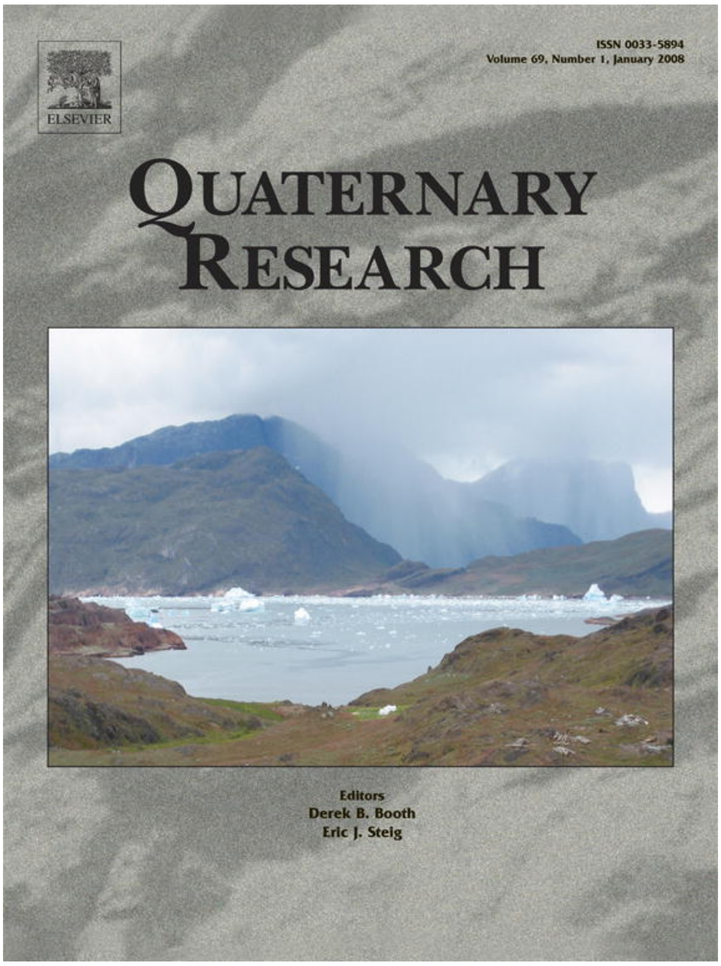
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Changing fire regimes in the temperate rainforest region of southern Chile over the last 16,000 yr

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Abstract

A high-resolution macroscopic charcoal record from Lago Melli (42°46′S, 73°33′W) documents the occurrence of forest fires in the lowlands of Isla Grande de Chiloé, southern Chile, over the last 16,000 yr. Our data suggest that fire activity in this region was largely modulated by the position/intensity of the southern westerlies at multi-millennial time scales. Fire activity was infrequent or absent between 16,000–11,000 and 8500–7000 cal yr BP and was maximal between ~11,000–8500 and 3000–0 cal yr BP. A mosaic of Valdivian/North Patagonian rainforest species started at ~6000 cal yr BP, along with a moderate increase in fire activity which intensified subsequently at 3000 cal yr BP. The modern transition between these forest communities and the occurrence of fires are largely controlled by summer moisture stress and variability, suggesting the onset of high-frequency variability in summer precipitation regimes starting at ~5500 cal yr BP. Because negative anomalies in summer precipitation in this region are teleconnected with modern El Niño events, we propose that the onset of El Niño-like variability at ~5700–6200 cal yr BP led to a reshuffling of rainforest communities in the lowlands of Isla Grande de Chiloé and an increase in fire activity.

Keywords: Fire history; Temperate rainforests; Southern Chile; Southern westerlies; Holocene

Introduction

Human-set fires have been a major and persistent disturbance agent in low-elevation evergreen, temperate rainforest communities of southern Chile since the arrival of European settlers in the 19th century. This artificial regime obscures the causes and consequences of natural fires – if at all present – and their dependence upon vegetation structure, composition, climatic regime, and variability. Historical records and fire statistics from the National Forest Service (CONAF) demonstrate the primary role of humans in driving wildfires in the Chilean Lake District. Moreover, fire scar records from *Fitzroya cupressoides* populations indicate that fires in the coastal range have been extremely rare events during the last 600 yr (Urrutia, 2002). Ecological studies in this region indicate that disturbance regimes constitute an important influence on forest structure and composition. A gradient in these regimes is evident along an E–W transect, with Andean forests being more susceptible to volcanism and earthquake-triggered landslides and mudflows (Veblen and Ashton, 1978). Rainforests in these areas are often dominated by pioneer *Nothofagus* species and shade-intolerant conifers. In contrast, low- and mid-elevation coastal forests are dominated by shade-tolerant tree species, associated with a lower frequency of (natural) catastrophic events (Veblen and Ashton, 1978; Lara, 1991). Regeneration in the latter communities appears to be dominated by small-scale gap dynamics (Veblen et al., 1981; Armesto and Fuentes, 1988; Lusk and Odgen, 1992; Gutiérrez et al., 2004).

Little is known about the occurrence and variability of natural fires in temperate broad-leaved evergreen rainforests at centennial-to-millennial time scales. In this regard, paleoenvironmental studies offer a unique opportunity to explore causal relationships between changes in the biota, climate, and fire regimes. Whitlock et al. (2006) studied the postglacial vegetation, climate, and fire history from fast sediment-accumulating lakes located along the east side of the Andes (41–42.5°S), Argentina. That study, the first of its kind in the region, is based

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on macroscopic charcoal sampled at continuous/contiguous intervals from lake sediment cores. Such detailed record allows the identification of local fire events by deconvoluting a "signal" component from a "background" noise in the charcoal time series. The area studied by Whitlock et al. (2006) is located about 200 km east from the coastal rainforest of Isla Grande de Chiloé. These regions exhibit interesting contrasts in terms of vegetation (the ecotone between the *Nothofagus–Austrocedrus* forests and the Patagonian steppe versus closed-canopy, multistory rainforests), climate (a strong eastward reduction in precipitation of westerly origin caused by the Andean rain shadow and the influence of Atlantic moisture sources east of the Andes), and disturbance regimes (frequent fires versus virtual absence of natural fires and low frequency of catastrophic events). Thus, comparisons between fire histories in these contrasting areas allow assessment of the possible role of vegetation as modulator of natural fires and regional paleoclimate controls on past fire occurrence.

A handful of palynological studies have postulated that the occurrence of past fires in southern Chile was associated with prehistoric human activities (Heusser, 1987, 1990, 1994; Haberle and Bennett, 2004; Huber et al., 2004). Other studies suggest that high climate variability rather than a mean climatic state with low effective moisture is the main driver of fire activity (Markgraf and Anderson, 1994; Moreno et al., 2001). By focusing on individual sites, all those studies fail to detect large-scale patterns in past fire activity that are related to changes in regional climate and vegetation. More recently, however, Whitlock et al. (2007) examined the geographic and temporal patterns in 31 radiocarbon-dated charcoal records in southern South America. These authors detected a multi-millennial pattern at sub-continental scale and proposed that meridional shifts in westerly activity, coupled with obliquity-driven positive anomalies in summer insolation, could account for a prominent phase of intensified fire activity during the early Holocene (11,000–8500 cal yr BP). The multi-millennial trends in fire activity are also found in records from the Lake District of southern Chile, with significant millennial and sub-millennial-scale variations among sites. Most notably, these records provide evidence for the first time of actual vegetation changes directly tied to the occurrence of local fires (Moreno and León, 2003; Moreno, 2004), i.e. stand-replacing fires that led to the abrupt expansion of the trees *Weinmannia trichosperma* and *Tepualia stipularis* at ~13,200 cal yr BP. Similar results have been reported from the Chonos Archipelago (44–47°S), which show the expansion of the same species at ~13,000 cal yr BP (Haberle and Bennett, 2004). Because the reconstructed fire history in these studies relies on microscopic charcoal particles, however, it is difficult to determine whether the stratigraphic record represents a local, extralocal, or regional signal (Patterson et al., 1987; Clark, 1988; Tinner et al., 1998; Tinner and Hu, 2003). This is an important distinction for understanding long-term vegetation and fire dynamics at the watershed or landscape level. Microscopic charcoal particles are generally considered to reflect regional or extralocal fires considering their susceptibility for long distance transport. Owing to their larger size and weight, the airborne dispersion of macroscopic charcoal particles is limited to a smaller area, normally restricted to the immediate watershed of small lakes (Whitlock and Anderson, 2003).

In this study, we report a high-resolution macroscopic charcoal record from a small, closed-basin lake that allows assessment of the following questions: (i) Are fires a natural component of temperate rainforests in Isla Grande de Chiloé (~43°S)? If so, (ii) what is the dependence of fire occurrence on mean climate state? (iii) What is the temporal evolution (frequency, magnitude, time between events, etc.) of fires in these environments since the last ice age? And (iv) is fire an important driver of vegetation change at ecological time scales (<100 yr)?

Study area

The modern climate in Isla Grande de Chiloé is temperate-humid with oceanic influence (Di Castri and Hajek, 1976) with wet winters (June–July–August [JJA] mean: ~320 mm) and relatively dry summers (December–January–February [DJF] mean: ~130 mm) (Castro city, Meteorological Station), resulting from the semi-permanent influence of the westerly winds. Interannual variability in precipitation is closely linked to El Niño events, as shown by Montecinos and Aceituno (2003). These authors detected a tendency toward negative anomalies in summer precipitation associated to El Niño events in the Lake District region of southern Chile. Fuel desiccation is a limiting factor for the occurrence of fires in this rainforest-dominated region, and this condition is exacerbated during El Niño-related summer droughts.

The vegetation of Isla Grande de Chiloé (~42°50′S, 74°W) is characterized by the intermingling of two temperate rainforest communities (Valdivian and North Patagonian), which, at a regional scale, show a clear latitudinal and altitudinal zonation (Páez et al., 1994). The Valdivian rainforest includes the trees *Eucryphia cordifolia*, *Caldcluvia paniculata*, *Gevuina avellana*, *Amomyrtus meli*, *Dasyphyllum diacanthoides*, and *Aextoxicon punctatum*. North Patagonian rainforests share many species with the Valdivian rainforest and features the occasional dominance of conifers such as *Podocarpus nubigena*, *Saxegothaea conspicua*, and *F. cupressoides*. Other important species of this community belong to the Nothofagaceae family (*Nothofagus dombeyi*, *Nothofagus nitida*), accompanied by *Myrceugenia planipes, Amomyrtus luma*, *Myrceugenia ovata* var. *ovata*, *Laurelia philippiana*, *W. trichosperma*, *Drimys winteri*, and *Lomatia ferruginea* (Villagrán, 1985).

E. cordifolia-dominated forests are mainly distributed in the northern portion of the Lake District (39°–41°S), where mean annual precipitation reaches 1331 mm (mean DJF: 57 mm/yr, Osorno city Meteorological Station, 40°36′S , 73°03′ W, 65 m.a.s.l.). Low-elevation North Patagonian forests with *P. nubigena* and *S. conspicua* are abundant in the southern portion of Isla Grande de Chiloé, with mean annual precipitation of 2105 mm (mean DJF: 120 mm/yr, Quellón city Meteorological Station, 43°10′ S, 73°43′W; 12 m.a.s.l). The mean annual temperature varies between 12.5° and 10.6 °C, respectively (Di Castri and Hajek, 1976). The segregation of these rainforest communities at a regional scale reflects these important gradients of temperature and precipitation of westerly origin (Oberdorfer, 1960; Schmithüsen, 1956). In the lowlands of Isla Grande de Chiloé, however, both communities form a fine-scale mosaic which, according to recent studies, became established at ~6500 cal yr BP in response to climate changes and varying disturbance regimes (Abarzúa et al., 2004).

Materials and methods

This study is based on sediment cores retrieved from Lago Melli (42°46′S; 73°33′W, ~70 m above sea level), a small (~9 ha) closed-basin lake located on the east-central portion of Isla Grande de Chiloé (Fig. 1). The lake rests on moraines

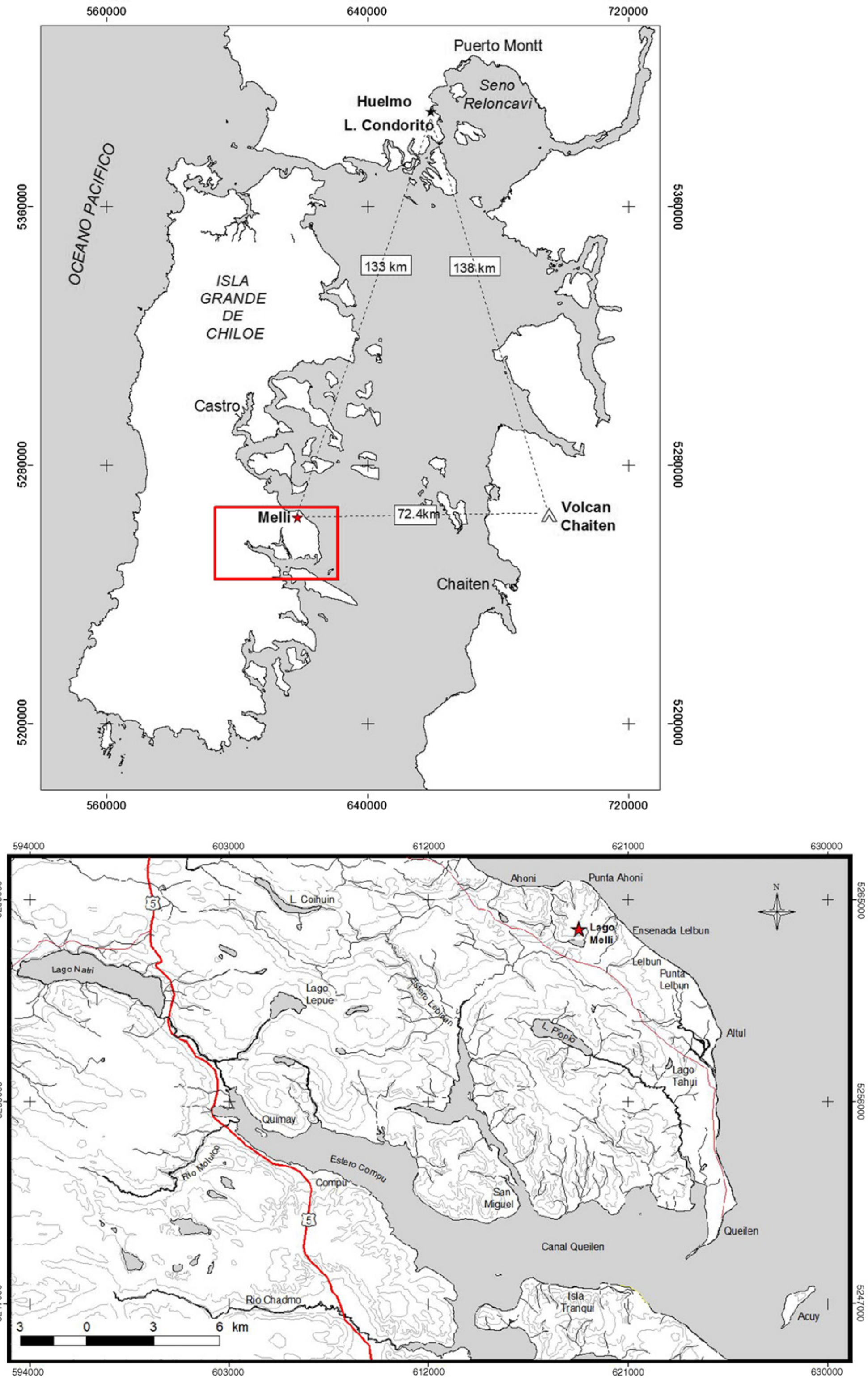

Figure 1. Map of Isla Grande de Chiloé and the Lago Melli area. Shown are the distances between Volcán Chaitén, Lago Melli, and the Huelmo-Lago Condorito area.

deposited during the final advance of the Golfo Corcovado ice lobe over Isla Grande de Chiloé during the Last Glacial Maximum.

We obtained a series of sediment cores from an anchored raft using a Wright piston corer and a sediment–water interface corer. The stratigraphy of the cores was characterized by textural descriptions, X-radiographs, and loss-on-ignition analysis (Bengtsson and Enell, 1986). The chronology of the sediments is constrained by $^{210}Pb_{ex}$ (γ decay method) and AMS radiocarbon dates. The isotope ^{137}Cs was measured for standard age calibration. All radiocarbon ages were calibrated with the Calib Rev 5.0.2 program (Stuiver et al., 2005).

We analyzed the macroscopic charcoal content of sediment samples (2 cc) obtained from contiguous 1-cm-thick intervals to document the local fire history. The sediment samples were disaggregated in a 10% KOH solution, and sieved using 106 and 212 µm mesh diameters. Charcoal particles were individually analyzed and tallied under a stereomicroscope. The raw charcoal counts were converted to charcoal accumulation rates (CHAR), following the method outlined by Long and Whitlock (2002). The charcoal peaks analysis software (CHAPS) permits the detection of "fire events" in CHAR through the separation of a background and a signal component. For that purpose, we interpolated samples at 20-yr intervals and calculated the background component using a moving average window with a width of 1000 yr and a threshold ratio value of 1.1 to identify fire episodes above background.

We conducted pollen and microscopic charcoal analyses on the same sediment core to document the local vegetation changes and for developing comparisons with the macroscopic charcoal record. The samples for pollen analysis (1 cc, from 1-cm-thick samples, with 1–4 cm spacing between samples) were processed following standard procedures (KOH deflocculation, HF digestion, and acetolysis; Faegri and Iversen, 1989). A vegetation index was constructed based on the percentage abundance of the trees *E. cordifolia* + *C. paniculata* + 1 divided by the combined abundance of *P. nubigena* + *S. conspicua* + 1. The resulting values were normalized following conversion to the logarithmic scale (Moreno, 2004). These groups of species represent the characteristic elements of Valdivian and North Patagonian forests along geographical and climatic gradients, respectively. Phyto-sociological (Ramírez and Figueroa, 1985) and ecological (Donoso et al., 1985; Villagrán, 1985) studies confirm the habitat and climatic preferences of these species, validating the index as a quantitative measure for the degree of mixture of these communities and a qualitative descriptor of the climatic conditions where these communities occur.

Results

Stratigraphy and chronology

We selected a 288-cm-long sediment core (0005C) obtained near the center of Lago Melli, at 500 cm water depth. The

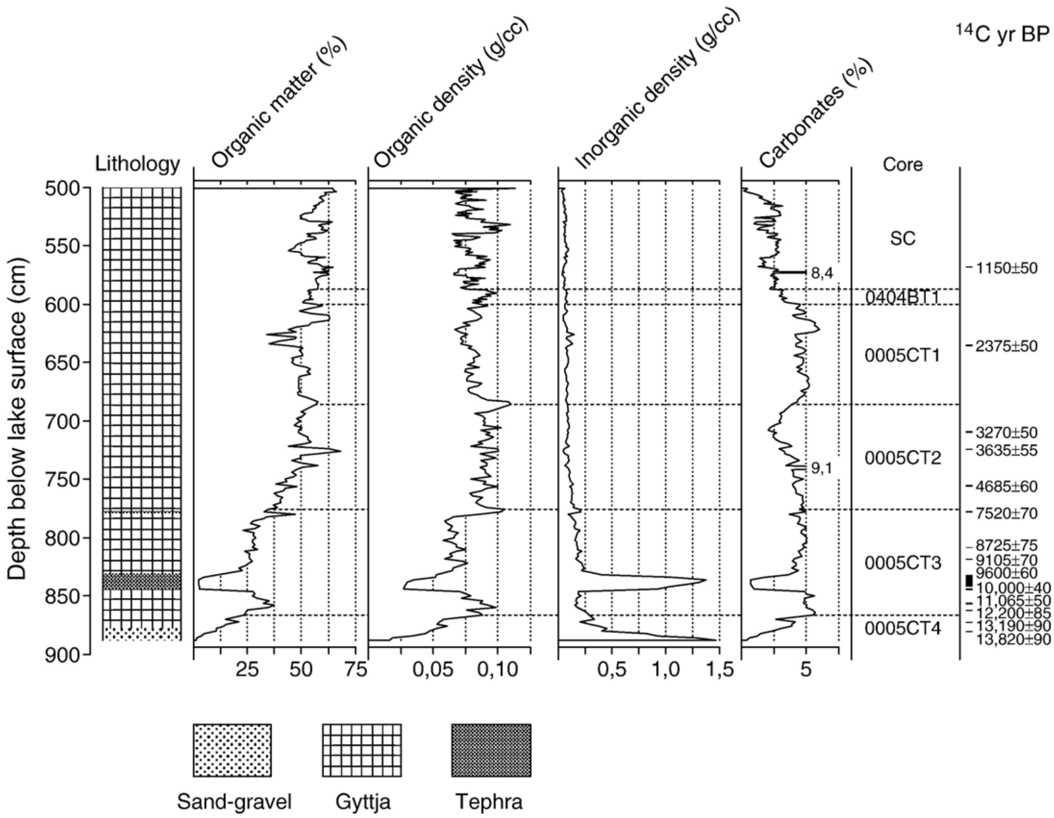

Figure 2. Stratigraphic column of the sediment cores from Lago Melli, showing the radiocarbon dates, and loss-on-ignition parameters. The horizontal dashed lines indicate individual core boundaries.

Table 1
Results of $^{210}Pb_{ex}$ and radiocarbon dates from the Lago Melli sediment cores

Depth range (cm)	$^{210}Pb_{ex}$ (dpm/g)	Material for dating	^{137}Cs (dpm/g)	Age of sediment (yr)
500–502	16.57	Bulk gyttja	0.64	7.1
502–503	17.37	Bulk gyttja	0.75	22.0
503–504	9.42	Bulk gyttja	1.46	34.3
504–505	6.33	Bulk gyttja	0.83	45.8
505–506	5.20	Bulk gyttja	0.54	59.0
506–507	2.82	Bulk gyttja	1.20	74.1
507–508	2.65	Bulk gyttja	0.49	91.0
508–509	2.37	Bulk gyttja	1.60	122.8
509–510	0.30	Bulk gyttja	1.18	195.2
Lab Code	**Depth range (cm)**	**Material dated**	**Age (^{14}C yr BP)± 1σ error**	**Median cal age (cal yr BP)**
ETH-27272	568–569	Terrestrial macrofossil	1150±50	1007
ETH-25894	635–636	Bulk gyttja	2375±50	2336
ETH-25248	709–710	Bulk gyttja	3270±50	3435
ETH-25895	724–725	Bulk gyttja	3635±55	3878
ETH-27273	755–756	Terrestrial macrofossil	4685±60	5379
ETH-25450	778	Bulk gyttja	7520±70	8277
ETH-27274	808–809	Bulk gyttja	8725±75	9651
ETH-25249	818–819	Terrestrial macrofossil	9105±70	10,211
Tephra	832	Bulk gyttja	9600±50	10,900
CAMS-115814	844	Bulk gyttja	10,000±40	11,471
CAMS-115815	856	Bulk gyttja	11,065±50	12,984
ETH-25250	862–863	Bulk gyttja	12,200±85	14,063
ETH-25251	872–873	Bulk gyttja	13,190±90	15,615
ETH-25252	880–881	Bulk gyttja	13,820±90	16,462

The isotope ^{137}Cs was measured for standard age calibration. The calibration of radiocarbon dates was done using the Calib 5 Program, the calibrated value shown is the median probability.

stratigraphy of this core was supplemented with the aid of overlapping core 0404BT1 and a sediment–water interface core to produce a continuous record devoid of hiatuses associated with core breaks (Fig. 2). All records were matched on the basis of their loss-on-ignition curves. The sediments consist of brown organic mud (gyttja), basal sand/gravel, and two tephras at 778 cm (1-cm-thick) and at 832–843 cm (depth below lake surface). The tephra at 832–843 cm is characterized by abundant black lithic fragments and small gray pumice fragments (<1 mm), low volcanic glass content, and charcoal particles. The loss-on-ignition data show low organic matter near the core base (<20%), followed by a steady increase, interrupted by a sharp decrease associated with the tephra layer. The 925 °C burn shows a mean loss of 4.1%, implying absence of carbonates throughout the record (Fig. 2) (Bengtsson and Enell, 1986; Heiri et al., 2001).

The chronology of the sediment core is constrained by thirteen AMS ^{14}C dates, nine ^{210}Pb dates, and chronostratigraphic correlation of the tephra layer found at 832–843 cm (Table 1). This regional tephra has been extensively reported and dated at ~9600±50 ^{14}C yr BP (10,900 cal yr BP) (Abarzúa et al., 2004; Moreno, 2004; Moreno and León, 2003). We developed a linear interpolation age model based on the calibrated radiocarbon dates to assign interpolated ages to the pollen and charcoal levels (Fig. 3).

Fire and vegetation records

The macroscopic (sieved) and microscopic (pollen slide) charcoal records from Lago Melli are shown in Figure 4. The CHAR and concentration data in each case exhibit the same trends, the only appreciable difference is the lower/larger magnitude of CHAR values between 14,000–12,500 and 3000–0 cal yr BP, respectively. Lower/higher sedimentation rates in those sections, respectively, can account for the observed differences (Fig. 3); these differences, however, only affected the "magnitude" parameter in the CHAPS and not the detection of individual events, frequency, time between intervals, etc., because the CHAR data are detrended prior to the time series

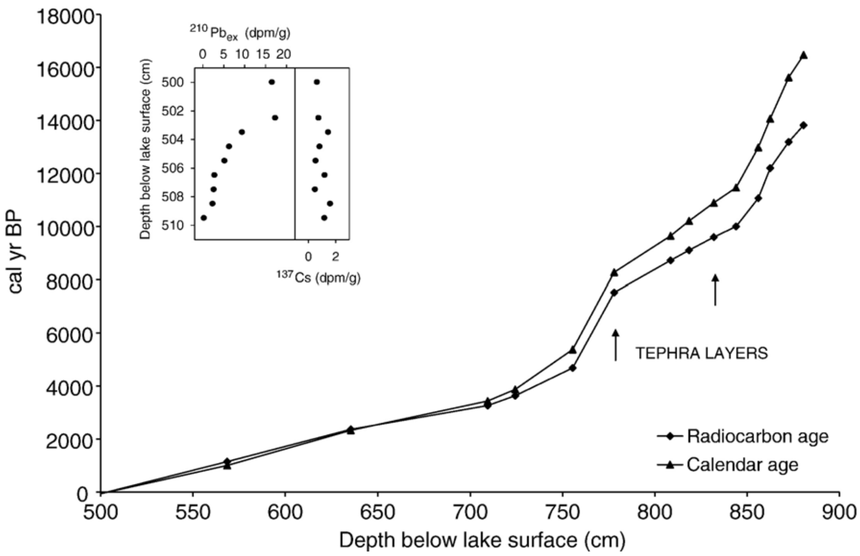

Figure 3. Age models from the Lago Melli record. Two age models (radiocarbon and calendar) were constructed through lineal interpolation between dated levels. We subtracted the tephra thickness from the underlying deposits for the purpose of developing the age models.

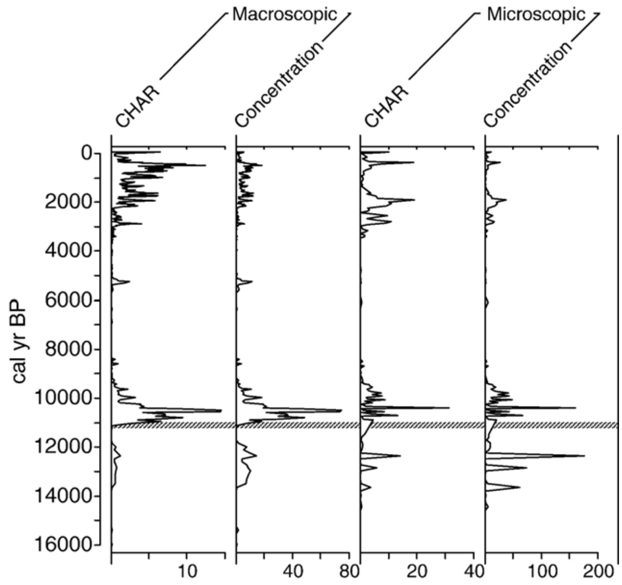

Figure 4. Macroscopic and microscopic charcoal data expressed as concentration and accumulation rate (CHAR). All data are expressed in arithmetic scale. The horizontal screen represents the thick tephra layer.

analysis. Three main differences are evident between the macroscopic and microscopic CHAR: (i) the higher resolution macroscopic record shows higher density of charcoal peaks during the last 3000 yr; (ii) the microscopic record shows large magnitude peaks between 14,000 and 12,500 cal yr BP; and (iii) a ramp-like increase starting at ~11,700 cal yr, underneath the tephra (Figs. 3 and 4). These differences might reflect the contribution of local (macroscopic CHAR) versus extralocal (microscopic CHAR) fires during those episodes.

Figure 5 shows a simplified version of the pollen record along with the macroscopic CHAR. The vegetation index shows a clear multi-millennial pattern of variation with negative values (values below the mean calculated over the last 16,000 yr) indicating the predominance of North Patagonian conifers under cold/humid climate conditions. A sharp increase in the index starts at ~11,000 cal yr BP, leading to extreme positive anomalies characterized by the dominance of Valdivian species under warm/dry conditions until ~8500 cal yr BP. This was followed by a steady decline between ~8500 and 5500 cal yr BP and stabilization (with internal variability) until the present. The latter fluctuations are caused by a decline in thermophilous Valdivian species at ~7400 cal yr BP and a re-expansion of North Patagonian conifers at ~6000 cal yr BP.

Six salient features are evident in the macroscopic charcoal record (Fig. 5): (i) near zero values characterize the intervals ~16,000–13,800 and 8500–3000 cal yr BP; (ii) a moderate, plateau-like rise between 13,700 and 11,800 cal yr BP; (iii) a short-lived, sharp increase in charcoal that peaks at ~ 5500 cal yr BP; (iv) large magnitude values between ~11,000–8500 and 3000–0 cal yr BP; (v) a prominent peak in CHAR between 400 and 800 cal yr BP; and (vi) a conspicuous rise in fire frequency and shorter fire return intervals (the parameter "time between peaks") starting at 5500 cal yr BP.

We selected four pollen taxa (the trees *W. trichosperma* and *T. stipularis*, the shrub *Ugni* sp., and Poaceae [possibly the bamboo *Chusquea* sp.]) to examine potential plant ecological responses to the incidence of past local fires (Fig. 5), based on their modern response to disturbance and their conspicuous stratigraphic variations. A remarkable correlation is evident between variations in *W. trichosperma* and charcoal variations between ~11,700 and 9300 cal yr BP and during the last 800 yr. During the former interval, the expansion of *W. trichosperma* was synchronous with a modest rise in microscopic CHAR but preceded a major increase in macroscopic CHAR, in the latter interval *W. trichosperma* rose abruptly during the culmination (800–400 cal yr BP) of multi-millennial trend in macroscopic CHAR. Also, we observe a gradual increase in *Tepualia* sp.,

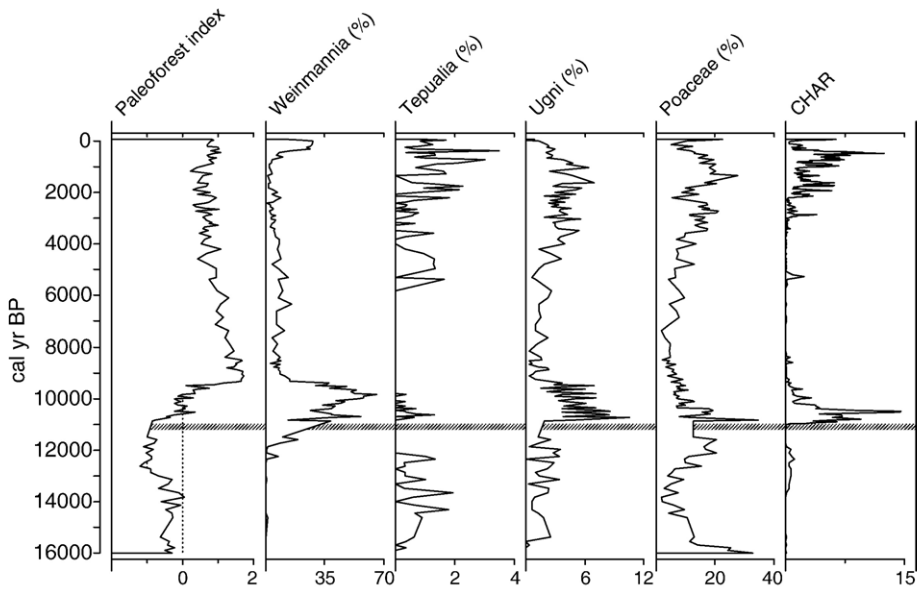

Figure 5. Paleovegetation index and percentage values of selected trees (*Weinmannia trichosperma* and *Tepualia stipularis*), non arboreal taxa (*Ugni* and Poaceae), and charcoal accumulation rates. The horizontal screen represents the thick tephra layer.

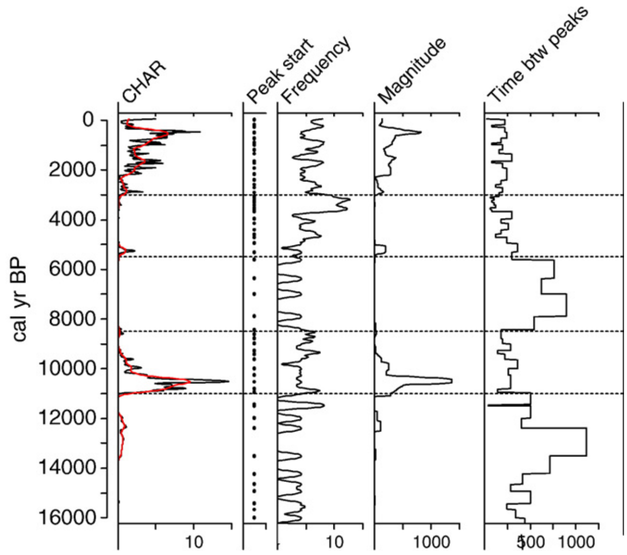

Figure 6. Results of the CHAPS analysis (charcoal accumulation rates = CHAR, peak start, frequency, magnitude, and time between peaks) applied to the Lago Melli record.

Ugni sp., and Poaceae over the last ~4000 yr which is mirrored by a steady increase in charcoal particles (frequency, magnitude).

The CHAPS analysis of the Lago Melli macroscopic charcoal record shows a multi-millennial trend underlying decadal to centennial-scale variability in frequency, magnitude, and fire-free intervals (time between peaks). Minimal frequency and high fire-free intervals occurred between ~16,000–11,000 and 8500–5500 cal yr BP. The opposite pattern is evident between ~11,000 and 8500 cal yr BP, and over the last 3000 yr, accompanied with high-magnitude values peaking at 800–400 cal yr BP. A conspicuous decrease in the fire return interval is evident starting at 5500 cal yr BP, accompanied by an increase in the parameter fire frequency (Fig. 6).

Discussion

Our results indicate the dominance of North Patagonian rainforest communities under cold and humid conditions between 16,000 and 11,000 cal yr BP, reflected as negative anomalies in the vegetation index. This condition was likely brought about by a northward shift and/or intensification of the southern westerly winds in terrestrial records from in southern Chile (Moreno and León, 2003; Abarzúa et al., 2004). Positive anomalies in the vegetation index between 11,000 and 8500 cal yr BP indicate the preponderance of Valdivian rainforest species (*E. cordifolia* and *C. paniculata*) during a prominent warm/relatively dry phase. This pattern is replicated in other pollen records from the central and southern portions of Isla Grande de Chiloé (Villagrán, 1985, 1988, 1990; Abarzúa et al., 2004). Moreno and León (2003) referred to this condition as an "extreme interglacial mode" of westerly activity, characterized by a poleward migration of its northern margin. Today, *E. cordifolia*-dominated forests occur only in well-drained soils in Isla Grande de Chiloé. Ecological studies indicate that excessive soil moisture limits the seed regeneration in this species (Donoso et al., 1985). A rise in precipitation is evident in the Lago Melli record during the last ~7400 yr (Abarzúa et al., 2004), suggesting an increase in westerly activity. The establishment of a mosaic of Valdivian and North Patagonian rainforest communities is a prominent vegetation signal that started at ~6000 cal yr BP and persists until today in the lowlands of Isla Grande de Chiloé (Abarzúa et al., 2004) and the mainland of the southern Lake District (Moreno, 2004).

The Lago Melli data demonstrate that fires are a natural and important disturbance agent in the temperate rainforests of southern Chile. A clear multi-millennial trend is observed in fire occurrence in the Lago Melli record, with maxima centered at ~11,000–8500 and 3000–0 cal yr BP. The fact that this trend covaries with paleoclimate reconstructions of westerly activity for the last 16,000 yr suggests that fire occurrence is largely governed by a climatic envelope.

Our data show that the establishment of an open *W. trichosperma* forest, associated with Poaceae and the shrub *Ugni* sp. (possibly *U. molinae*), was near-synchronous with the onset of intense fire activity at ~11,000 cal yr BP. A close examination of the Lago Melli record indicates that *W. trichosperma* expanded prior to the onset of local fire activity, suggesting that either the vegetation change preceded fire activity, or the expansion of this species occurred in the vicinity of Lago Melli but was triggered by extra local fires. It is possible that during the *W. trichosperma*-dominated interval an important understory of shrubs and grasses developed, supplying fine fuels for the occurrence of surface forest fires. Ecological studies indicate that the regeneration of *W. trichosperma* in tree-fall gaps is uncommon (Veblen, 1985); this species occurs in well drained—with high slope soils in Isla Grande de Chiloé (Donoso et al., 1985). Their longevity (>750 yr), slow growth, very small seeds (<1 mm), and light-demanding attributes suggest that this species requires large gaps for regeneration (Lusk, 1999). The absence of *W. trichosperma*-dominated woodlands in modern lowland temperate rainforests can be related with a lower frequency of large-scale disturbance and the prevalence of gap-phase dynamics (Gutiérrez et al., 2004). A positive feedback between fire disturbance and vegetation type could have permitted the recruitment and persistence of *W. trichosperma* until 9300 cal yr BP.

The occurrence of fires between ~11,000 and 9300 cal yr BP is a widespread persistent pattern in southern Chile and Argentina (Heusser, 1994; Moreno, 2000; Haberle and Bennett, 2004; Whitlock et al., 2007). The increase in dominance of *W. trichosperma* at ~11,700 cal yr BP is also recorded in other pollen records from Isla Grande de Chiloé (Villagrán, 1985, 1990; Abarzúa et al., 2004) and further south in the Chonos Archipelago (47°S) (Bennett et al., 2000; Haberle and Bennett, 2004). The exact timing for the onset of the *W. trichosperma* rise varies geographically, with pollen records from the mainland of the Chilean Lake District (Lago Condorito and Huelmo sites) showing the oldest dates (~12,800 cal yr BP) (Fig. 7). Moreno et al. (2001) pointed out that this rise was near-synchronous with increased fire activity (12,800–11,500 cal yr

BP) and could have resulted from local burning by humans, considering that the Lago Condorito and Huelmo sites are located only ~25 from the Monte Verde archeological site. Although the age span of the Monte Verde 2 cultural horizon (15,000–13,800 cal yr BP) (Pino and Dillehay, 1988) does not overlap with the disturbance interval, it was likely that humans occupations persisted in the vicinity of the Monte Verde, Lago Condorito, and Huelmo sites. The earliest increase in macroscopic charcoal in the Lago Melli record occurs between 13,700 and 11,700 cal yr BP, postdating the age of the Monte Verde occupation (located ~145 km NE from Lago Melli). The onset of the *W. trichosperma* rise in the Lago Condorito and Huelmo sites predates the same expansion in the Lago Melli record by ~1100 yr (Fig. 7).

The Pleistocene–Holocene transition in this part of Chile is also characterized by an increase in volcanic activity (Naranjo and Stern, 2004). A regional tephra layer, dated at 10,900 cal yr BP (9600 ^{14}C yr BP), can be related to an explosive surge from Volcán Chaitén (42.85°S, 72.52°W), located ~100 km SE from Lago Melli (Naranjo and Stern, 2004). The expansion and persistence of the *W. trichosperma*-dominated woodlands, however, predate the deposition of this tephra, indicating a primary climatic/fire disturbance control.

Determining the environmental conditions conducive to fire occurrence is one important aspect when deciphering the fire history. Another key, though elusive, aspect is determining the (paleo) ignition agents. Heusser (1987, 1994) alluded to the primary role of paleoindians as drivers of past forest fires in the temperate zone of southern Chile, whenever volcanic activity could be ruled out. The modern-day climatology and atmospheric stability in the SE Pacific sector precludes the occurrence of convection and lightning storms. Climate at the beginning of the Holocene, however, was substantially different from the modern condition during the “extreme interglacial mode” of the southern westerlies (Moreno and León, 2003) and a stronger-than-present and/or southwardly displaced Pacific anticyclone. Perhaps these conditions favored increased convective activity and fire ignition by lightning in the Lake District and Isla Grande de Chiloé during the first millennia of the Holocene.

Maximum fire activity during the warm and relatively dry interval between ~11,000 and 9300 cal yr BP in Chilean Lake District contrasts with the vegetation, fire, and climatic history described by Whitlock et al. (2006) in two sites located east of the Andes, ~200 km east from Isla Grande Chiloé. One possible explanation for the lack of a prominent fire signal and a conspicuous multi-millennial dry phase in the early Holocene on the eastern slopes of the Andes is the advection of moisture from Atlantic sources, which might have compensated the decline in precipitation of westerly origin well recorded in palynological and lake-level fluctuations in the Chilean Lake District (Moreno and León, 2003; Moreno, 2004; Abarzúa et al., 2004).

The reshuffling and intermingling of the Valdivian and North Patagonian rainforest communities, which today occupy the end extremes of environmental conditions along an elevation and climatic gradient in Isla Grande de Chiloé the Lake District (Villagrán, 1985; Donoso et al., 1985; Páez et al., 1994), in conjunction with the onset of more frequent fires suggests the onset of high-frequency variability in summer moisture stress. This was probably associated with the onset of large magnitude/frequency of summer droughts, which today are teleconnected with El Niño events in this region (Montecinos and Aceituno, 2003; Moreno, 2004). Tree ring and fire scar records in the adjacent Lake District of southern Argentina indicate the occurrence of fires at interannual and decadal time scales, in phase with ENSO variability (Kitzberger, 2002). Geoarcheological and limnogeological studies in tropical South America indicate that the ENSO/ENSO-like variability started at ~ 6000 cal yr BP (Moy et al., 2002; Sandweiss et al., 2001), with significant variability at millennial time scales. One data set suggests that this variability became more pronounced starting at ~3000 cal yr BP (Sandweiss et al., 2001). We note that the Lago

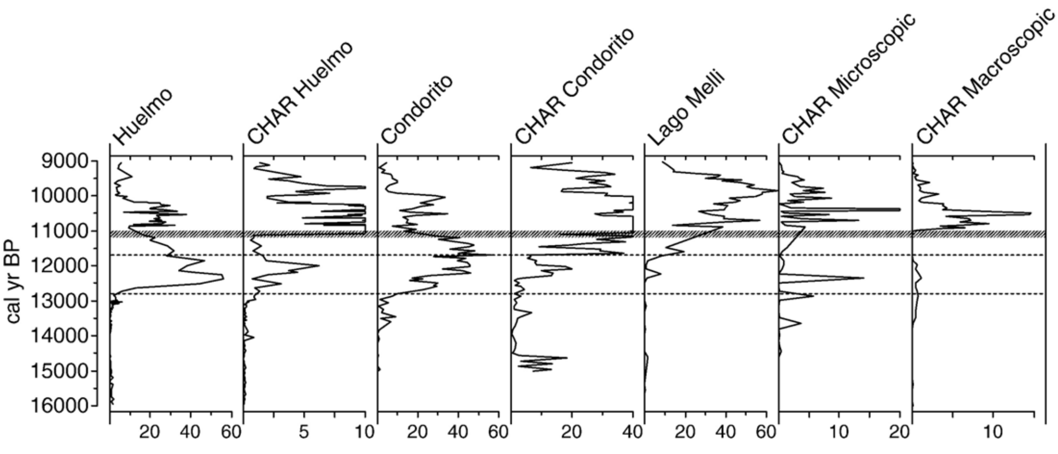

Figure 7. Comparison of the *Weinmannia trichosperma* percentages and charcoal accumulation rates (CHAR) from the Huelmo, Lago Condorito, and Melli sites in the interval between 16,000 and 9000 cal yr BP. The CHAR values from the Huelmo and Lago Condorito sites consist of microscopic particles (pollen slide charcoal); in the case of Lago Melli, we show the microscopic and macroscopic CHAR (truncated to emphasize the temporal relationship with the *Weinmannia* rise). All data are expressed in arithmetic scale. The horizontal screen represents the regional tephra recorded in the three sites. The horizontal dashed lines indicate the timing for the expansion of *W. trichosperma* attributable to local fire disturbance.

Melli charcoal record shows a prominent and persistent increase in fire activity at the same age. Whitlock et al. (2006) showed a shift from stand-replacing events that burned woody vegetation to a regime of more frequent and probably smaller surface fires to surface-fire regimes starting at ~7500 cal yr BP east of the Andes. This was followed by the expansion of *Austrocedrus chilensis* at ~6000 cal yr BP, interpreted as cooler/wetter conditions. We note that the timing of these shifts matches important events in the Lago Melli record and thus suggesting a common cause, most probably cooling and increase in precipitation of westerly origin at ~7500 cal yr BP and subsequent increases in precipitation variability at sub-centennial time scales.

Several archaeological sites younger than ~5500 cal yr BP have been reported along the coast of southern Chile (Gaete et al., 2000; Ocampo and Rivas, 2003; Pino et al., in preparation), coincident with the onset and subsequent intensification of fire activity in the Lago Melli record. Although these findings lend the human ignition hypothesis a plausible explanation, they are not conclusive evidence for a causal relationship for the temporal trends in regional fire occurrence and prehistoric human activities. Additional fire history records are required to allow precise testing of the contributions of vegetation type and vegetation change, mean climate state and variability, and human and/or volcanic ignition agents at a regional scale.

Conclusions

Fires have been natural component of temperate rainforests in the east-central portion of Isla Grande de Chiloé (~43°S) over the last 16,000 yr. Fire occurrence in the past has led to the opening of North Patagonian rainforests and has favored the persistence of shade-intolerant pioneer species, causing greater patchiness in the forested landscape.

Fire activity has varied over the last 16,000 yr, with peak activity between ~11,000 and 8500 cal yr BP and over the last 3000 yr. Intermediate levels are recorded between 13,800 and 11,800 cal yr BP, and fire activity was virtually absent between ~16,000–13,800 and 8500–3000 cal yr BP.

The occurrence of fire in the east-central portion of Isla Grande de Chiloé has largely been modulated by the position and intensity of the westerly winds at multi-millennial time scales, and by their decadal–centennial variability over the last 3000 yr.

Increased fire activity over the last ~5500 cal yr BP may be related to the onset of high variability in summer precipitation regimes. The ignition agents for the occurrence of fire in the past may well be natural or related to human activities.

Fire is an important driver of vegetation change at ecological time scales, this was particularly the case during two rapid vegetation changes that involved the expansion of the shade-intolerant tree *W. trichosperma* at ~ 11,700 and ~ 800 cal yr BP.

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