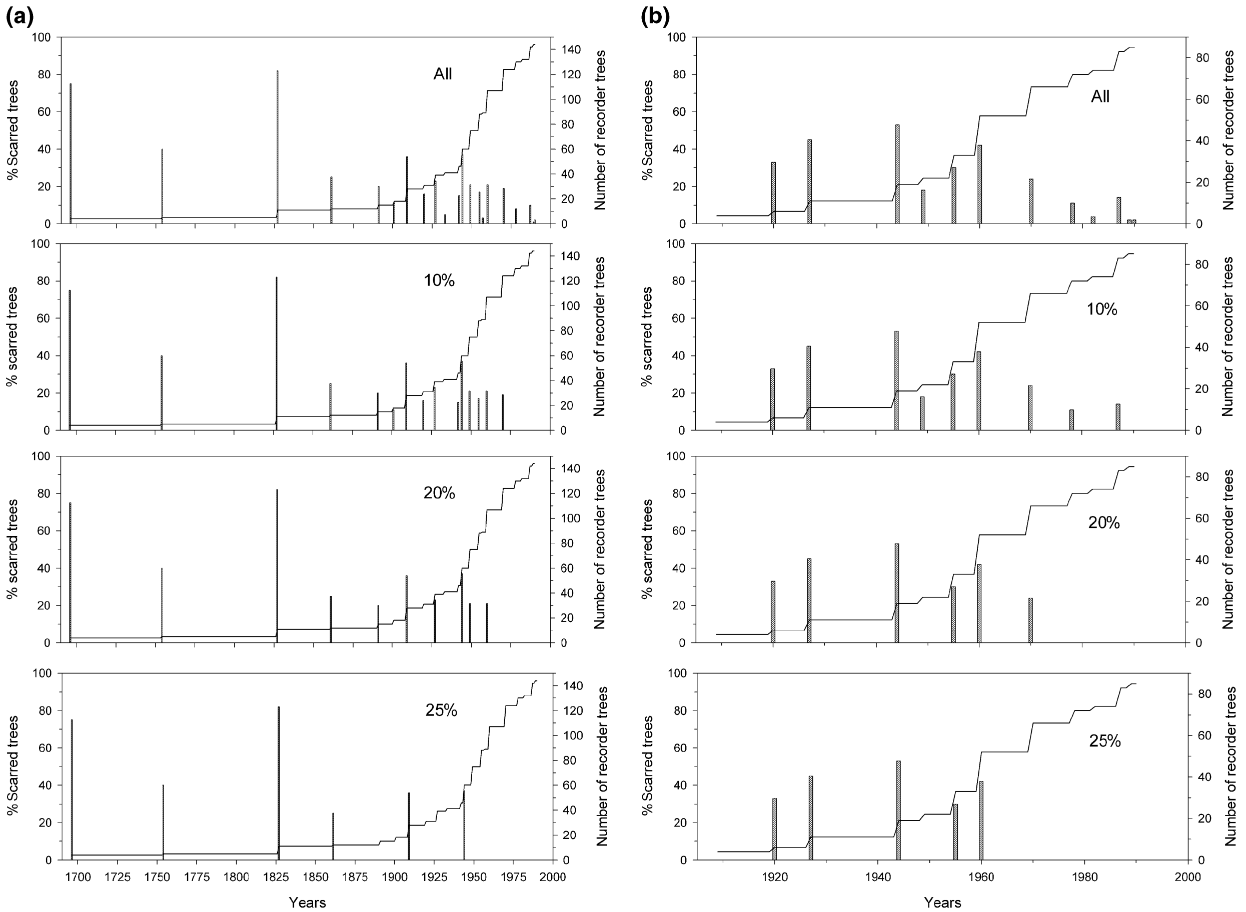

Figure 3 Percentage of fire-scarred trees for the records based on all species combined (a) and on *Nothofagus* alone (b). 'All' refers to years in which ≥ 2 scarred trees recorded fire, and the percentages from 10% to 25% are the percentages of recorder trees recording a fire scar. The sample depth (horizontal line) is the cumulative number of recorder trees over the same time period.

Table 2 Point fire interval statistics for the fire records from all species and for *Araucaria* and *Nothofagus* spp. separately. Fire statistics are shown over the complete period from 1696 to 2000. For the *Nothofagus* spp. fire record, statistics are shown over the period from 1909 to 2000

Fire record and time period	No. of intervals (years)	WMPI (years)	PFI (years)	SD (years)	Max. FI (years)	Min. FI (years)
All species (1696–2000)	65	23.6	32.6	35.6	151	2
Araucaria (1696–2000)	45	25.1	36.0	40	151	2
Nothofagus (1909–2000)	18	18.2	20.2	13.2	43	5

WMPI, Weibull median probability distribution; PFI, mean point fire interval; SD, standard deviation of the PFI; Max. FI, maximum fire interval; Min. FI, minimum fire interval.

high-severity events as suggested by the locations of *Nothofagus* stands of similar age across the landscape. For example, the most recent large stand-destroying event, which occurred in 1944, was followed by a synchronous pulse of *N. pumilio* and *N. antarctica* establishment, representing the clearest and most ubiquitous evidence of the *Nothofagus* response after a stand-replacing fire (Fig. 5). The 1827 fire event was estimated to have burned *c.* 45% of the forested area. Similarly, the fire years 1909 and 1944 were estimated to have burned 36% and 43% of the forested area, respectively, certainly overburning the previous extensive fires (Fig. 4). Albeit less widespread than the former fire events, the fire in 1949 also was a stand-replacing event, burning *c.* 6% of the study area (Fig. 4). This crown fire affected one of the more mesic communities of *Araucaria–N. pumilio* forests dominated by dense thickets of *C. culeou* bamboo. The 1944 fire was also estimated to have burned the large sparsely vegetated patch located in the foothills of Lanin volcano (Fig. 1), formerly dominated by semi-dense *Araucaria–N. pumilio* forests. The relatively well-preserved large fallen dead trees were interpreted to have died in the 1944 fire based on nearby fire-scar dates and sparse post-fire tree establishment primarily located on protected aspects and gentle slopes. The largely failed tree establishment at this site appears to be the result of the combination of the high severity of the event, subsequent burning, few or non-existent seed sources, and perhaps equally as important, the heavy grazing by cattle coincident with the decades of intense burning practised by settlers.

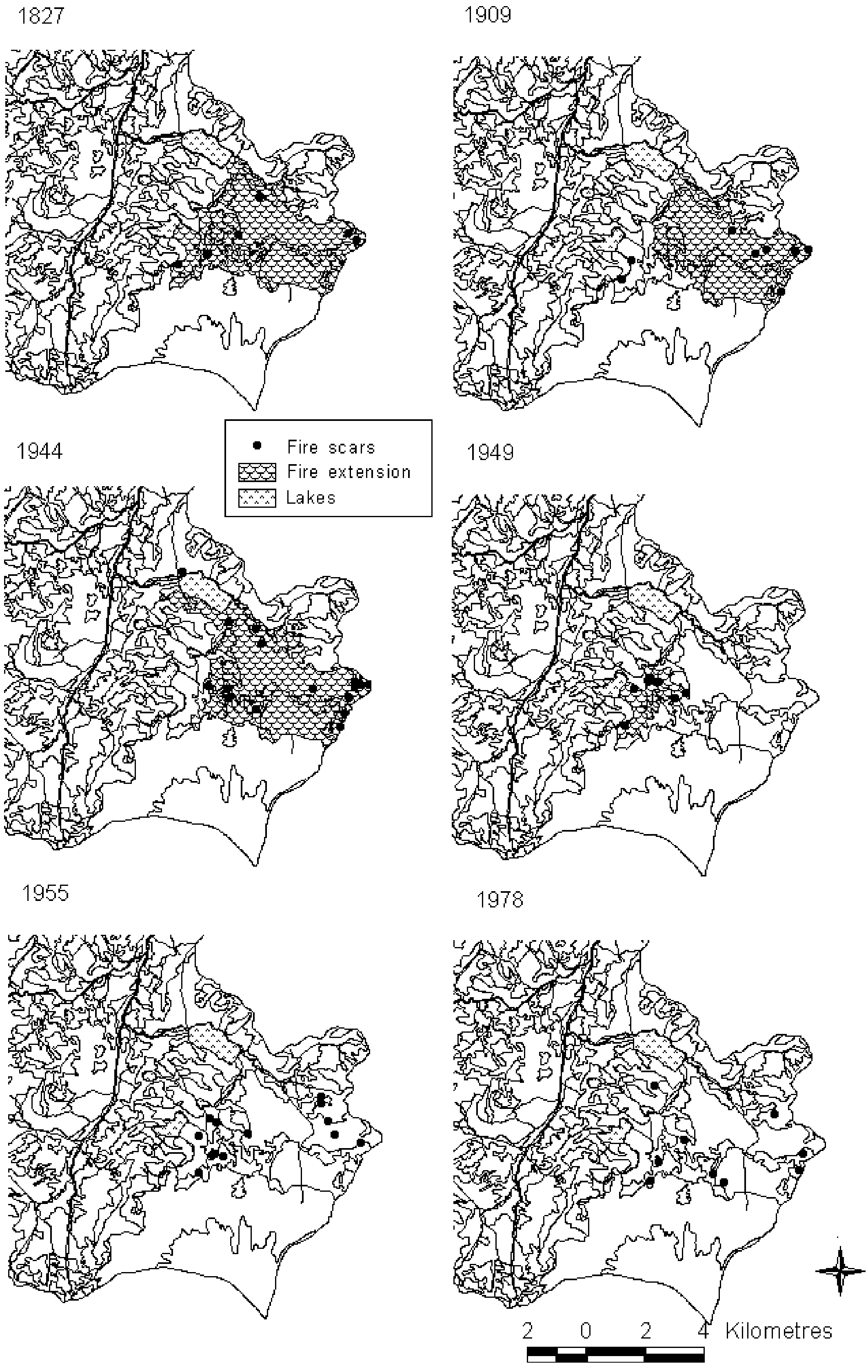

Figure 4 Maps showing the spatial extent of the most extensive fires inferred from stand ages and locations of fire-scarred trees. The reference map used is for the year 2000.

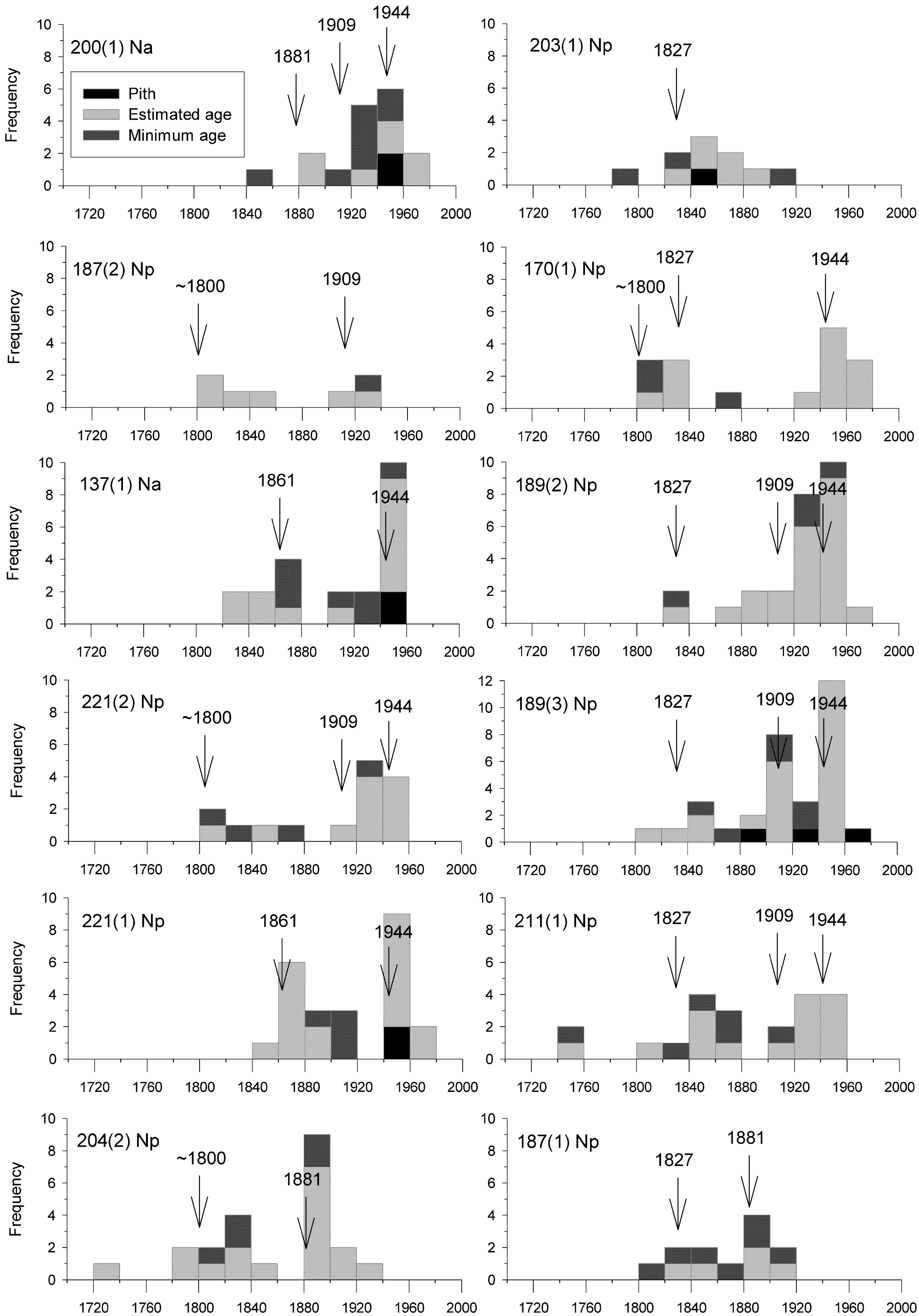

Figure 5 Tree-age frequency diagrams for patches containing post-fire *Nothofagus* spp. cohorts for the fire years 1800, 1827, 1861, 1881, 1909, 1944, 1949, 1960 and 1970. Arrows indicate fire events (∼ indicates inference of fire from age structure). The codes in the upper left of each histogram refer to patch and site numbers, and species (Np, *N. pumilio*; Na, *N. antarctica*).

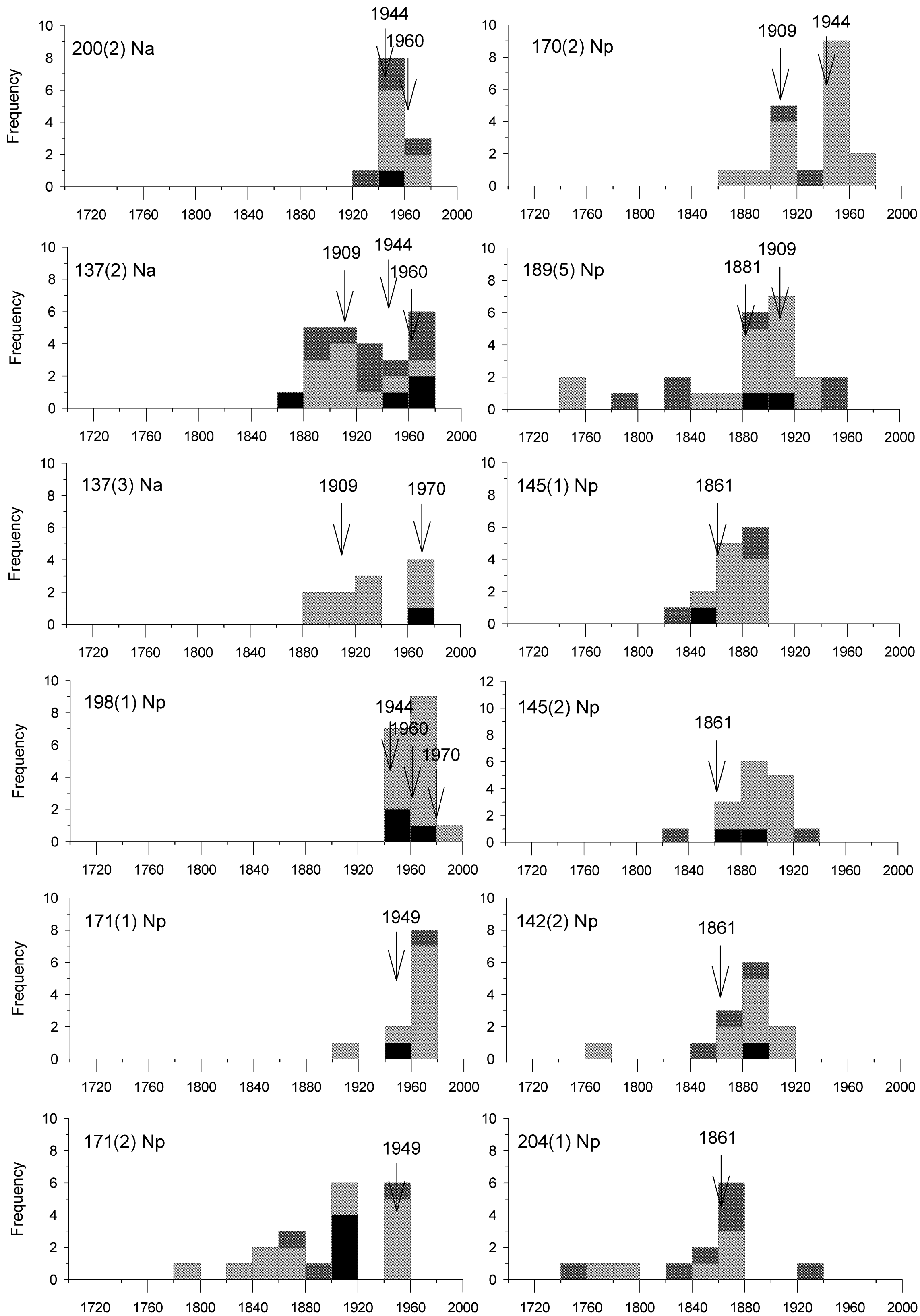

Figure 5 *continued*

More mesic sites, dominated mostly by pure old-growth *Nothofagus* forests with a dense bamboo understorey, located in more complex topography in the western and southern part of the study area, typically lacked fire scars. Topographic complexity, barriers to fire spread (e.g. lakes) and changes in fuel characteristics (i.e. fuel type, loading and condition) probably restricted fire occurrence and spread during years in which other parts of the landscape burned. Typically, these mesic forests constituted the edge of fires that burned extensively over contiguous and more open *Araucaria–Nothofagus* forests.

DISCUSSION AND CONCLUSION

Fires have been a pervasive disturbance in this mountainous landscape of *Araucaria–Nothofagus* forests over at least the past 500 years of tree-ring records of fire obtained in this study. Although both *Araucaria* and *Nothofagus* spp. yielded fire scars that could be reliably dated, their fire records differ in important ways. *Nothofagus* spp. recorded many low–moderate-severity surface fires during the twentieth century which were not always recorded by *Araucaria*. The record of fire by *N. pumilio* and *N. antarctica* is quite short, with the first scar dating from 1827 and 1944, respectively, whereas *Araucaria* recorded scars as early as AD 1446.

These differences in the fire recording properties of the species appear to reflect differences in their longevities and fire resistance. *Araucaria* commonly attains ages over 500 years whereas *N. antarctica* and *N. pumilio* rarely exceeds 200 and 350 years of age, respectively (Veblen *et al.*, 1996). The thick bark of *Araucaria* prevents it from being scarred by low or moderate-severity surface fires, unless it has previously been wounded by an intense fire (i.e. stand-replacing fire), which makes it susceptible to scarring by less intense fires. In contrast, the thin-barked *Nothofagus* spp. record low-severity surface fires not recorded by *Araucaria*. Although *Nothofagus* spp. is easily killed by more intense fires, making scars from these events less common, resprouting of *N. antarctica* and new establishment of *N. pumilio* after stand-replacing fires results in cohorts that can be used for approximately dating fire events, and more importantly for estimating the spatial extent of stand-replacing fires. These differences in the fire-recording properties of *Araucaria* and *Nothofagus* spp. must be taken into account in interpreting historical evidence of fire. In particular, the short fire record from *Nothofagus* spp. will result in an underestimation of the number of older fires.

There is abundant evidence that forest and woodland patterns in this *Araucaria–Nothofagus* landscape were shaped by a mixed-severity fire regime including both surface and stand-replacing fire components. Spatial patterns of fire reconstructed from fire-scar data and post-fire stand ages show that fires affected primarily tall *Araucaria–N. pumilio* forests and woodlands dominated by *Araucaria–N. antarctica*. In contrast, more mesic, old-growth *N. pumilio* forests showed signs of much less frequent fires (e.g. > 200 years as inferred from cohort ages), which appear to have been primarily stand-replacing events, as a result of greater fuel loads and species sensitivity to fire. Crown fires are especially favoured when tall bamboos dominate the understorey, facilitating access of fires to the canopy (Veblen *et al.*, 1992). In contrast, in the *Araucaria–Nothofagus* forests in drier, warmer environments, fire intervals were shorter (i.e. CFI of 7–62 years). Particularly during the twentieth century, surface fires were recorded by *N. pumilio*, *N. antarctica* and *Araucaria*; in the case of the latter species, surface fires were only recorded if the tree had been previously scarred by a more intense fire. Although fires recorded by *Nothofagus* were primarily low-severity events, sometimes burning large tracts of the landscape, some sites were presumably affected more severely. For example, in several fire years (e.g. 1920, 1927, 1955 and 1978), groups of trees fire-scarred in the same year and located at relatively mesic sites were separated by post-fire woodlands of *N. antarctica*. Thus, due to the higher severity and frequency of fires affecting the more xeric *N. antarctica* woodland communities, fire evidence of many twentieth century surface fires was limited.

Crown fires also appear to have moulded the *Araucaria–Nothofagus* forests. A few fires were relatively widespread and severe events as suggested by the abundant and widely dispersed fire-scarred trees and the conspicuous presence of post-fire cohorts. Widespread *Nothofagus*-replacing fires occurred in 1827, 1909 and 1944, each re-burning more than one-third of roughly the same forested area. Furthermore, nearly 90% of the fire dates for the 1827 and 1909 fires, and 55% for the 1944 fire, were obtained from remnant fire-resistant *Araucaria* trees, suggesting that fire intensity was high enough to kill most of the old *Nothofagus*. This result indicates both the ability of *Araucaria* to survive *Nothofagus*-replacing fires and its uniqueness in recording (century-long) past fire events. In contrast, the more fire-sensitive *Nothofagus* species were mostly destroyed in major fires; however, their rapid and vigorous reestablishment allowed for a more precise determination of the spatial extent of fires.

All of the years of extensive and severe burning were associated with severe drought conditions as shown by the instrumental and tree-ring proxy records (González, 2002). For example, extremely dry spring–summer climatic conditions before and during the 1944 fire appeared particularly critical to the widespread and severe characteristics of this fire. Moreover, during this fire year many nearby areas burned, as indicated by oral and written records (Gómez, 1986; Urrutia & Lanza, 1993) and by the extensive presence of even-aged forest patches dating to this year. Similarly, 1827 was a regionally extensive fire year for North Patagonia (from 40 to 42°S; Veblen *et al.*, 1999). Thus, fire appears to be highly dependent on drought during the summer of the same year in which fire occurred (González, 2002). As has already been previously recognized, inter-annual variability of moisture availability related to El Niño Southern Oscillation (ENSO) strongly influences fire regimes in northern Patagonia (Veblen *et al.*, 1999; Kitzberger & Veblen, 2003).

Although years of major fires coincide with drought (González, 2002), humans have probably contributed to fire frequency in this landscape. Native Americans (Pehuenche and Mapuche people) used fire to hunt guanaco and probably to clear undergrowth to facilitate collection of *Araucaria* seeds, one of their staple foods (Montaldo, 1974; Veblen, 1982; Veblen & Lorenz, 1988; Aagesen, 1998). By the seventeenth century, the indigenous population had adopted livestock introduced by the Spaniards (i.e. late 1500s; Nuñez de Pineda y Bascuñan, 1863; Bengoa, 2000), which would also have motivated burning to improve pasture. Moreover, this study area corresponds to an ancient subalpine pass well known by native inhabitants and frequently used for herding animals from north Patagonia to the west side of the Andes (Wilhelm, 1930; Rosales, 1989). Indeed, the name Mamuil-Malal means corral made from wood, implying a place for gathering cattle. Therefore, while Euro-Chilean settlers could have dramatically increased fire occurrence in the twentieth century, Native tribes may have also impacted the natural fire regimes to a certain degree prior to the 1900s. This idea is supported by the unique old-growth *Araucaria* tree that registered 17 pre-1900s fire-scars.

Fire-scar evidence shows an increase in fire frequency following the beginning of permanent Euro-Chilean settlement in the late nineteenth century. During the Euro-Chilean period (1883–2000), fire occurrence was more frequent than in the Native American period (1696–1882; CFI of 4.3 vs. 10.8, respectively). However, the apparent increase in fire occurrence after 1883 may be an artefact of the limitations of estimating past fire occurrence from woody materials that gradually disappear from the landscape. In our study, these limitations include: (1) the short longevity of *Nothofagus* spp., especially *N. antarctica*, results in a bias of recording fewer older fires; and (2) the widespread, severe fires of the twentieth century (e.g. 1909 and 1944) may have destroyed older fire evidence resulting in an underestimation of the fire frequency during the Native American period. Although these are important limitations, the *Araucaria* fire record, which is much less likely to have been truncated by recent, intense fires, also shows a significant decrease in fire intervals after 1883 (Table 1). Thus, in combination with other evidence, we cautiously interpret the tree-ring record as showing a trend towards more fires after 1883, which may be at least partially attributed to the intentional burning of forests by Euro-Chilean settlers in an effort to open the forested landscape for livestock raising. According to oral and written sources (Castro *et al.*, 1974; González, 1986), during the first decades of the 1900s, these areas started to be heavily used for cattle ranching by new settlers. Former settlers in the area mention that the heavy use of the Quillelhue area for livestock raising 'permanently maintained the more xeric woodland communities as short bushes making it possible for someone to see clearly for several kilometres' (L. Esparza, pers. comm.).

The most recent and well-documented stand-destroying fire of 1944 illustrates the long-lasting effect of a fire, allegedly set by humans (L. Esparza, pers. comm.). The 1944 fire was estimated to have burned most of the *Araucaria*-dominated communities, including the sparsely forested foothills of Lanin volcano, which were formerly covered by relatively semi-dense *Araucaria–Nothofagus* forests. Although occurring nearly 60 years ago, the extreme stand-destroying fire of 1944, followed by severe grazing pressure and likely subsequent burning, appears to have prevented the complete forest recovery of an extensive portion of the landscape (*c.* > 400 ha).

In addition to drought and abundant human-set fires during the early 1940s, abundant dry fuels from a massive flowering of bamboo in the region may have contributed to the severity and extent of the 1944 fire. Throughout this Andean region, the bamboo *C. culeou* dominates the understorey of most forest types and appears to be important in determining the sensitivity of forest to fire (Veblen *et al.*, 1992). This bamboo species flowers and dies synchronously over large areas at long intervals of *c.* 60–70 years (González *et al.*, 2002). The massive withering of bamboo over hundreds of thousands of hectares provides an extraordinarily abundant dry understorey fuel for at least 3–5 years after flowering (Veblen *et al.*, 2003). From historical and oral sources, two distinct populations of *C. culeou* are reported to have massively flowered and died in the region in *c.* 1910s and *c.* 1940s (San Martin, 1940; Tortorelli, 1947; González, 1986). Coincidentally, these years are associated with both dry periods and major fires in this region (Tortorelli, 1947; von Buch, 1975; Gómez, 1986; Villalba & Veblen, 1997). It is likely that settlers took advantage of these opportunities of abundant fine and desiccated fuels to open and transform parts of this otherwise wet and mesic forested areas into pasture (Castillo & Dey, 1908; Elizalde, 1958).

Tree-ring evidence clearly shows a long history of fire in these *Araucaria–Nothofagus* forests. Reconstructions of past extent and severity of fires indicates that this landscape has been shaped by a mixture of infrequent stand-replacing fires and more frequent surface fires. It is likely that during the same fire event, intensity varied according to fuel structures in this heterogeneous landscape. Although there is abundant evidence of the impact of Euro-Chilean settlers after *c.* 1883, their relative influence on the temporal pattern of fire could only be tentatively established. Overall, the catastrophic blaze that burned more than half of the Tolhuaca National Park and Malleco National Reserve in 2002, interpreted by most observers as an ecological novelty, must be considered to be within the historical range of variability of fire for these temperate forests.

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