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Temperate rainforest response to climate change and disturbance agents in northwestern Patagonia (41°S) over the last 2600 years

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ABSTRACT

We present detailed pollen and charcoal records from Lago Pichilafquén (~41°S) to decipher the effects of climate change and varying disturbance regimes on the composition and structure of the vegetation on the Andean foothills of northwestern Patagonia during the last 2600 yr. Here, temperate rainforests have dominated the landscape since 2600 cal yr BP with variations ranging from cool-temperate and wet north Patagonian rainforests to relatively warm and summer-drought-resistant Valdivian rainforests. We interpret relatively warm/dry conditions between 1900–2600, 690–750 and 320–430 cal yr BP, alternating with cold/wet conditions between 1500–1900, 750–1100 and 430–690 cal yr BP. Rapid deforestation and spread of plants introduced by Europeans occurred at 320 and 140 cal yr BP. The record includes five tephras with ages of 2130, 1460, 1310, 1210, and 340 cal yr BP, all of which precede local fire events and increases in trees favored by disturbance by less than 100 yr. We conclude that centennial-scale changes in the southern westerlies were the primary driver of vegetation shifts in northwestern Patagonia over the last 2600 yr. Within this interval, local disturbance regimes altered the structure, composition, and dynamics of the lowland rainforest vegetation during several discrete, short-lived episodes.

Introduction

Historical and paleoclimate records from the Northern Hemisphere reveal an alternation of centennial-scale changes in temperature over the last 2000 yr, the most recent of which are the Medieval Warm Period (MWP; 550–1150 cal yr BP, AD 1400–800) and the Little Ice Age (LIA; 50–370 cal yr BP, AD 1900–1580) (Mann and Jones, 2003; Moberg et al., 2005; Osborn and Briffa, 2006). These climatic anomalies occurred prior to profound land-use changes during historical times and large increases in atmospheric greenhouse gas concentrations associated with the Industrial Revolution since the later part of the 18th century. Studying the timing, structure, magnitude, direction, and geographic variability of climate change during events such as the MWP and the LIA may help understand the causes and consequences of global change under natural boundary conditions not very different from the modern.

Tree-ring-based paleoclimate reconstructions from northwestern Patagonia (38–42°S; 71–74°W) reveal centennial-scale trends somewhat similar to those reported from the Northern Hemisphere. A chronology from Río Alerce (41°10′S, 71°46′W) (Villalba, 1990), located in the Andean region of northwestern Patagonia (Fig. 1), shows cold and relatively moist conditions between ~880–1050 cal yr BP, above-average summer temperatures between ~700–870 cal yr BP (coincident with the final part of the MWP), a long cold/moist period between 280 and 680 cal yr BP (coincident with the LIA), and above-average temperatures during the last 150 yr. According to Villalba et al. (2003), the first half of the 20th century constitutes the warmest interval of the last 400 yr in northwestern Patagonia. A recent synthesis that includes more than 20 annually resolved summer temperature reconstructions from southern South America (>20°S) reveals values above the modern mean (AD 1901–1995) between 600 and 1050 cal yr BP, coincident with the final part of MWP, followed by rapid cooling at 500 cal yr BP and negative temperature anomalies that persisted until 250 cal yr BP (covering the early part of LIA). A subsequent temperature increase led to warm summers between 150 and 250 cal yr BP, followed by cooling between 100 and 125 cal yr BP and sustained warming since then. This synthesis identifies marked centennial-scale variations over the last millennium in SSA, although large uncertainties and low replicability are evident before 458 cal yr BP.

Detailed, radiocarbon-dated palynological studies that span the last 2000 yr in the Chilean Lake District, northwestern Patagonia, include lakes Condorito (41°40′15.33″S; 73°04′54.64″ W; 78 m asl), Tahui (42°49′37.48″S, 73°29′58.58″W, 71 m asl), and Melli (42°46′42.25″S, 73°33′4.69″W, 72 m asl) (Abarzúa et al., 2004; Moreno, 2004; Abarzúa and Moreno, 2008) (Fig. 1). These records feature rainforest dominance punctuated by abrupt increases in *Weinmannia trichosperma*, a shade-intolerant pioneer tree species known to respond to intense disturbance (Moreno, 2004) at different times over the last 2000 yr (1800, 800 and 650 cal yr BP, respectively). A fire-history study based on lake sediments from two sites in the

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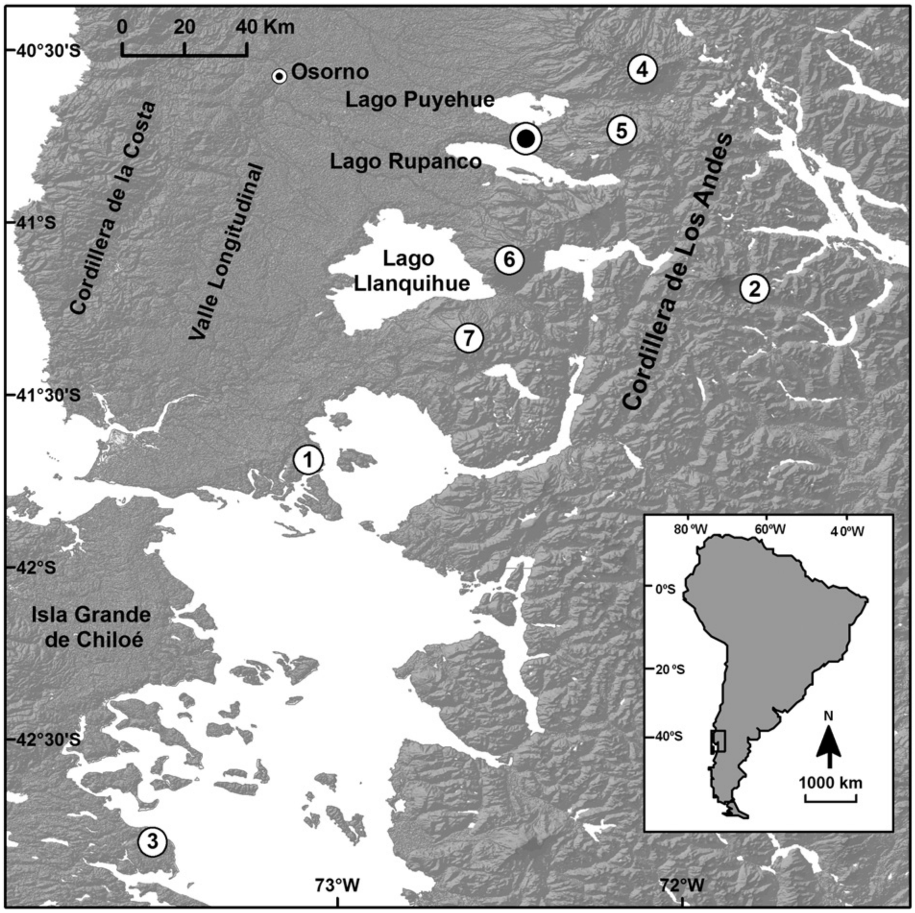

Figure 1. Simplified map of the study area. The Digital Elevation Model shows the location of Lago Pichilafquén (black circle) in conjunction with other sites discussed in the text, the largest lakes, the postglacially active volcanic centers and the main physiographic units present in the region. (1) Lago Condorito (Moreno, 2004); (2) Rio Alerce (Villalba 1990); (3) Laguna Tahui (Abarzúa et al., 2004) and Lago Melli (Abarzúa and Moreno, 2008); (4) Volcán Puyehue-Cordón Caulle; (5) Volcán Antillanca; (6) Volcán Osorno; and (7) Volcán Calbuco. ASTER data obtained from http://gcmd.nasa.gov.

Argentine Lake District (Whitlock et al., 2006), located at the same latitude on the opposite side of the Andes, indicates peak fire activity between 500 and 1500 cal yr BP, followed by a decline associated with the eastward expansion of *Nothofagus* woodlands. Altogether, these studies suggest heterogeneous changes in vegetation, disturbance regimes, and fuel dynamics at small spatial scales, posing a challenge to extract an unambiguous centennial-scale climatic signal at regional scale in northwestern Patagonia.

Volcanic and fire disturbance

Fine-resolution paleoecological records allow assessment of the effects of climatic variability and volcanism on the composition, structure, and dynamics of plant communities. Sedimentary sequences from areas adjacent to active volcanic centers often contain pyroclastic layers deposited during explosive volcanic events, offering the opportunity to examine potential relationships between past volcanic eruptions, vegetation change and paleofire (Wilmshurst and McGlone, 1996). Besides the immediate devastation produced by lava and incandescent pyroclastic flows, more distal effects such as ash fallouts can also produce considerable damage on forest vegetation including defoliation, canopy openings and burial of understory plants (Tsuyuzaki, 1995). Volcanic disturbance tends to generate optimal conditions for the establishment and proliferation of fast-growing shade-intolerant plants, and consequently forest communities subject to relatively high frequency of volcanic disturbances are usually dominated by tree species or herbs having these autoecological features (Veblen et al., 1992). Another type of disturbance associated with volcanism is fire, which can be ignited directly by incandescent material ejected from eruptive centers or by any volcanic particle with the capacity to hold sufficient heat to initiate biomass burning (Swanson and Major, 2005). The generation of large amounts of dead biomass by an eruptive event can alter local fire regimes several years after the actual volcanic event, promoting large stand-replacing fires.

Table 1
Radiocarbon and calibrated ages from Lago Pichilafquén.

Laboratory code	Core	Original length (cm)	Modified length (cm)	^{14}C yr BP $\pm 1\sigma$	Median probability cal yr BP	2σ range cal yr BP
CAMS-137863	0601BT1	38–39	37–38	340 ± 35	390	461–301
CAMS-137864	0601BT2	51–52	50–51	560 ± 35	533	622–500
CAMS-128989	0601AT1	77–78	73–74	1345 ± 30	1232	1192–1152
CAMS-137865	0601BT2	111–112	95–96	2425 ± 30	2406	2676–2333

These volcanic-related disturbances have been documented as agents of short-term vegetation change; however, very few paleoecological studies have investigated the structure and dynamics of vegetation change in areas where volcanic events are a recurrent factor. Most studies of this type have documented rapid increases in grasses, ferns, and charcoal (i.e., fire events) following the deposition of tephra layers (Birks and Lotter, 1994; Wilmshurst and McGlone, 1996; Wilmshurst et al., 1999). Although most of the catastrophic disturbances associated with volcanism have been detected during the first days or weeks after an eruption, fire events and/or sulfur released from deposited tephras might continue to affect the vegetation for more than a century after a major eruption.

At multi-millennial timescales, paleofire activity in the Patagonian region has been linked to insolation-driven changes in the latitudinal position and intensity of the subtropical anticlyclone and the southern westerly winds (SWW) (Whitlock et al., 2007). A spatially homogeneous trend in fire activity during the last 12,000 yr has been linked to multi millennial-scale variations in the position/intensity of the SSW (Whitlock et al., 2007; Abarzúa and Moreno, 2008; Power et al., 2008). Fire activity during the last 3000 yr has been more geographically variable in comparison with the preceding millennia since 12,000 cal yr BP. The latter heterogeneity has been attributed to the establishment and intensification of high frequency and geographically differentiated climate variability modes such El Niño Southern Oscillation (ENSO) or the Southern Annular Mode/Antarctic Oscillation.

In this study we present high-resolution pollen and charcoal records from sediment cores collected in Lago Pichilafquén (40°44′45.70″S, 72°28′55.38″W; 218 m asl), a small lake located in the lowlands of northwestern Patagonia (Fig. 1). These data allow a detailed examination of the timing, direction, and magnitude of changes in the local vegetation and fire activity during the last 2600 yr. Our aim is to decipher the effects of climate change and varying disturbance regimes on the composition and structure of the temperate rainforest vegetation of northwestern Patagonia at centennial timescales.

Study area

Three main physiographic units characterize northwestern Patagonia: (i) Cordillera de la Costa, a north–south oriented and unglaciated coastal range composed of metamorphic rocks of Paleozoic age with mean elevations of 1000 m asl running north–south adjacent to the Pacific coast; (ii) Cordillera de Los Andes, a prominent mountain chain that extends more than 6000 km along western South America, with local elevations ranging between 2000 and 3500 m asl and several small glaciers on the highest summits; and (iii) Valle Longitudinal, a low-elevation (<200 m asl) north–south oriented tectonic depression located between the Coastal and Andean ranges that descends to sea level at its southern end as a consequence of tectonic subsidence. The Valle Longitudinal contains many large lakes of glacial origin that extend westward from the Andean foothills (Fig. 1). Numerous small lakes and bogs have developed on glacial landforms deposited over the course of multiple glaciations during the Quaternary.

The modern climate in northwestern Patagonia features a marked precipitation decline during the austral summer as a result of a poleward displacement in the subtropical anticlyclone and the SWW. Annual precipitation in this region is positively correlated ($r > 0.7$) with SWW strength over a broad portion of the southern mid-latitudes (Garreaud, 2007; Moy et al., 2009), implying that past precipitation variations in this region constitute a good proxy for SWW behavior at hemispheric scale. At interannual timescales, the Chilean sector of northwestern Patagonia (between 38 and 41°S) experiences anomalously dry summers during El Niño years (Montecinos and Aceituno, 2003) and a decline in precipitation associated with positive phases of the Southern Annular Mode (Garreaud et al., 2008; Moy et al., 2009).

The abrupt relief of both mountain ranges contributes to the establishment of strong altitudinal gradients in temperature and precipitation, inducing a marked zonation of broad-leaf evergreen temperate rainforest communities. In the Andean foothills of northwestern Patagonia (<300 m asl) the vegetation is dominated by the Valdivian rainforest, which features the shade-intolerant trees *Eucryphia cordifolia* and *Nothofagus dombeyi* (Villagrán, 1993), and several species of the myrtle family, among others *Myrceugenia planipes*, *Amomyrtus luma* and *Luma apiculata*. Abundant vascular vines such as *Hydrangea serratifolia* and *Mitraria coccinea*, ferns, and epiphytic mosses characterize this community (Heusser, 1984), along with the multi-branched bamboo *Chusquea quila* (Poaceae) which forms dense thickets in disturbed stands and treefall gaps (Veblen et al., 1980). The Valdivian rainforest is superseded by the North Patagonian rainforest above ~400 m asl, in which the most abundant tree is *N. dombeyi* and, to lesser degree, *W. trichosperma*, *Drimys winteri*, *T. stipularis* and several species of the myrtle family (Villagrán, 1993). Above ~600 m asl this forest community features abundant podocarps (*Saxegothaea conspicua*, *Podocarpus nubigena*) and cupressaceous conifers (*Fitzroya cupressoides*) (Villagrán, 1993). Sectors above ~900 m asl are dominated by the deciduous trees *Nothofagus pumilio* and *N. antarctica*, which outcompete *N. dombeyi* under cooler conditions in the subalpine zone, forming the Deciduous Subantarctic Forests in the Andes and establishing the tree line between 1200 and 1300 m asl (Daniels and Veblen, 2003).

Patagonia is an ideal region for studying the recurrence and consequences of volcanic disturbance on the vegetation considering that there are more than 60 volcanic centers along the Andes, many of them with reported postglacial activity (González-Ferrán, 1994; Stern, 2004; Singer et al., 2008) (Fig. 1). Rainforest communities that thrive on the Andean slopes of northwestern Patagonia (37–42°S) are frequently affected by catastrophic disturbance regimes such as landslides, volcanic eruptions and snow avalanches (Veblen and Ashton, 1978). Pioneer and shade-intolerant species of the genus *Nothofagus* have been reported to dominate the vegetation in the Andean slopes at middle and high elevations (>400 m asl) (Villagrán, 1991; Donoso, 1993).

Large-scale vegetation disturbance in the region started with the arrival of Europeans on the mid-19th century (Otero, 2006) and caused a large reduction of the lowland native vegetation, which is now currently confined to national parks and protected wilderness areas in the slopes of the Andes and the Coastal ranges.

Materials and methods

We studied sediment cores from Lago Pichilafquén, a small closed-basin lake adjacent to the Andean foothills of northwestern Patagonia at ~41°S. Lago Pichilafquén lies on an intermorainal depression between Lago Puyehue and Lago Rupanco along the eastern edge of Valle Longitudinal of the Chilean Lake District (Fig. 1). The lake is located close to volcanic centers with reported postglacial activity such as the Puyehue-Cordón Caulle volcanic complex (~36 km from Lago Pichilafquén), Volcán Antillanca (~28 km), V. Osorno (~41 km) and Volcán Calbuco (~67 km). The sediment cores were collected from the deepest part of the lake using an anchored platform equipped with a 10-cm diameter aluminum casing tube. Sediment coring was carried out using a 5-cm-diameter Wright square-rod piston corer (Wright et al., 1984) and a 7.5-cm-diameter water–sediment interface piston corer equipped with a 1-m-long clear plexiglass chamber. The water-sediment interface core was sectioned in 1-cm-thick slices in the field immediately after recovery, and stored in a cold room (4°C) at Universidad de Chile along with the Wright cores.

The stratigraphy of the cores was documented with textural descriptions, radiographs, and Loss-On-Ignition analysis (LOI) (Heiri et al., 2001). We performed LOI on 1-cm-thick contiguous sediment samples of known volume (1 cm^{-3}) through sequential burns at 550°C and

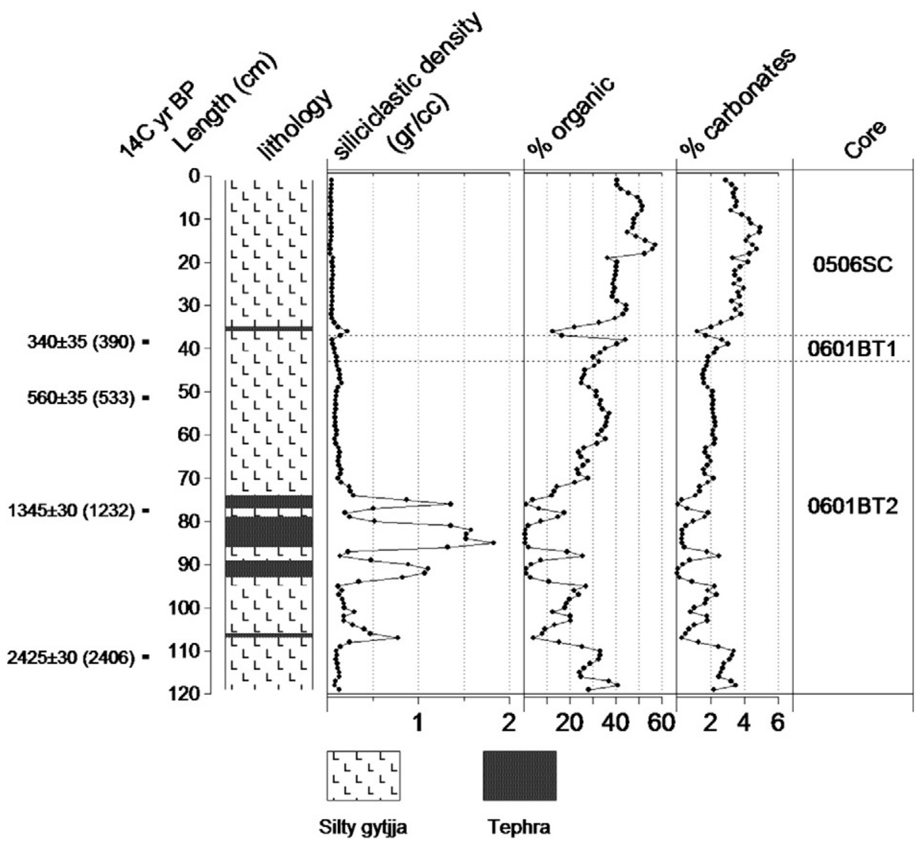

Figure 2. Stratigraphic column of the Lago Pichilafquén record discussed in the text, along with the radiocarbon dates and selected parameters generated by the Loss-on-Ignition Analysis. The numbers in parentheses indicate the median probability calibrated age for each radiocarbon date.

925°C for 2 h and 4 h, respectively. LOI allows quantification of the organic content (LOI_{550}), and a differentiation of the siliciclastic and carbonate components (LOI_{925}) of the inorganic sediments (Fig. 2). The chronology is constrained by 4 AMS radiocarbon dates obtained from 1-cm-thick bulk sediment samples. We calibrated the radiocarbon ages using the CALIB 6.0 program (Stuiver et al., 2005) and then developed an age model based on the median probability of each calibrated date and their corresponding depths after subtracting the thickness of all tephras (Fig. 3). This approach explicitly takes into account the instantaneous deposition of the tephra layers. We built an age model to assign interpolated ages to the palynological and charcoal levels and allow the calculation of accumulation rates of charcoal particles, using a cubic spline with the R software version 2.10.1 (www.R-project.com).

We processed sediment samples (1 cm^3) for palynological analysis obtained from 1-cm-thick contiguous sections throughout the cores. The samples were processed following standard procedures which include deffloculation with 10% KOH, sieving (106 μm), silicate dissolution with 40% HF, and acetolysis (Faegri and Iversen, 1989). The concentrates were mounted in silicon oil and analyzed at 400× and 1000× magnification in a ZEIZZ AXIOSKOP 40 stereomicroscope. Known amounts of exotic *Lycopodium* spores were added to the sediment samples to calculate microscopic charcoal concentrations and accumulation rates. At least 300 grains produced by terrestrial plants were counted in each palynological sample. We developed a Stratigraphically Constrained Incremental Sum of Squares ordination (CONISS) to aid in the definition of pollen assemblage zones by considering all terrestrial taxa with percentages >2%, after recalculating sums and percentages (Fig. 4).

The identification of fossil pollen grains was conducted with the aid of modern reference samples stored at the Paleoecology laboratory at the Universidad de Chile, along with descriptions, photographs, and taxonomic keys (Heusser, 1971; Villagrán, 1980). In most cases the pollen taxonomic resolution reaches to the family and genus level, and in a few instances to the species level (*P. nubigena*, *W. trichosperma*). The palynomorph *N. dombeyi* type is very abundant in the record and includes the species *N. dombeyi*, *N. nitida*, *N. betuloides*,

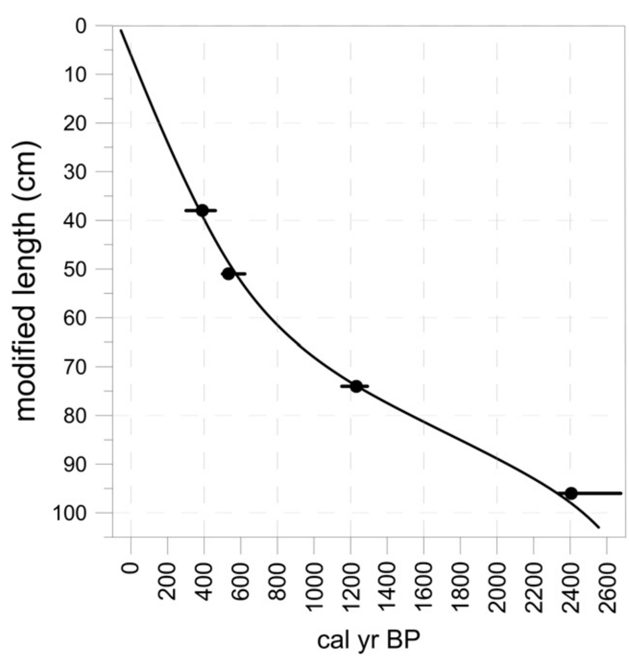

Figure 3. Age model of the Lago Pichilafquén record discussed in the text. Black circles indicate the median probability of the calibrated radiocarbon dates and the solid black horizontal lines indicate age range for the $\pm 2\sigma$ range intercepts.

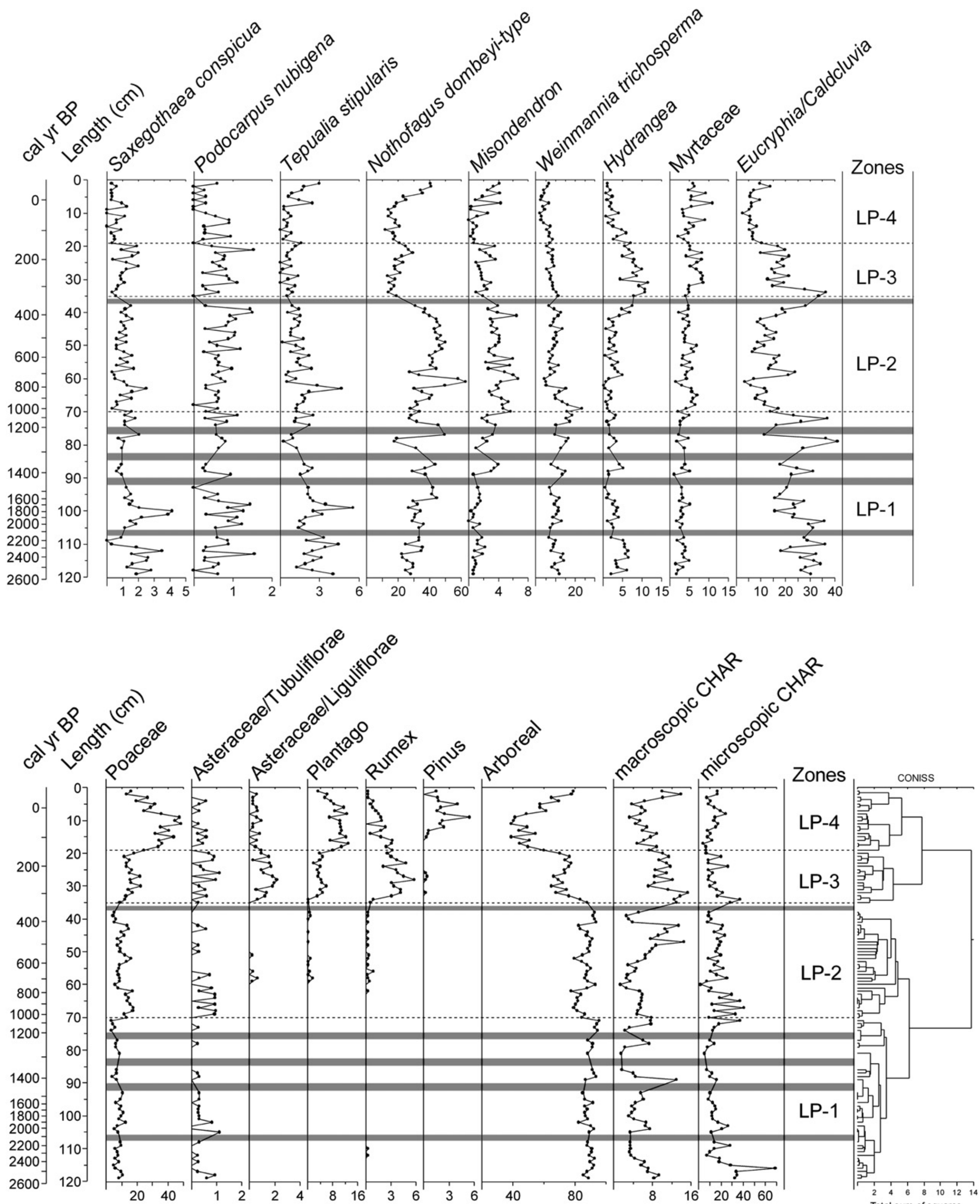

Figure 4. Selected arboreal (upper diagram) and non-arboreal pollen and introduced taxa (lower diagram) from Lago Pichilafquén. Also shown are the macroscopic and microscopic CHAR and results of the CONISS ordination. Dashed horizontal lines indicate the boundaries of the local pollen assemblage zones, the codes on the right identified their respective zones. The gray horizontal bars indicate the position of the tephras detected in this study.

N. pumilio, *N. antarctica*, *N. alessandri*, and *N. leoni*. Less abundant is the palynomorph *Nothofagus obliqua* type, which includes the species *N. obliqua*, *N. alpina*, and *N. glauca*.

We tallied macroscopic (>106 μm) and microscopic (<106 μm) charcoal particles to document local and regional paleofires, respectively. Microscopic particles were counted in each pollen slide; macroscopic charcoal was quantified from 2-cm^3 sediment samples taken from 1-cm-thick contiguous sections. The charcoal counts in each sample were converted to concentration and then to charcoal accumulation rates (CHAR = particles cm^{-2} yr^{-1}) considering the depositional time of each sample (Fig. 4).

We conducted time-series analysis of the macroscopic charcoal and siliciclastic density (obtained from the LOI analysis) records to examine possible associations between local fires and pyroclastic layers using the

CharAnalysis software (Higuera et al., 2010). The rationale behind this approach is that both macroscopic charcoal particles and pyroclastic materials (i) were delivered to the site primarily through aerial fallout (L. Pichilafquén is a closed-basin lake, with no inlets or outlets), (ii) were disseminated to the landscape during short-lived discrete events, and (iii) are susceptible to post-depositional reworking and redistribution in the basin. Utilization of the same procedures for signal detection and event validation for the macroscopic charcoal and siliciclastic density time series provides analytical consistency for examining phasing relationship between statistically significant events.

Results

Stratigraphy and chronology

We spliced cores 0506SC, 0601BT1, and 0601BT2 to develop a 119-cm-long record that spans uninterruptedly the last 2600 yr (Fig. 2), judging from four AMS radiocarbon dates obtained throughout the cores (Table 1). The sediments consist of highly homogeneous silty gittja (mean organic content [LOI_{550}] = 28%) with negligible carbonate content (mean LOI_{925} < 3%). We distinguish 5 tephras in the sedimentary record with ages of 2130, 1460, 1310, 1210, and 340 cal yr BP (Table 2). All tephras were easily detected as horizontal, high-density zones in the X radiographs with sharply defined upper and lower contacts and discrete siliciclastic density peaks in the LOI data (Fig. 2). Tephra thickness ranged from 6 to 63 mm (Table 2). The age model consists of a cubic spline with a weighing of 0.15 and features relatively minor variations in sedimentation accumulation rate (Fig. 3).

Pollen record

We studied the pollen and charcoal content of every centimeter excluding the tephras (total number of palynological samples = 104), with a median time step of 18 yr between samples. The pollen data are expressed in diagrams as percentage units and charcoal data as CHAR (Fig. 4). We divided the pollen stratigraphy in 4 pollen assemblage zones based on the visual recognition of major changes in the record and supplemented with a CONISS ordination. In the following section we describe the pollen zones, indicating their stratigraphic and chronologic range and their leading palynologic components (Fig. 4). Whenever pertinent we express the mean abundance of important palynomorphs in parenthesis.

Zone LP1 (70–119 cm original length; 1030–2550 cal yr BP). *N. dombeyi* type (30%) and *Eucryphia*/*Caldcluvia* (29%) co-dominate this assemblage with nearly identical mean abundances. We note intervals of relatively higher abundance of *Eucryphia*/*Caldcluvia* between 1900–2600 and 1100–1400 cal yr BP. *N. dombeyi* type features a gradual and oscillatory increase in the interim, while *Eucryphia*/*Caldcluvia* and *W. trichosperma* (10%) show high variability with distinct peaks overlying tephras #2, #3 and #4, and to a lesser degree, tephra #5. Other important taxa are Poaceae (8%), *Hydrangea* (4%), and Myrtaceae (3%). Arboreal pollen attains high values (89%) during this zone.

Zone LP2 (36–70 cm original length; 340–1030 cal yr BP). This zone features a rise in *N. dombeyi* type (39%) and a rapid decline of *Eucryphia*/*Caldcluvia* (14%) that coincided with the onset of a tephra-free interval. These changes are accompanied by increases in *Misodendron* (4%) and Myrtaceae (5%). *W. trichosperma* (10%) reaches its highest abundance of the record between 810 and 1000 cal yr BP (maximum = 23%) then declines and remains relatively invariant for the remainder of the zone. Poaceae (11%) shows a step increase between 790 and 1030 cal yr BP and subsequent oscillations until 340 cal yr BP.

Zone LP3 (19–36 cm original length; 140–340 cal yr BP). This zone starts with a major decline in *N. dombeyi* type (20%) and a slight decrease in *Misodendron* (2%). *Eucryphia*/*Caldcluvia* (18%) attains its maximum abundance (~35%) at the beginning of this zone, representing the culmination of a rising trend that started during the previous zone. This peak occurs shortly after the deposition of tephra #1 at 37–35 cm (~340 cal yr BP) and was followed by a steep decline to ~15%. Although some arboreal taxa such as Myrtaceae (7%) and *Hydrangea* (8%) exhibit considerable increments, the arboreal percent declined (72%) as a consequence of prominent increases in Poaceae (16%), *Plantago* (4%) and *Rumex* (4%).

Zone LP4 (1–19 cm original length; AD 2005–140 cal yr BP). This zone features prominent increases of Poaceae (33%), *Plantago* (9%) and *Pinus* type (2%), while *Rumex* shows a steady decline that led to its minimum abundance in the top samples. Arboreal pollen declines to a minimum (~45%) at 30 cal yr BP (AD 1920), resulting from decreases in *W. trichosperma* (8%), *Eucryphia*/*Caldcluvia* (7%) and *Hydrangea* (3%). Interestingly, *N. dombeyi* type shows a rapid rise from 15% to 40% since AD 1870.

Paleofire and tephras

The micro- and macroscopic charcoal records show high accumulation rates between 2400 and 2600 cal yr BP, followed by relatively low values until ~1300 cal yr BP (microscopic CHAR) and ~700 cal yr BP (macroscopic CHAR) (Fig. 4). We note discrete peaks at ~2000 cal yr BP in both fractions directly overlying tephras #5, a prominent increase of macroscopic CHAR above tephra #4, and minor increments in macro and microscopic CHAR within ~100 yr after the deposition of tephras #2 and #3. Microscopic CHAR shows maximum and highly variable values between 800 and 1100 cal yr BP and then experienced a rapid decline that led to values approaching zero by 740 cal yr BP (Fig. 4). Microscopic CHAR then remained relatively stable until the present, with the exception of a conspicuous peak at 320 cal yr BP and a more subtle peak that started at 110 cal yr BP. Meanwhile, macroscopic CHAR exhibits relatively low values between 700 and 1400 cal yr BP, followed by a rapid increment that led to its highest values of the entire record between 140–500 cal yr BP. Macroscopic charcoal then attained low accumulation rates until −30 cal yr BP, followed a prominent increase until the present.

We conducted time series analysis of the macroscopic charcoal data using the CharAnalysis software with an interpolation time window of 18 yr (median time resolution of the macroscopic charcoal series). This analysis revealed fifteen local fire events (positive values of the high-frequency signal that surpass the threshold) with a global signal-to-noise index of 0.33 (Fig. 6) the majority of which (12) occurred between 1100–1700 cal yr BP and during the most recent 500 yr. CharAnalysis applied to the siliciclastic density data identified 6 significant peaks (Fig. 5), five of which correspond to the tephras identified in the X radiographs and shown in the stratigraphic column (Fig. 2), and one minor clastic peak at 48–49 cm (521 cal yr BP) unrelated to volcanic activity.

Table 2
Original length, thickness and age of the tephras found in Lago Pichilafquén.

Tephra #	Original length (cm)	Thickness (mm)	Interpolated age (cal yr BP)
1	35–36	6	340
2	74–77	27	1210
3	79–66	63	1310
4	89–93	36	1460
5	106–107	9	2130

Discussion

Vegetation and climate

The most recent 2600 yr of the Lago Pichilafquén record is dominated by rainforest taxa found today at low and mid-elevations in the Andes of northwestern Patagonia. The range of inferred vegetation variability varies from lowland (<400 m asl) Valdivian rainforest assemblages characterized by abundant *Eucryphia*/*Caldcluvia*, to mid-elevation (400–900 m asl) North Patagonian rainforest assemblages characterized by abundant *N. dombeyi* type. Because the modern altitudinal zonation of these forest communities is driven by gradients in precipitation and temperature, it is possible to infer relative changes in these climatic variables on the basis of their alternating dominance in the pollen record.

We find a gradual and persistent multi-millennial trend toward higher abundance of *N. dombeyi* type between 400 and 2600 cal yr BP, which we interpret as increasing dominance of North Patagonian rainforest communities. Based on its distribution and abundance in the modern climate space and the palynological context in which this increase takes place, we attribute this signal to a multi-millennial trend toward cooler and wetter conditions. This tendency is overprinted by centennial-scale changes in rainforest composition, chiefly, *Eucryphia*/*Caldcluvia*, *W. trichosperma* and Poaceae (most likely bamboo species of the genus *Chusquea*) (Figs. 4, 5). *Eucryphia*/*Caldcluvia* attained high abundance between 1900 and 2600 cal yr BP, indicative of relatively warm/dry conditions, followed by an interval with relatively low abundance of *Eucryphia*/*Caldcluvia* between 1500 and 1900 cal yr BP along with modest increments in *T. stipularis* and the conifers *S. conspicua* and *P. nubigena* (Fig. 4). The latter are cold-resistant conifers of the North Patagonian rainforest community that occur mainly at elevations between 600 and 1000 m asl in the Andes of northwestern Patagonia (Villagrán, 1993), suggesting relatively cool/wet conditions during this interval.

Between 1100 and 1500 cal yr BP *Eucryphia*/*Caldcluvia* experienced large and rapid fluctuations that coincide in timing and direction with changes observed in *W. trichosperma* (but lower in magnitude; Figs. 4, 5), local fires, and are set in motion right after the deposition of tephra layers #2, 3, and #4. The character of this vegetation change (increases in rainforest trees favored by disturbance; González et al., 2002; Moreno, 2004; Donoso, 2006; Newton et al., 2009) and stratigraphic context suggest intense volcanic and fire activity in the Lago Pichilafquén record between 1100 and 1500 cal yr BP. An interval of overall dominance of *N. dombeyi* type occurred between 420 and 1100 cal yr BP accompanied by low abundance of *Eucryphia*/*Caldcluvia* (Figs. 4, 5), which we interpret as indicative of predominance of a north Patagonian rainforest community under relatively cold/wet conditions. Within this period we also distinguish an interval of particularly high abundance of *N. dombeyi* type between 750 and 800 cal yr BP, followed by a short-lived rise in *Eucryphia*/*Caldcluvia* between 690 and 750 cal yr BP and a subsequent expansion of *N. dombeyi* type that lasted until 430 cal yr BP (Figs. 4, 5). We interpret this sequence of events as an accentuation of the cold/wet scenario that led to the coldest/wettest interval of the record between 750 and 800 cal yr BP, a warm/dry reversal between 690 and 750 cal yr BP and a reestablishment of colder/wetter conditions between 420 and 690 cal yr BP.

A rapid increase of *Eucryphia*/*Caldcluvia* started at 420 cal yr BP and persisted until 320 cal yr BP, when abrupt increases in open ground taxa (Poaceae, Asteraceae) and exotic herbs of putative European origin (*Rumex* sp. [possibly *R. acetosella*], *Plantago* sp. [possibly *P. major*] and Asteraceae/Liguliflorae [possibly *Taraxacum officinale*]) truncated and reversed the increasing trend in *Eucryphia*/*Caldcluvia* (Figs. 4, 5). We interpret these results as reflecting a blend of climatic and disturbance-related responses, with the onset of a warm pulse and/or decline in precipitation at 420 cal yr BP that terminates the cold/wet phase that started at 1100 cal yr BP, and intense volcanic and paleofire disturbance that led to an abrupt opening of the rainforest vegetation and favored the expansion of exotic plants during the last 320 yr. The overwhelming and cumulative effect of those

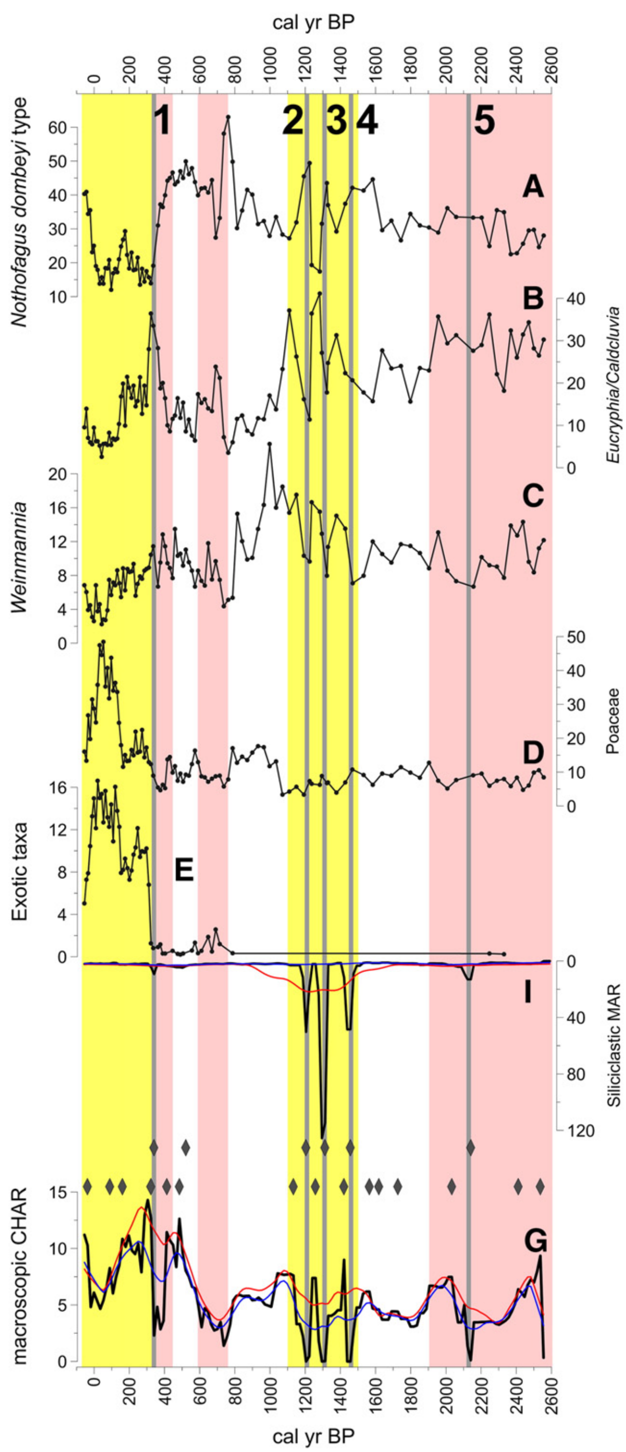

Figure 5. Summary of the Lago Pichilafquén pollen and charcoal record. From top to bottom: (A) percent abundance of *N. dombeyi* type; (B) percent abundance of *Eucryphia*/*Caldcluvia*; (C) percent abundance of *Weinmannia trichosperma*; (D) percent abundance of Poaceae; (E) percent abundance of Exotic taxa (sum of *Plantago*, *Rumex* and *Pinus*); (F) interpolate accumulation rate of siliciclastic mass (regular 18-yr intervals); and (G) interpolated macroscopic CHAR. We also show the calculated background (blue lines), the 95% percentile thresholds for curves F and G (red lines), and the statistically significant peaks detected by CharAnalysis as gray diamonds. The red vertical rectangles indicate the timing and duration of undisputed centennial-scale warm/dry intervals, the yellow rectangles indicate periods with intense vegetation disturbance. The gray vertical lines represent the tephras found in Lago Pichilafquén, and are shownalong with their sequential number as discussed in the main text and shown in Table 2. We emphasize the rapid, instantaneous increases of the trees *Eucryphia*/*Caldcluvia* and *Weinmannia trichosperma* following tephras #2, #3, and #4. A somewhat delayed increase is evident in the case of tephra #5. Notice the association between tephras and local fire events (statistically significant CHAR peaks) within 100 yr after the deposition of each tephra.

disturbance agents on the vegetation impedes recognition of a climatic response of the vegetation since 320 cal yr BP.

Considering that the southern westerly winds (SWW) are the only source of precipitation in the region, the centennial-scale changes in moisture patterns revealed by the pollen record from Lago Pichilafquén suggest variations of the SWW over the last 2600 yr. We interpret these palynological results as indicative of weaker SWW influence between 1900–2600, 690–750 and 320–430 cal yr BP, alternating with stronger influence between 1500–1900, 750–1100 and 430–690 cal yr BP.

Volcanic and fire disturbance

The Lago Pichilafquén record contains five tephras deposited over the last 2600 yr, four of which have ages between 1200 and 2200 cal yr BP and one deposited at 340 cal yr BP (Table 2) (Figs. 2, 4). Considering the lack of inlets into the lake, the gentle rolling mostly horizontal terrain surrounding the site, and the sharpness of the upper and lower contacts of each tephra, we interpret these pyroclastic layers as resulting exclusively from aerial fallout. Having met these criteria, we interpret each layer as resulting from a discrete volcanic event.

We find a tight stratigraphic/chronologic association between all tephras and conspicuous macroscopic CHAR peaks (Figs. 4). This relationship, further substantiated by time-series analyses using CharAnalysis (significant local fire events detected at 2033, 1421, 1259, 1133, and 323 cal yr BP) (Fig. 5), suggests that the deposition of these pyroclastic layers triggered local fires around Lago Pichilafquén. Fire peaks detected by CharAnalysis at 1565, 1619, and 1727 cal yr BP are not in direct stratigraphic/chronologic association with any tephras (Fig. 5), suggesting the occurrence of local fire events triggered by other ignition agents. The lack of tephras between 500 and 1100 cal yr BP (Fig. 5) coincided with relatively low macroscopic CHAR and absence of local fire events detected by CharAnalysis (Figs. 4, 5). CharAnalysis identifies an interval with high frequency of local fires during the last 500 yr, with discrete events occurring at 485, 413, 323, 161, 89, and −37 cal yr BP (Fig. 5).

A comparison of the pollen record with the charcoal and tephrostratigraphy between 1100 and 1500 cal yr BP shows that three short-lived peaks of *Eucryphia*/*Caldcluvia* and *W. trichosperma* (centered at 1380, 1290, and 1150 cal yr BP) overlie tephras #2, #3 and #4, and coincide with statistically significant peaks in macroscopic CHAR (1421, 1259, and 1133 cal yr BP) (Fig. 5). The stratigraphic/chronologic correspondence between vegetation change, pyroclastic layers, and local fire history suggests that these specific ashfall events triggered changes in the local vegetation through their direct disturbance effect and/or through the ignition of the resulting dead, dry biomass within 80 yr after their occurrence.

The species *E. cordifolia* (one of the two species incorporated into the palynomorph *Eucryphia*/*Caldcluvia*) and *W. trichosperma* have been characterized as pioneer and shade-intolerant trees that colonize open landscapes after major disturbance events in the lowlands of northwestern Patagonia; hence the abrupt increases in *Eucryphia*/*Caldcluvia* and *W. trichosperma* following the deposition of tephras between 1100 and 1500 cal yr BP in the Lago Pichilafquén record might reflect the dynamic behavior of mixed *E. cordifolia*–*N. dombeyi* forests to volcanic and fire disturbance at centennial timescales. One implication of these results is that volcanic disturbance not only affects the Andean slopes but also extends their influence into the Longitudinal Valley of northwestern Patagonia. Another implication is that low-elevation forest communities dominated by *E. cordifolia* could represent early or intermediate successional stage after periodic catastrophic disturbances, in a manner analogous to the forest communities dominated by *Nothofagus* at middle and high elevation (>400 m asl) in the Andes (Veblen and Ashton, 1978).

We note high abundance and variability of microscopic CHAR between 800 and 1100 cal yr BP, along with increases in *W. trichosperma* and Poaceae (possibly bamboo species of the genus *Chusquea*), suggesting that extra-local fire activity favored the extra-local spread of pioneer, shade intolerant forest taxa. A climatic cause for these changes is suggested by the fact that they persisted for ~300 yr and occurred more than 100 yr after the deposition of tephra #2. Fire occurrence in this temperate-rainforest dominated region is viable when dry summers permit the desiccation of fuels, a condition made possible by diminished SWW influence through latitudinal (poleward) shifts or by high-frequency climate variability akin to El Niño events (Montecinos and Aceituno, 2003) or negative phases of the Southern Annular Mode/Antarctic Oscillation (Garreaud et al., 2008). The latter seems more plausible considering the predominance of a North Patagonian rainforest community under relatively cold/wet conditions between 750 and 1100 cal yr BP, implying that fire occurrence was driven by high-frequency precipitation changes superposed on a long-term climate trend.

A sudden rise in *Eucryphia*/*Caldcluvia* at ~420 cal yr BP terminated the dominance of *N. dombeyi* type while macroscopic CHAR experienced rapid increments (Figs. 4). The rise of *Eucryphia*/*Caldcluvia* precedes the deposition of tephra #1 by 80 yr (5 cm below the tephra), suggesting a climatic forcing; nevertheless, the peak abundance of this taxon occurred ~20 yr after the occurrence of this volcanic event (2 cm above the tephra layer), suggesting that tephra #1 and the accompanying local fires might also have contributed to its increment.

European disturbance

The pollen record shows a rapid decline of native forest vegetation and the spread herbs and exotic species since 320 cal yr BP (AD 1630). This abrupt deforestation is unprecedented in the context of the last 2600 yr (Figs. 4, 5) and was followed by an accentuation at 140 cal yr BP (AD 1810). Poaceae and *Plantago* reached peak abundance between 50 and 80 cal yr BP (AD 1900–1870), contemporaneous with the appearance of *Pinus* at ~60 cal yr BP (AD 1890) (Fig. 4). All taxa that increase after 320 cal yr BP comprise at least one widely distributed invasive genus or species (the Poaceae genus *Triticum*, *Plantago major*, *Rumex acetosella*, *Pinus radiata* and the Asteraceae/Liguliflorae species *Taraxacum officinale*), suggesting a major floristic and physiognomic conversion from native forests to grasslands dominated by exotic species.

Deforestation and exotic plant invasion in the Lago Pichilafquén record was associated with abundant macroscopic CHAR between 140 and 340 cal yr BP, a rise in microscopic CHAR during the last 110 yr (Fig. 4), and local fire events detected by CharAnalysis at 323, 161, 89 and −37 cal yr BP (Fig. 5). These changes started shortly after the foundation of the cities of Valdivia and Osorno in the years AD 1552 and 1558, respectively (398 and 392 cal yr BP) (Villalobos, 1980), located 120 and 60 km from Lago Pichilafquén, respectively (Fig. 1). Local and regional fires contributed to the decimation of the native forest vegetation and promoted the colonization of burned areas by exotic taxa that are favored by intense and frequent disturbance.

Paleoclimatic implications

Few records from northwestern Patagonia have sufficient time-resolution to examine sub-millennial-scale vegetation, paleofire, and climate changes over the last 3000 yr; among them is the Lago Condorito site, which shows a warm/dry interval between 1800 and 2900 cal yr BP that matches the period of relatively warm/dry conditions recorded in Lago Pichilafquén, dated locally between 1900 and 2600 cal yr BP (Moreno, 2004). The regional character of this climatic signal is suggested by the fact that both sites are separated by ~110 km, supporting the idea of a southward shift of weakening in the SWW during this period. The Lago Pichilafquén pollen data suggests slight cooling and/or increase in precipitation between

1500 and 1900 cal yr BP, not recorded in other paleoclimatic records in the region, followed by discrete peaks in *Eucryphia*/*Caldcluvia* and local fires between 1100 and 1500 cal yr BP attributable to vegetation disturbance induced by local fires and volcanic ashfalls. Centennial-scale changes in vegetation and fire regimes in Lago Melli over the last 1000 yr occurred in the absence of pyroclastic layers, suggesting that besides volcanic perturbations and European disturbance, other agents (climatic or Mapuche activities) have also played an important role shaping the lowland vegetation in northwestern Patagonia.

The pollen record from Lago Pichilafquén shows oscillations superimposed on a multi-centennial scale cooling/increasing precipitation trend between 430 and 1100 cal yr BP. Within this interval we interpret peak cooling between ~750 and 800 cal yr BP, followed by a short-lived warm oscillation between ~690 and 750 cal yr BP and reestablishment of cool/wet conditions between 430 and 690 cal yr BP. This pattern of change is in partial agreement with a tree-ring reconstruction from Río Alerce in the Andes of northwestern Patagonia (~41°S), which indicates cold/wet intervals between 1050–880 and 680–290 cal yr BP (Villalba, 1990; Neukom et al., 2011). Additional detailed stratigraphies and chronologies are necessary to characterize and constrain the chronology of centennial-scale climatic fluctuations in northwestern Patagonia over the most recent millennia.

Conclusions

The record from Lago Pichilafquén indicates the dominance of temperate rainforests on the Andean foothills of northwestern Patagonia during the last 2600 yr. The paleoenviromental reconstruction based on the pollen and charcoal record suggests: (1) relatively warm/dry conditions with high fire activity between 1900 and 2600 cal yr BP; (2) a trend toward slight cooling and/or rise in precipitation with low fire activity between 1500 and 1900 cal yr BP; (3) a period with high frequency of volcanic eruptions and local fires between 1100 and 1500 cal yr BP; (4) overall cold/wet conditions and low fire activity between 430 and 1100 cal yr BP; (5) a warming and drying pulse and relatively low fire activity from 340 and 430 cal yr BP; and (6) a period of intense volcanic, fire and anthropogenic disturbance starting at 340 cal yr BP. We interpret most of these changes as a response to variations in the position and/or strength of the southern westerly winds, with a southward shift and/or weakening between 1900–2600, 690–750 and 320–430 cal yr BP, and a northward shift and/or intensification between 750–1100 and 430–690 cal yr BP. The 2600-yr paleoclimatic reconstruction from Lago Pichilafquén is in partial agreement with the tree-ring paleoclimate reconstruction from Río Alerce in northwestern Patagonia (Villalba, 1990); however, additional high-resolution paleoecological records are needed to determine the regional and hemispheric significance of these centennial-scale fluctuations.

We found 5 tephras dated at 340 1210, 1310, 1460, and 2130 cal yr BP. The ashes dated between 1210 and 2130 cal yr BP are associated with local fires near Lago Pichilafquén and major increases in the palynomorph *Eucryphia*/*Caldcluvia* (most likely the species *E. cordifolia*) and *W. trichosperma*. These findings suggest that volcanic and fire disturbances were key drivers of the structure, composition, and maintenance of the lowland vegetation at centennial timescales repeated at times during the last 2600 yr in northwestern Patagonia.

A rapid and unprecedented expansion of herbs, exotic species and prominent increments in local fires near Lago Pichilafquén during the last 320 yr coincide with European settlement in northwestern Patagonia. Large-scale disturbance started in Lago Pichilafquén ~70 yr after the Spanish arrival to the Chilean Lake District. The overwhelming and cumulative effect of those pulses of large-scale disturbance on the vegetation impedes recognition of a climatic response of the vegetation during this period.

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