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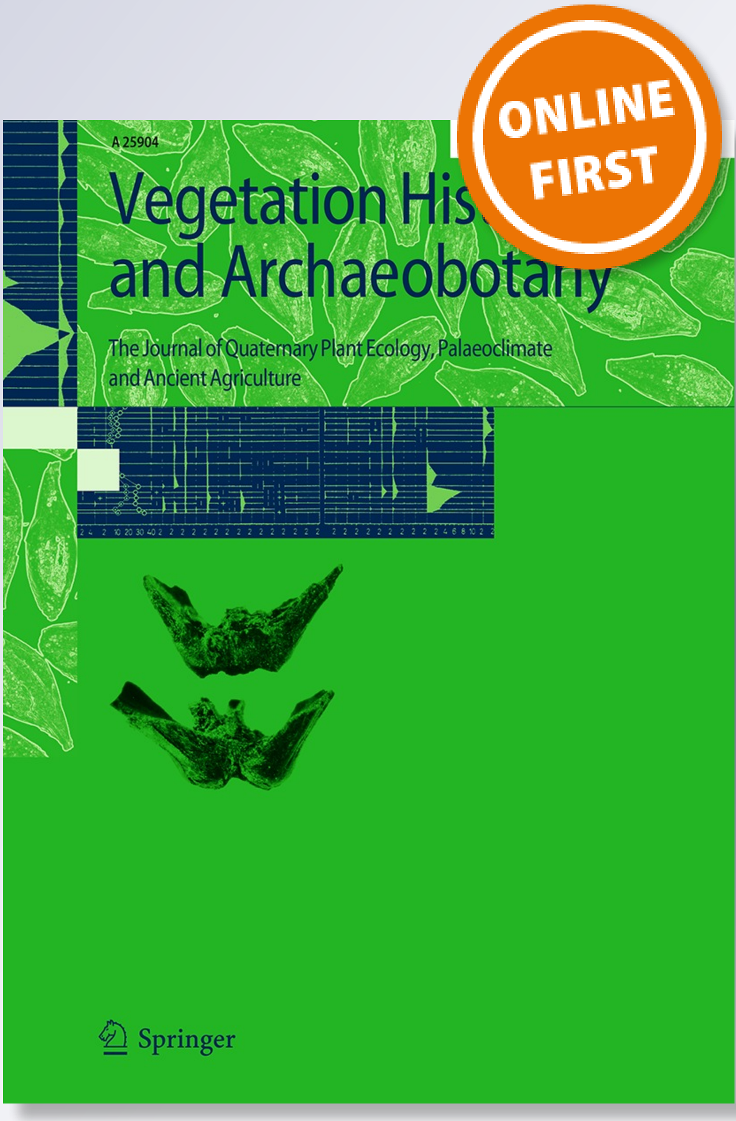

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ORIGINAL ARTICLE

Late Pleistocene and Holocene palaeoenvironmental changes in central Tierra del Fuego (~54°S) inferred from pollen analysis

Lorena Laura Musotto[1] · Ana María Borromei[1] · Andrea Coronato[2] · Brian Menounos[3] · Gerald Osborn[4] · Robert Marr[4]

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Abstract A pollen record was obtained from a coring site at La Correntina mire (54°33′S, 66°59′W, 206 m a.s.l.) to the east of Lago Fagnano, centre of Tierra del Fuego. The results indicate that the valley bottom was free of ice shortly before 15,400 cal BP. Pioneer vegetation included dwarf shrub heaths, grasses and herbs with sparsely distributed *Nothofagus* trees, indicative of dry conditions. *Nothofagus* expanded by 10,000 cal BP and the forest-steppe ecotone was established by 9,400 cal BP, implying warm conditions and an increase in available moisture. After ca. 5,000 cal BP, the development of a closed-canopy forest is interpreted as the result of wetter and colder conditions. After 3,000 cal BP, *Nothofagus* forest became more open, and by about 400 cal BP there was a further decline of the forest. A closed-canopy *Nothofagus* forest re-established after 400 cal BP.

Keywords Pollen · Late Pleistocene-Holocene · Lago Fagnano · La Correntina mire · Tephrochronology · Forest-steppe ecotone

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✉ Lorena Laura Musotto
loremusotto@criba.edu.ar

Ana María Borromei
borromei@criba.edu.ar

[1] Departamento de Geología, Universidad Nacional del Sur, INGEOSUR-CONICET, San Juan 670, B8000ICN, Bahía Blanca, Argentina

[2] Laboratorio de Geomorfología y Cuaternario, CADIC-CONICET, B. Houssay 200, ICPA-UNTDF Onas 450, 9410 Ushuaia, Argentina

[3] Natural Resources and Environmental Studies Institute and Geography Program, University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9, Canada

[4] Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4, Canada

Introduction

Tierra del Fuego (53°–55°S) is the main island of the vast archipelago in which South America ends. It belongs to the southernmost land in the Southern Hemisphere outside Antarctica. Furthermore, the island is currently situated in the path of the Southern Westerlies winds (SWW), which are the main source of precipitation in the region. Due to the orographic effects of the Andean Cordillera, a distinct vegetation pattern corresponds to the different moisture conditions over the island. As a result, the changes in the composition and distribution of the plant communities can be used for inferring past changes in precipitation regimes based on fossil pollen records.

Several palaeoecological studies have been performed in the region since the first studies of Markgraf (1980) and Heusser and Rabassa (1987), following the pioneering work of von Post (1929) and Auer (1933, 1958). Most of them offer information about the environments along the Canal Beagle (Heusser 1998, 2003; Markgraf and Huber 2010) and on the inner Fuegian Andean valleys (Markgraf 1993; Mauquoy et al. 2004; Borromei et al. 2007, 2010). In contrast, fewer palynological studies consider northern and central parts of Tierra del Fuego (Markgraf 1980; Heusser 1993, 2003; Heusser and Rabassa 1995; Burry et al. 2007; Musotto 2013;

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Waldmann et al. 2014). Collectively, these studies show the development of an impoverished steppe-tundra vegetation with scattered trees after deglaciation, followed by a forest-steppe ecotone and a closed-canopy forest as a consequence of increased effective moisture of westerly origin (Heusser 2003; Markgraf and Huber 2010; Kilian and Lamy 2012). According to the pollen data, the *Nothofagus* expansion started on the Pacific slope of the Fuegian Andes axis and reached the Atlantic slope later, following the southwest to northeast direction of the rainfall gradient. These vegetation changes have been related to variations in the latitudinal position and/or strength of the SWW, Antarctic sea-ice extension, position of the Antarctic Polar Front, solar irradiation, or a combination of these factors (Heusser 2003; Markgraf and Huber 2010; Waldmann et al. 2010).

Here we analyse vegetational changes which occurred to the east of Lago Fagnano, at La Correntina mire (54°33′S, 66°59′W, 206 m a.s.l., Fig. 1a), situated in the deciduous forest environment on the Atlantic side of Fuegian Andes. The pollen record from this site provides new insights into the late Pleistocene and Holocene vegetation and environmental changes in central Tierra del Fuego where the palaeoenvironmental information is still scarce. We consider that this mire would be sensitive to environmental changes as its location at the bottom of a valley oriented in the direction of the prevailing SWW may promote diurnal to seasonal temperature changes. The comparison with other pollen records from Tierra del Fuego allows us to infer the hypothetical location of the limits between steppe and ecotone (SEL) and ecotone and forest (EFL) after the last deglaciation in order to get a better understanding of the vegetation changes on both sides of the Fuegian Andes. Our findings are complemented by existing published geological and palaeoecological data to examine the main climate variations since Late-glacial times.

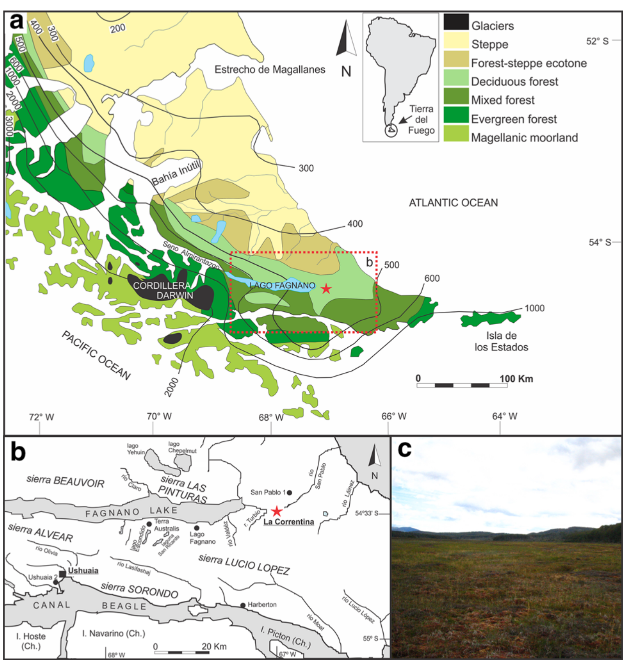


Fig. 1 **a** vegetation map of Isla Grande de Tierra del Fuego with the mean annual precipitation isohyets. The *star* indicates the location of La Correntina mire. The highlighted area in the *rectangle* is shown enlarged in b; **b** map showing the sites mentioned in the text; **c** photograph of coring site

Physical setting

The studied site, La Correntina mire, is located 14 km east of the southeastern tip of Lago Fagnano, at 54°S, in the central part of Isla Grande de Tierra del Fuego (Fig. 1a). The lake is ~105 km long and 5–10 km wide and it is the largest ice-free water body close to Antarctica. The region constituted one of the most important glaciated areas of southernmost South America during the Last Glacial Maximum (LGM, 25,000 cal BP, Rabassa 2008) because of the large volume of ice contained by the glacier network that covered the region (Coronato et al. 2009). The evolution of the lake basin was mostly conditioned by tectonic processes, and it was later affected by glacial and glacio-lacustrine depositional events (Esteban et al. 2014).

La Correntina mire, 0.63 ha in size, is situated at the bottom of a tributary valley of the Río San Pablo, on the northern slope of the Sierra Lucio López eastern Fuegian Andes (ca. 1,000 m a.s.l., Fig. 1b, c). It is surrounded by peaty grassland and shrubs on the valley bottom and by open forest of *Nothofagus pumilio* and *N. antarctica* in the surrounding hills. The mire was formed at the bottom of the valley which follows the fault trace of continental boundary plates. The valley is formed by meta-sedimentary rocks belonging to the Formación Beauvoir (Lower Cretaceous, Olivero and Malumián 2008) forming the mountains on the south side and by marine sedimentary rocks of the Formación Río Claro (early Tertiary, Buatois and Camacho 1993) forming isolated hills on the north side of the valley. Bedrock exposures are rare, as Quaternary glacial deposits and peat bogs cover most of the landscape. The Magallanes-Fagnano transforming fault system separates both mountain alignments, forming a tectonic valley with a left-lateral slip rate of 5–6 mm y^{-1} (Smalley et al. 2003). Vertical displacements of 0–1 m with no coseismic horizontal strike-slip displacement occurred twice during the last 8,000 years along the bottom of the valley where La Correntina mire is situated (Costa et al. 2006).

Modern climate and vegetation

The climate of Tierra del Fuego is cold-temperate; it is affected by the seasonal movements of the Antarctic Polar Front and the cyclonic activity related to the SWW (Pisano

1977). The latitudinal position and strength of the SWW are controlled by the intensity and latitudinal location of the subtropical high pressure cells in the Pacific and the circum-Antarctic low pressure belt. Seasonal changes in the temperature gradient promote latitudinal shifts of the westerlies so they migrate toward the South Pole in summer and toward the Equator in winter (Markgraf and Huber 2010). Cyclonic systems originating over the Pacific Ocean migrate eastward and become diverted southeastward by the axial trend of the Andes (Pisano 1977). These disturbances lose most of their moisture in the mountains and a notable rain shadow exists on the eastern side of the Andes (Heusser 1989a). Mean annual precipitation ranges from over 3,000 mm on the west coast of Chile and decreases to less than 200 mm along the eastern Atlantic coast (Tuhkanen 1992; Schneider et al. 2003). Although proximity to the Antarctic continent and the Circum-Antarctic Current cause southern Patagonia's temperature to be cool, maritime conditions mitigate temperatures on both sides of the Andes, with mean annual values ranging from 5.3 °C in the Canal Beagle at Ushuaia to 5.5 °C on the Atlantic coast at Río Grande and winter temperatures remaining above freezing (Schneider et al. 2003; National Weather Service Argentina 2013).

Present vegetation reflects the strong trans-Andean climatic and topographic gradients (Moore 1983; Tuhkanen 1992) (Fig. 1a). Northern steppe changes southwards into deciduous beech forest, evergreen beech forest and Magellanic moorland. Steppe of grassland, scrub and heath occupies the driest areas of the island where mean annual precipitation is less than 400 mm. Grasses include *Festuca gracillima* as the dominant species. Scrub is dominated by shrubby composites and dwarf shrub heath is typified by *Empetrum rubrum* (Heusser 1989a). Contact of steppe with deciduous beech forest occurs through an ecotone with 350–500 mm annual precipitation (Tuhkanen 1992). The deciduous forest is characterized by two species, *N. pumilio* (*lenga*) and *N. antarctica* (*ñire*), and the latter is present at all elevations on poor, disturbed soils (Pisano 1977; Moore 1983). Both deciduous *Nothofagus* taxa grow from sea level to the tree line at 550–600 m a.s.l. and become dominant where precipitation exceeds 450 mm yr^{-1}. Sheltered inland areas on the western and southwestern slopes of the Andes are covered by enclaves of evergreen forest dominated by *Nothofagus betuloides* (*guindo*) where the annual precipitation is >700 mm. These communities occur either in pure stands or in association with *Drimys winteri*, *Maytenus magellanica* and abundant ferns and mosses (Moore 1983). Initially, *N. betuloides* is intermingled with *N. pumilio* in an association that has been distinguished as mixed evergreen-deciduous forest, which can be better considered as ecotonal between the two communities (Moore 1983). The forest throughout is often broken by scrub, heath, and bog communities. Magellanic moorland occurs beyond the forest along the exposed outermost coast under conditions of increased precipitation of >1,500 mm yr^{-1}, high winds and poor drainage. Mostly treeless, the moorland is distinguished by the cushion plants *Astelia pumila* and *Donatia fascicularis* and the dwarf conifer *Lepidothamnus fonkii*. Between the tree line and snow line, Andean tundra is characterized by the cushion plants *Azorella lycopodioides*, *Bolax gummifera* and *Drapetes muscosus*, *E. rubrum* heaths, herbs and grasses (Heusser 1989a).

Materials and methods

Lithology and chronology, age-depth model

A 466 cm sediment core from the mire was obtained using a Russian-type peat corer with a chamber length 0.5 m and 5 cm diameter (Jowsey 1966). Core segments were extruded in the field, wrapped in plastic film and stored in plastic half pipes. The stratigraphy of the section was characterized by lithological descriptions in the field. The chronology of the core is based on seven AMS radiocarbon dates on bulk organic matter, obtained at the AMS Facility of the University of Arizona, U.S.A. We converted both our ages and those cited from the literature to calendar years BP using the CALIB 7.0 software (Stuiver et al. 2014) and the Southern Hemisphere curve SHCal13 (Table 1; Hogg et al. 2013). Based on these data, an age-depth model for the core was constructed using the program Bacon (Fig. 2; Blaauw and Christen 2011). The Bayesian approach determines 95 % confidence limits of the age-depth model using the uncertainties of the calibrated radiocarbon ages, expected sedimentation rates at the core location (priors) and Markov Chain Monte Carlo (MCMC) simulation. In this study, the mean accumulation rate based on the age of a tephra described below was used as a prior for the model.

Tephrochronology

We identified tephras on the basis of their colouration, lithic content and shard vesicularity. Shard morphology, including the approximate size and shape of grains, was also recorded as it is diagnostic of some tephras (Stern 2008). The relative abundance of microphenocrysts was later determined with a scanning electron microprobe. Individual glass shards from tephra samples were analyzed at the University of Calgary Laboratory for Electron Microbeam Analysis (UCLEMA) to determine their provenance. Prior to analysis, organic matter was removed with hydrogen peroxide, the samples were washed and wet-sieved on a 230 mesh (63 µm) screen, and the coarse

Table 1 Radiocarbon dates and calibrated ages of selected samples of bulk organic matter from La Correntina mire

Sample depth (cm)	Lab. code	^{14}C age (yrs BP)	δ^{13}C (‰)	Cal. age, yrs BP (median)	1σ range	2σ range
29–30	AA83315	217 ± 33	−25.8	193	148–220	138–231
98–99	AA86257	2,241 ± 37	−25.4	2,226	2,154–2,207	2,145–2,330
159–160	AA83316	4,030 ± 37	−26.5	4,469	4,464–4,518	4,379–4,570
247–248	AA83318	6,410 ± 210	−27.2	7,251	7,145–7,471	6,775–7,623
255–256	AA86263	7,218 ± 48	−27.3	7,992	7,945–8,025	7,928–8,069
300–301	AA83319	7,686 ± 51	−25.7	8,443	8,388–8,462	8,365–8,548
465–466	AA83317	12,775 ± 64	−29.7	15,168	15,076–15,277	14,872–15,400

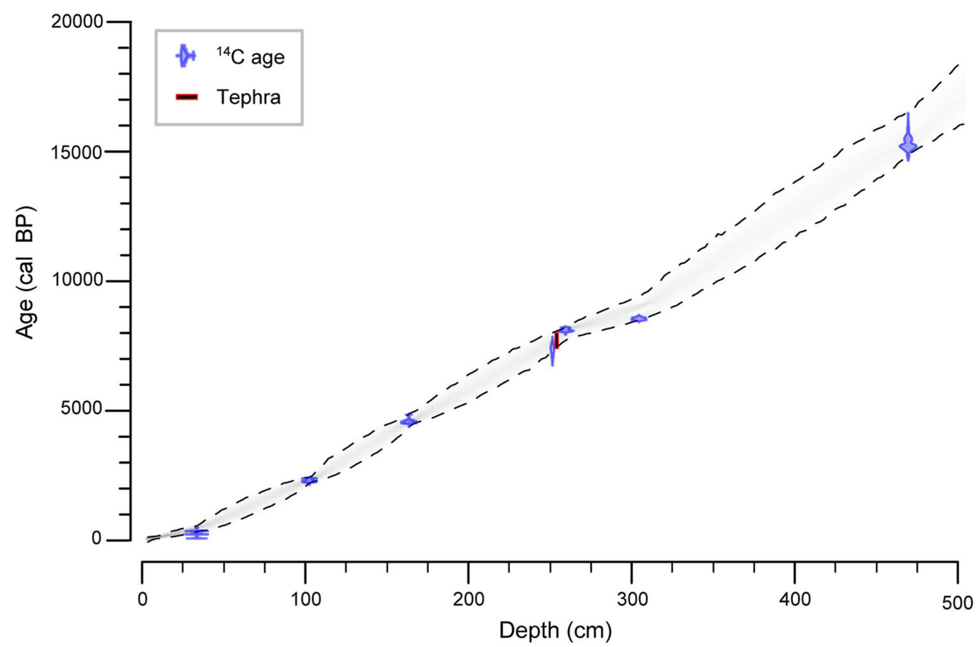


Fig. 2 Age-depth model based on methods described in Blaauw and Christen (2011). The probability distribution of the ^{14}C ages is shown in *blue*. The *black, dashed lines* and *grey shading* denote 95 % confidence limits of the age-depth model

fraction was mounted in epoxy, polished and carbon-coated. Typically 60 inclusion-free glass shards were analyzed for K_2O, CaO, FeO, SiO_2, Na_2O, TiO_2, MnO, MgO and Al_2O_3 with wavelength-dispersive spectrometers (WDS) on a JEOL JXA-8200 electron microprobe. The accelerating voltage used was 15 kV with a beam current of 10 nA and a beam diameter of 5 µm. Data were corrected using the ZAF matrix correction routine to account for compositional differences between the calibration standards and the samples (Armstrong 1984). The resultant data were compared with those reported on tephra from known eruptions of specific source volcanoes in the region (Stern 2008).

Pollen analysis

Sediment samples of 1 cm thickness were taken at 4 cm intervals and prepared using standard techniques (Fægri and Iversen 1989). To calculate the pollen concentration per gram of sediment, *Lycopodium* spore tablets were added to each sample prior to treatment (Stockmarr 1971). In most samples, a minimum of 300 terrestrial pollen grains were counted, except for some Late-glacial samples, at 394, 414, 419 and 434 cm depth, with lower pollen sums. Frequencies of terrestrial plant taxa were based on a sum of pollen from trees, shrubs and herbs. Pollen of *Caltha*, Cyperaceae, *Myriophyllum*, *Tetroncium* and spores as well as other aquatics and cryptogams were calculated separately and related to the sum of terrestrial pollen. "Other shrubs and herbs" including taxa with low (<1 %) values are plotted, such as *Berberis*, *Ephedra*, Plantaginaceae, Plumbaginaceae, Primulaceae, Solanaceae and Urticaceae. "Other aquatics and cryptogams" includes Iridaceae, Juncaceae, Juncaginaceae and Polypodiaceae. We combined pollen from the evergreen species *N. betuloides* and the deciduous *N. pumilio* and *N. antarctica*, given the difficulty in species separation, and report these as "*N. dombeyi*-type".

We subdivided the pollen spectra into zones based on visual inspection of the pollen record and a stratigraphically constrained cluster analysis using the Cavalli-Sforza and Edwards Distance (TGVIEW 2.0.2, Grimm 2004). Modern pollen data from surface soil samples (Heusser 1989a; Trivi de Mandri et al. 2006; Musotto et al. 2012) and from present-day vegetation on Tierra del Fuego (Pisano 1977; Moore 1983) were used to interpret the palaeovegetation changes seen in the fossil pollen spectra.

Results

Lithology and chronology

The core consisted of organic rich clayey silts containing gravel [466–450 cm] which were overlain by 250 cm of dark brown peat with fibres of vascular plants such as *Carex* and grasses. This upper unit contained a tephra layer dispersed in organic sediment at 401 cm, dark compact peat layers interspersed with dark grey charcoal lenses [350–300 cm] and a unit of tephra [255–250 cm]. From 200 to 160 cm the core consisted of dark brown peat of *Sphagnum* with Cyperaceae fragments. The upper 160 cm of the core were composed of dark brown *Sphagnum* peat, changing into light brown *Sphagnum* peat from 15 cm to the surface. The peat core also contained elevated amounts of pyrite, which occurred as disseminated euhedral crystals (<3 µm) or agglutinated masses [466–429 cm].

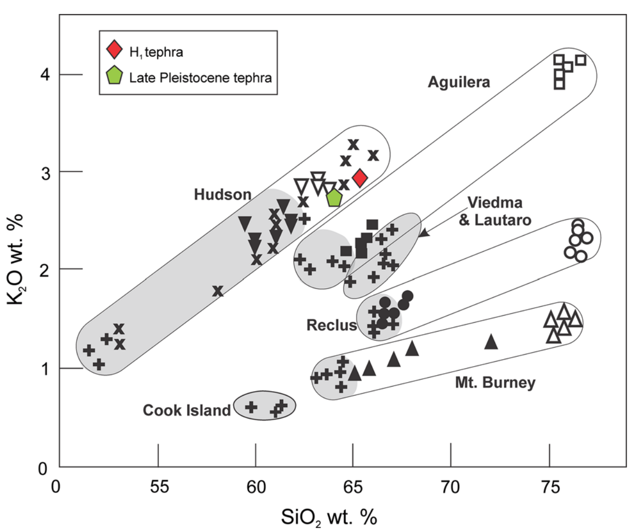


Fig. 3 Diagram of chemical data (SiO_2 versus K_2O) showing the compositional fields of Quaternary volcanic centres of the southern Andes defined by Stern (2008). The *pentagon* marks the sample from tephra layer collected at 401 cm depth. The *diamond* indicates the sample corresponding to tephra layer (H_1), collected at 255 cm depth. Other symbols denote tephra samples from Stern (2008)

Geochemical and petrological analyses on the two tephra samples collected at 401 and 255 cm depths respectively indicate that both correspond to eruptions of Volcán Hudson (45°54′S, 72°58′W, 1,905 m a.s.l.), which is located in the southern portion of the Zona Volcánica Sur (ZVS, 33–46°S) (ESM Tables 1, 2, Fig. 3). The deeper sample consists of tephra with an interpolated age of 12,845 cal BP according to the age-depth model for the core. Tephra layers preserved in deposits near Volcán Hudson between 44° and 47°S in southern Chile indicate some volcanic eruptions during the late Pleistocene and early Holocene (Mena 1983; Haberle and Lumley 1998). Recently, evidence of a large Late-glacial eruption of Volcán Hudson has been obtained from lake cores near Coyhaique, Chile, about 100 km northeast of the volcano (Weller et al. 2013). The upper sample is attributed to the mid Holocene tephra (H_1) layer erupted from Volcán Hudson, dated 7,423–7,960 cal BP (Stern 2008).

Pollen analysis

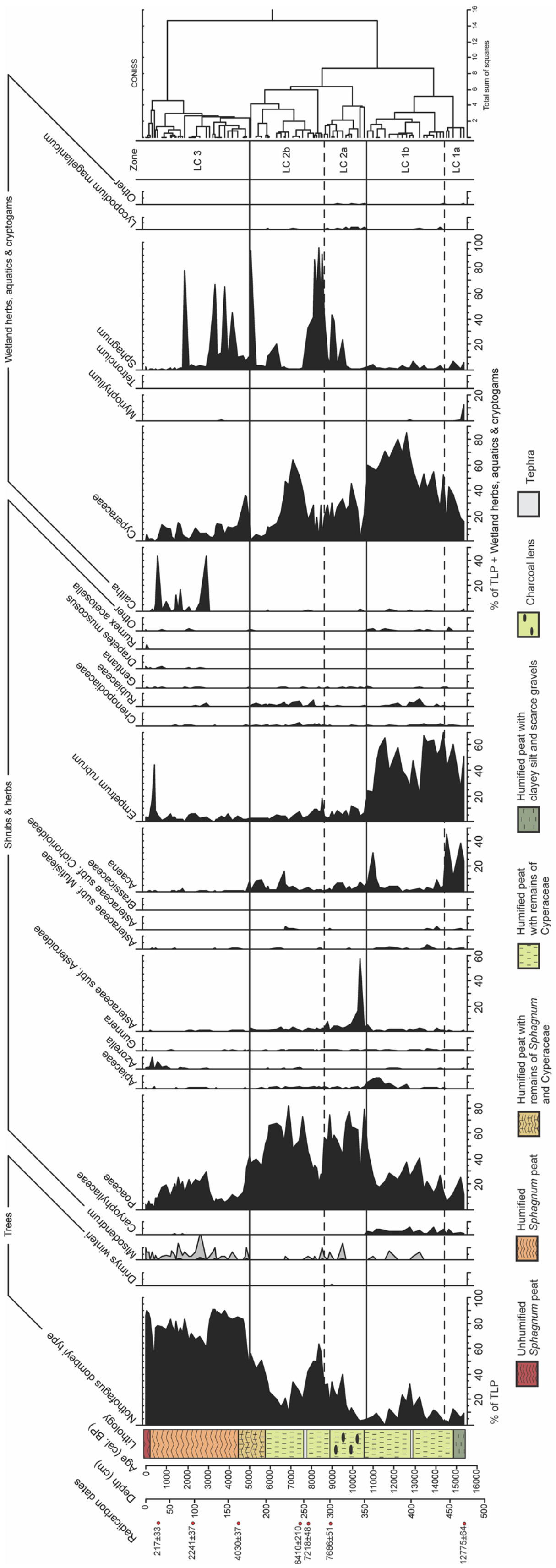
The pollen record from La Correntina has been divided into three local pollen assemblage zones, LC-1–LC-3 (Fig. 4). Zones LC-1 and LC-2 are divided into two subzones, respectively. Late-glacial and Holocene vegetation succession is shown in Table 2. As a means of assessing independent behaviour of pollen types and to provide better insight of the direction of vegetation change around the mire, we calculated the main pollen concentrations (Fig. 5).

Zone LC-1 (464–354 cm; 15,400–10,600 cal BP)

Subzone LC-1a (464–444 cm; 15,400–14,400 cal BP). This subzone is characterized by high *E. rubrum* values, 26–60 %, accompanied by *Acaena* (12–44 %) and Poaceae (7–25 %). *Nothofagus dombeyi*-type shows low values up to 12 %. Among the aquatic taxa, Cyperaceae reaches 42 % and *Myriophyllum* 12 %.

Subzone LC-1b (439–354 cm; 14,400–10,600 cal BP). In this subzone *E. rubrum* fluctuates between 21 and 70 % and Poaceae increases up to 48 %. *Acaena* shows values below 10 % with a peak of 31 % at the top of the subzone. Apiaceae reaches up to 8 % at the end of the subzone. Rubiaceae, Caryophyllaceae and Asteraceae subf. Asteroideae present low values <7 %. *N. dombeyi*-type increases up to 32 % followed by a conspicuous decline to 5 % towards the end of the zone. Cyperaceae fluctuates between 27 and 85 %, and *Sphagnum* presents low values <7 %.

Pollen concentration. Total pollen concentration is low (<30,000 grains g^{-1}) in the lowermost part of Subzone LC-1a and increases up to 214,000 grains g^{-1} in Subzone LC-1b, contributed mainly by Cyperaceae with 130,000 grains g^{-1}.



◀**Fig. 4** Fossil pollen/spore frequency percentage diagram and stratigraphy at La Correntina mire. Exaggeration percentage curve (10×) is shown in grey for *Misodendrum* and *Rumex acetosella* pollen. *TLP* total land pollen

Zone LC-2 (349–184 cm; 106,00–5,000 cal BP*)*

Subzone LC-2a (349–289 cm; 10,600–8,600 cal BP). In this subzone Poaceae expands to 79 % and *E. rubrum* decreases to 4–12 %. *N. dombeyi*-type shows an increasing trend up to 40 %. Asteraceae subf. Asteroideae peaks at 57 % at the beginning of the subzone and then decreases to less than 7 %. *Acaena* records low values <8 %. Among the aquatic taxa and cryptogams, Cyperaceae decreases to 2–45 % and *Sphagnum* increases up to 44 % at the end of the subzone.

Subzone LC-2b (284–184 cm; 8,600–5,000 cal BP). Poaceae fluctuates between 22 and 81 % and *N. dombeyi*-type between 10 and 63 %. *Acaena* (16 %), Asteraceae subf. Asteroideae (4 %) and Rubiaceae (5 %) are present. Cyperaceae increases up to 64 % and then decreases to 1 % at the end of the subzone. *Sphagnum* reaches two peaks, up to 96 and 93 %.

Pollen concentration. In Subzone LC-2a, total concentration values are similar to those of the previous Subzone LC-1b, in spite of the increase in Poaceae up to 87,100 grains g^{-1}. In the middle of Subzone LC-2a, total pollen concentration rises to 266,800 grains g^{-1}, contributed mainly by Cyperaceae with 144,900 grains g^{-1}. A decline in total concentration at 254 cm to 12,300 grains g^{-1} coincides with the tephra layer. Meanwhile, in Subzone LC-2b, total pollen values increase up to 1,990,500 grains g^{-1}, primarily driven by Poaceae and Cyperaceae which show similar concentrations of ca. 890,000 grains g^{-1}.

Zone LC-3 (179–0 cm; 5,000–0 cal BP*)*

Zone LC-3 (179–0 cm; 5,000–0 cal BP). This zone displays an increase in *N. dombeyi*-type from 44 to 91 %, meanwhile Poaceae drops to 6 %. *Empetrum rubrum* maintains low frequencies <7 %, as in the previous Subzone LC-2b. *Misodendrum*, a hemiparasite on *Nothofagus*, records low values <1 % and becomes continuous. Cyperaceae at 36 % increases at the beginning of the subzone and afterwards decreases to <4 %. *Sphagnum* fluctuates between 8 and 78 %. After 3,000 cal BP, *N. dombeyi*-type pollen declines to 32–82 % along with increases in Poaceae to 25 %. *Azorella* (3 %) is present in the uppermost part of the zone, *Caltha* reaches two peaks of 43 %, and *Sphagnum* declines to <4 %. After 800 cal BP, *N. dombeyi*-type decreases and reaches 51 % at ca. 400 cal BP. Afterwards, *N. dombeyi*-type increases again up to 86 % along with a maximum of

Table 2 Local pollen assemblages zones identified from La Correntina mire

Zones	Age (cal BP)	Dominant taxa	Associated taxa	Wetland herbs, aquatics and cryptogams	Palaeovegetational evolution
LC 3	5,000 – present	*Nothofagus dombeyi*-type (32-91%), Poaceae (<32%)	*Empetrum rubrum*, *Azorella*	*Caltha* (up to 43%), Cyperaceae (<36%), *Sphagnum* (up to 93%)	Closed-canopy *Nothofagus* forest dominates the landscape; *Sphagnum* bog develops in connection with the forest. After 3,000 cal BP, *Nothofagus* forest becomes more open
LC 2b	8,600 – 5,000	Poaceae (21-81%), *N. dombeyi*-type (10-63%)	*Acaena*, *E. rubrum*, Asteraceae subf. Asteroideae Rubiaceae	Cyperaceae (<63%), *Sphagnum* (up to 96%)	*Nothofagus* forest retraction; expansion of herb-like grasslands and cushion heaths, interspersed with shrubs; change in bog communities with increase of sedges
LC 2a	10,600 – 8,600	Poaceae (28-79%), *N. dombeyi*-type (<40%)	*E. rubrum*, Asteraceae subf. Asteroideae	Cyperaceae (<45%), *Sphagnum* (up to 44%)	Abrupt vegetation change toward grassland communities; decline of *E. rubrum* heaths; expansion of *Nothofagus* forest, establishment of forest–steppe ecotone; ombrogenous mire
LC 1b	14,400 – 10,600	*E. rubrum* (21-70%), Poaceae (13-48%), *N. dombeyi*-type (<31%)	Caryophyllaceae, *Acaena*, Apiaceae	Cyperaceae (26-84%)	Development of grassland, *E. rubrum* heath and sedge plant communities; expansion and retraction of small populations of *Nothofagus* trees
LC 1a	15,400 – 14,400	*E. rubrum* (26-60%), *Acaena* (12-44%), Poaceae (<25%), *N. dombeyi*-type (<12%)	Caryophyllaceae, *Gunnera*, *Azorella*	Cyperaceae (14-42%), *Myriophyllum* (<12%)	Dominance of *E. rubrum* heaths accompanied by grasses and herbs; sparsely distributed *Nothofagus* trees; *Myriophyllum* is replaced by Cyperaceae under minerotrophic conditions

E. rubrum to 44 %. *Drapetes muscosus* (<2 %) and *Rumex acetosella* (<1 %) are also present.

Pollen concentration. N. dombeyi-type concentration records its highest values up to 1,446,000 grains g^{-1} between 5,000 and 3,000 cal BP. Afterwards, total pollen concentration drops abruptly to 136,900 grains g^{-1} to attain its previous values again. Over the last ca. 400 cal year BP, total pollen concentration increases to 206,000–535,000 grains g^{-1}, contributed primarily by *N. dombeyi*-type with 461,000 grains g^{-1}.

Palaeoenvironmental reconstruction at La Correntina mire

The Cordillera Darwin (54–55°S, 69–70°W, Fig. 1a) was the principal source for the complex of glaciers that descended not only northwards into the Estrecho de Magallanes (Magellan Straits), but also eastwards into Bahía Inútil and the Seno Almirantazgo–Lago Fagnano depression and the Canal Beagle (Heusser 2003). During the LGM, the Fagnano palaeoglacier was one of the most extensive ones in Tierra del Fuego, reaching its maximum frontal position at 66°45′W and covering the studied area (Coronato et al. 2009). This palaeoglacier receded towards the west during Late-glacial times (Coronato et al. 2009). The basal ages of the nearest San Pablo 1 peat bog located further down the valley, and the studied mire at La Correntina, indicate a minimum age range for the ice recession between 15,400 and 13,830 cal BP (Coronato et al. 2009; this paper). The basal age of the Terra Australis peat bog (Musotto 2013), located 50 km westwards, on the southern side of Lago Fagnano, also reveals that the glacier front was located to the west of this region.

The earliest pollen assemblage, between 15,400 and 11,500 cal BP (Zone LC-1), shows the dominance of dwarf shrub heath with *E. rubrum* accompanied by grasses (Poaceae) and herbs (*Acaena*, Caryophyllaceae, *Gunnera*) with sparsely distributed *Nothofagus* trees. The low total pollen concentration recorded throughout this pollen zone, if compared with those of the following pollen zones, reflects a scarce vegetation cover. Presently, heaths of *Empetrum* which form dense carpets of dwarf shrubs are associated with soils that are being eroded, contain high C/N ratios and amounts of aluminium together with low pH, reduced calcium content and poor base saturation (Collantes et al. 1989). The southeastern Patagonian steppe, where precipitation is less than 200 mm annually (Markgraf and Huber 2010), affords a modern analogue for this initial mire vegetation.

In the lowermost section between 15,400 and 14,400 cal BP (Subzone LC-1a) the strong presence of *Acaena*, the most frequent associate of grassland communities, indicates a substantial amount of open-ground landscape

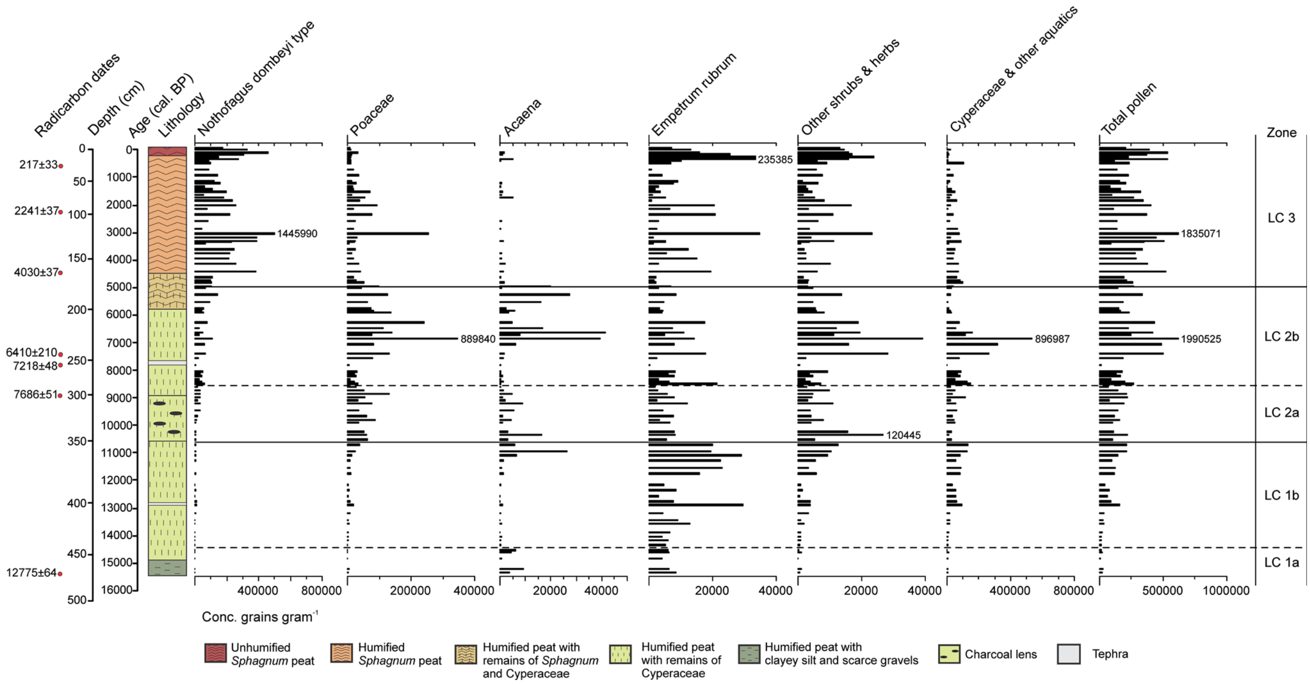


Fig. 5 Diagram of fossil pollen concentration in grains gram^{-1} and stratigraphy at La Correntina mire

(Pisano 1977; Moore 1983). The low frequency (<12 %) and concentration values (220–1,500 grains g^{-1}) of *N. dombeyi*-type pollen at the beginning of the record imply pollen coming from regional glacial refuges (Premoli et al. 2010) and/or small populations of *Nothofagus* close to the site. Pollen data from steppe surface samples near the steppe-ecotone edge showed relatively high concentrations of *Nothofagus* pollen (11,050–34,198 grains g^{-1}) (Musotto et al. 2012). Therefore, the low density of *Nothofagus* pollen recorded throughout the Late-glacial suggests the existence of small groups of trees in the landscape. Hygrophilous taxa such as *Myriophyllum* and *Caltha* indicate the presence of water during the initial stages of the formation of the peat bog. Then, *Myriophyllum* is rapidly replaced by Cyperaceae (sedges), reflecting the transition from a limnic to a telmatic stage (Birks and Birks 1980). The mire became drier as it was colonized by sedges and grasses under minerotrophic conditions related to the development of a fen. Today, herbaceous fens are found in parts of the arid Argentinean steppe ecoregion with less than 400 mm of rain per year. These steppe bogs are dominated by grasses, sedges, rushes and a few shrubs (Loisel and Yu 2013). The crystals of biogenic pyrite in the lowermost levels of the core (466–429 cm) also suggest anaerobic conditions in the mire during this time. Biogenic pyrite crystals are most commonly found in the lower minerotrophic layers and rarely in overlying ombrotrophic peats (Franzén 2006).

Between 14,400 and 10,600 cal BP (Subzone LC-1b), the total pollen concentration values imply high environmental variability in terms of variations in effective moisture due to temperature change. This period is characterized by the development of *E. rubrum* heath, herb-rich grassland with Poaceae, Caryophyllaceae and Rubiaceae, and Cyperaceae (sedge) plant communities. By about 13,000 cal BP, an increase in frequencies and concentration values of *N. dombeyi*-type may suggest that *Nothofagus* trees were growing closer to the site under moderating climatic conditions, since the total concentration also increases. However, the still low arboreal concentration values of 230–8,800 grains g^{-1} imply small populations of *Nothofagus*. Evidence of presence of small groups of *Nothofagus* trees surrounding the mire is supported by the record of *Misodendrum* pollen. The seeds of this hemiparasite of beech are wind-dispersed within a short distance <10 m from the plant (Tercero-Bucardo and Rovere 2010).

Between 10,600 and 8,600 cal BP (Subzone LC-2a), the *E. rubrum* heathland was replaced by grassland communities along with herbs such as *Acaena* and Apiaceae, indicative of more mesic and open ground environments. A peak of Asteraceae subf. Asteroideae pollen, which comprises many drought tolerant taxa, may indicate less damp conditions locally. After 10,000 cal BP, *Nothofagus* began to spread, and by about 9,400 cal BP, the landscape was probably a forest-steppe ecotone, implying warmer climatic conditions. Analogous communities exist today in central Isla Grande de Tierra del Fuego, where there is mean annual precipitation of 350–500 mm and summer temperatures average 11 °C (Pisano 1977; Tuhkanen 1992). The bog communities also changed and *Sphagnum* became dominant, reflecting greater water depth and less mineral input. The mire became an ombrogenous bog supplied by increased precipitation. Presently, *Sphagnum*-dominated peat bogs are found on the lee side of the Andes as well as throughout the deciduous and evergreen cool-temperate ecoregions of Tierra del Fuego with 400–1,000 mm of rain per year (Loisel and Yu 2013).

After 8,600 cal BP, *Nothofagus* pollen frequencies start to decline and the Poaceae percentages and abundances rise again accompanied by the herbs *Acaena*, Rubiaceae and Apiaceae together with the shrubs *E. rubrum* and Asteraceae subf. Asteroideae, probably as a consequence of decreasing effective moisture levels. During this interval, at 254 cm, the total pollen concentration drops abruptly due to a probably instantaneous deposition of a thick tephra layer (H_1) from Volcán Hudson. The bog communities changed and the sedges spread again, perhaps in response to the large input of nutrients leached from the surroundings into the mire and promoting minerotrophic environments.

Between 5,000 and 3,000 cal BP (Zone LC-3), closed-canopy *Nothofagus* forest (>80 %) dominated the landscape accompanied by grasses (<10 %), implying a change to colder conditions and an increase in effective moisture levels. The beech hemiparasite *Misodendrum*, though in low frequencies of up to 1 %, is recorded in coincidence with increases in *N. dombeyi*-type to >80 %. Its presence indicates the local presence of *Nothofagus* forest communities. This inference is supported by similar frequency values recorded from surface samples in deciduous *N. pumilio* and *N. antarctica* forest (Musotto et al. 2012). These plant communities evolve when precipitation exceeds 450 mm yr^{-1} (Tuhkanen 1992). During this time, a *Sphagnum* bog developed in connection with the forest and was sufficiently wet to keep the surface waterlogged. Hummock-forming species such as *S. magellanicum* probably colonized the bog surface. The irregular spore production of *Sphagnum* may explain the virtual absence of spores in levels with abundant macroremains in the peat core (Heusser and Rabassa 1995). The presence of *E. rubrum* reflects hydrological conditions within the bog, since this plant colonizes dry, elevated areas such as unhumified hummocks, while sedges grow on submerged bog surfaces (Birks and Birks 1980; Markgraf and Huber 2010). Also, the record of grasses and sedges may be related to the minerotrophic part of the bog, named lagg, which develops around *Sphagnum* bogs (Birks and Birks 1980; Musotto et al. 2012).

After 3,000 cal BP, *Nothofagus* forest became more open, accompanied by development of mesic grasslands with Poaceae, *Caltha* and Cyperaceae. At present, these plant communities grow in flat areas where the water table approaches the surface; they also grow in openings within the forest communities or along their margins (Moore 1983). Dwarf shrub heath with *E. rubrum* and cushion heath with *Azorella* and *D. muscosus* communities may be included as important associates within the deciduous forest zone (Moore 1983). The record of *Caltha* would be related to fluctuations in the water table level at the site, as it grows in wet areas where the water table is near the surface. All these plant assemblages resemble the modern ones growing in the deciduous forest in the centre of Tierra del Fuego (Moore 1983).

By about 400 cal BP, the decline in frequency and concentration values of arboreal taxa along with increase in *E. rubrum* and *Azorella* pollen are indicative of a reduction of *Nothofagus* forest and a drier bog surface.

After ca. 400 cal BP, *Nothofagus* forest expanded again and the landscape resembled a closed-canopy forest, as shown by the increase in percentage and concentration values of *N. dombeyi*-type pollen. The record of *Rumex acetosella*, an introduced taxon, indicates human disturbance and landscape degradation (Moore 1983; Heusser 2003).

Palaeoenvironmental changes, the Pacific versus Atlantic side of the Fuegian Andes

Postglacial vegetation changes in Tierra del Fuego, based on the existing pollen records and this study, are summarized in Fig. 6. In spite of temporal resolution and/or radiocarbon control, these data allow us to infer the hypothetical location and displacement of the SEL (steppe-ecotone limit) and EFL (ecotone-forest limit) over the last 18,000 years. The Post-glacial pattern of vegetation across Tierra del Fuego occurred under climatic conditions of increased precipitation following a precipitation gradient caused by the Andean Cordillera (Heusser 2003; Markgraf and Huber 2010). The *Nothofagus* seed dispersal by wind was through transecting valleys and over low passes of the Fuegian Andes (Heusser 1993). In addition, local conditions at different sites such as soil types, drainage, slope, orientation of the slope, and of plant ecology such as dispersal and disturbance history (Kilian and Lamy 2012), volcanic fallout (Fontana and Bennett 2012) and extensive fires (Markgraf and Huber 2010) may have played an important role in the internal dynamics of vegetation change.

Late-glacial pollen records show that, immediately following deglaciation, a non-arboreal palaeovegetation dominated the landscape (Fig. 6b), not only in the central part of the island but also along the Canal Beagle area and towards the northwestern archipelago, at sites as far as Bahía Inútil and Onamonte (Heusser 2003; Markgraf and Huber 2010). The low abundance of *Nothofagus* pollen

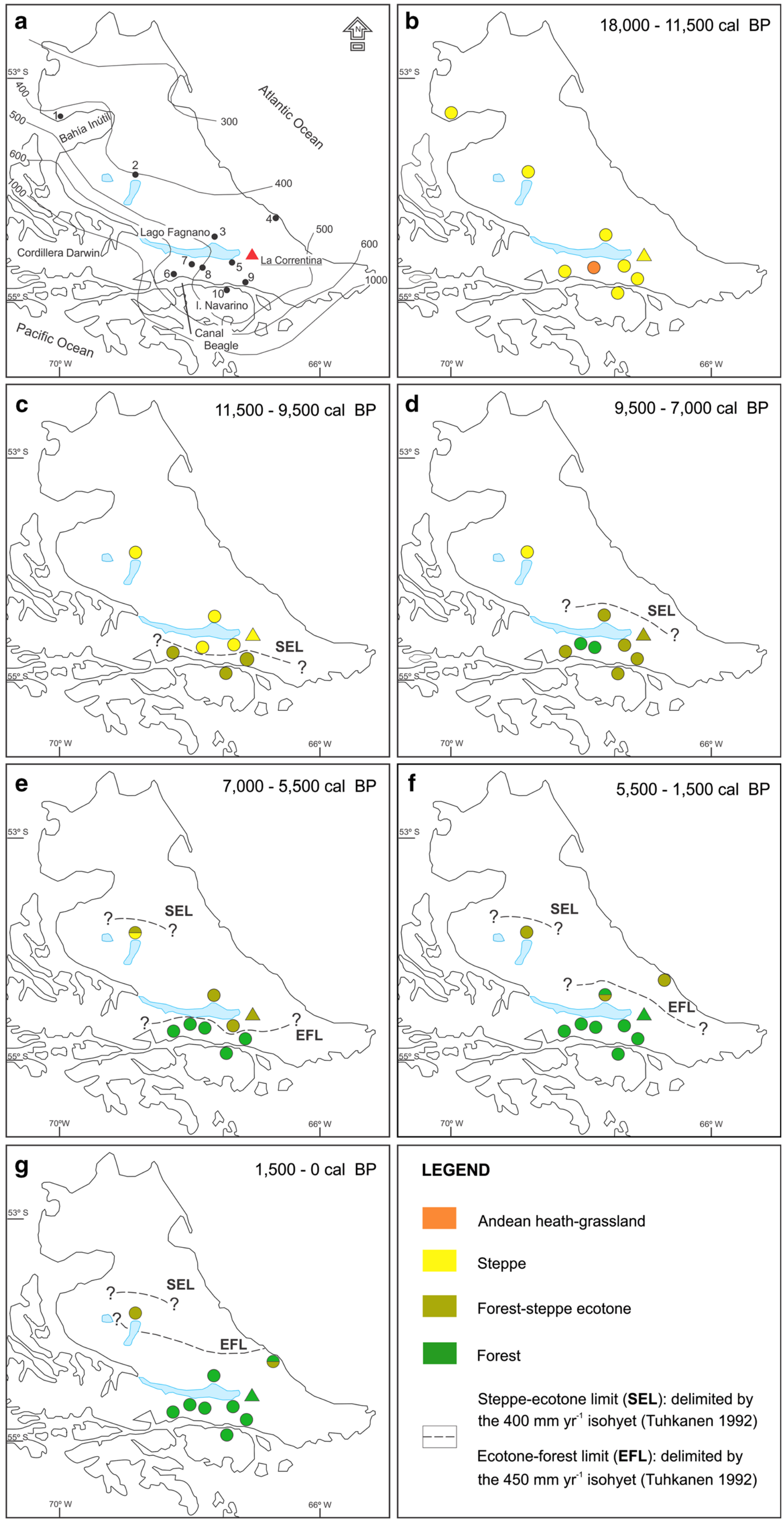


Fig. 6 Vegetation changes in Tierra del Fuego during the late Pleistocene and Holocene, according to different peat records from the Fuegian Archipelago. Reference: **1,** Bahía Inútil (Heusser 2003); **2,** Onamonte (Heusser 1993); **3,** Lago Yehuin (Markgraf 1983); **4,** Cabo San Pablo (Heusser and Rabassa 1995); **5,** Lago Fagnano (Heusser 2003); **6,** Ushuaia 1, 2 and 3 (Heusser 1998); **7,** Las Cotorras (Borromei et al. 2010); **8,** Paso Garibaldi (Markgraf and Huber 2010); **9,** Puerto Harberton (Heusser 1989b; Markgraf and Huber 2010); **10,** Caleta Róbalo (Heusser 1989a)

suggests the survival of small tree populations in ice-free refuges during glacial times, located within the present extent of the forests (Heusser 1998; Fontana and Bennett 2012). An important aspect to consider remains the problem of determining which kinds of vegetation developed during this period. The pollen assemblages resemble both steppe and/or high Andean tundra environments. Nowadays, many plants are common to both vegetation units, thereby making the identification of the environment more difficult. Particularly, a steppe-like vegetation is inferred from the La Correntina mire, characterized by heaths, grasses and herbs with scarce trees. Similar plant communities were also reported from low-elevation sites along the Canal Beagle (Heusser 2003; Markgraf and Huber 2010). Meanwhile, the initial vegetation at an upper tree line site at Paso Garibaldi was herbaceous, species-rich alpine heath-grassland, similar to modern high Andean vegetation and indicating cooler and windier conditions than today (Fig. 6b; Markgraf and Huber 2010). The low temperatures might have favoured the expansion of alpine plant communities down to lower altitudes as they competed for suitable habitats. However, the low elevation vegetation did not include the presence of upland taxa characteristic of the Andean tundra (Moore 1983).

Noteworthy is the asynchroneity in the *Nothofagus* forest expansion on each side of the Fuegian Andes. Pollen records from the Canal Beagle area, on the Pacific slope, reveal a *Nothofagus* woodland vegetation after 11,500 cal BP (Heusser 1989a, 1989b, 1998; Markgraf and Huber 2010). The SEL, delimited by the 400 mm yr^{-1} isohyet (Tuhkanen 1992), was situated on the lowlands of the Canal Beagle (Fig. 6c). On the Atlantic slope of the Fuegian Andes, the forest started to spread later. The forest-steppe ecotone communities evolved in the Lago Fagnano area by ca. 9,500 cal BP under lower moisture levels, as indicated by the pollen data from the mires at Lago Fagnano (Heusser 2003) and Lago Yehuin (Markgraf 1983) and from our record. By this time, the SEL migrated northwards of Lago Fagnano on the Atlantic slope (Fig. 6d). At the Onamonte site, the forest-steppe ecotone was established even later, after ca. 5,800 cal BP (Fig. 6e; Heusser 1993). Several authors stated that fire acted as an important ecological factor in the spread of forest (Huber et al. 2004; Whitlock et al. 2007; Markgraf and Huber 2010). High fire incidence in Tierra del Fuego during the early Holocene has been attributed to greater climate variability and/or deliberate burning by prehistoric peoples (Whitlock et al. 2007). Fires may have caused the trees to survive mainly by vegetative reproduction for long periods, restricting their dispersal rate (Fontana and Bennett 2012). Although no charcoal analysis was performed on the La Correntina peat core, grass communities dominated the pollen spectrum at times in the early Holocene probably related to regional fires. High density of charcoal was reported at the Fagnano site, 35 km southwest from La Correntina, between about 11,000 and 8,000 cal BP (Heusser 2003; Huber et al. 2004). At this time, the closed-canopy forest developed at the high elevation sites Las Cotorras and Paso Garibaldi, ca. 450 m a.s.l. (Fig. 6d). According to Markgraf and Huber (2010), fires were absent at the upper tree line at Paso Garibaldi and did not affect the forest communities there.

After ca. 7,000 cal BP, the closed-canopy forest established along the Canal Beagle area and fire activity declined due to an increase in effective moisture (Heusser 1998; Markgraf and Huber 2010). Meanwhile, the forest-steppe ecotone communities prevailed on the Atlantic side of the Fuegian Andes. The EFL (ecotone-forest limit), delimited by the 450 mm yr^{-1} isohyet (Tuhkanen 1992), was positioned on the lowlands of the channel (Fig. 6e). On the Atlantic side, the expansion of closed-canopy forest occurred after ca. 5,500 cal BP at La Correntina and Lago Fagnano (Heusser 2003), and after ca. 2,000 cal BP at Lago Yehuin (Heusser 2003). During this time, the EFL was displaced to the centre of the island (Fig. 6f). Toward the northwest, the forest margin apparently approached Onamonte at ca. 1,500 cal BP (Heusser 1993). In eastern Tierra del Fuego, at Cabo San Pablo, the forest-steppe ecotone prevailed until about 380 cal BP, when the forest spread (Fig. 6g; Heusser and Rabassa 1995).

Palaeoclimatic inferences

The late Pleistocene-Holocene transition in Tierra del Fuego was characterized by multi-millennial temperature and precipitation variability, suggesting mainly changes in SWW strength and/or latitudinal position (Heusser 2003; Markgraf and Huber 2010). All the pollen records from Tierra del Fuego show highly fluctuating *N. dombeyi*-type frequencies and mostly low abundances for the period. The La Correntina pollen assemblage also displays the lowest concentration values of arboreal pollen before ca. 13,000 cal BP, indicating drier and colder conditions than present. By this time, an advance of alpine glaciers at about 14,830–12,850 cal BP was reported near Ushuaia, which has been correlated with the Antarctic Cold Reversal of 14,500–12,900 cal BP (Menounos et al. 2013). After 13,000 cal BP, our pollen data show an increase in total pollen concentration, indicating moister and more moderate conditions than before. However, geological evidence from a recessional moraine in the Fuegian cirque glaciers indicates a later glacial advance or stabilization in the Younger Dryas Chronozone at 12,900–11,700 cal BP (Menounos et al. 2013).

During the early Holocene climate optimum at ca. 11,000–9,500 cal BP (Bentley et al. 2009), at the La Correntina site, the development of grassland communities accompanied by a gradual advance of *Nothofagus* forest into the steppe imply a change to wetter and warmer conditions. The high fire activity reported from Tierra del Fuego at the beginning of the Holocene may have maintained a considerable openness in the landscape (Heusser 2003; Whitlock et al. 2007; Markgraf and Huber 2010). Also, in agreement with pollen data, there is no evidence for glacier activity and moraine formation during the early Holocene in the southernmost mountains of Tierra del Fuego (Menounos et al. 2013).

There is still no detailed chronology of Holocene glacier fluctuations in Tierra del Fuego. Menounos et al. (2013) reported at least two mid Holocene glacier advances in cirques of Fuegian hanging valleys (ca. 700–1,100 m a.s.l.), one between 7,960–7,340 cal BP and 5,290–5,050 cal BP, and the other after 5,290–5,050 cal BP. These advances were only 10–100 m more extensive than the maxima achieved during the Little Ice Age (LIA), 600–100 cal BP (Menounos et al. 2013). During the mid and late Holocene, most of the pollen records from the Canal Beagle area show no clear evidence of changes in *Nothofagus* abundance. However, the intervals of low influx, at 6,380–5,000 cal BP, 2,334–360 cal BP and after 360 cal BP at Puerto Harberton, and between 6,310 and 4,510 cal BP at Ushuaia 2, suggest cooler episodes (Heusser 1989b, 1998). This apparent discrepancy indicates either that the cooling events were not as severe in the lowlands or alternatively, the regional expansion of a closed-canopy forest associated with increased precipitation masked the evidence of glacier advances.

An abrupt decline of *Nothofagus* is seen at 3,000 cal BP in the La Correntina pollen record. Similar vegetation change has been reported from Bahía Franklin in southwestern Isla de los Estados after 2,700 cal BP (Ponce et al. 2011). In western Tierra del Fuego, in the Glaciar Ema valley, a glacial advance was recognized shortly before 3,135 ^{14}C BP (3,290 cal BP) (Strelin et al. 2008).

In the Fuegian cirques, innermost moraines have been assigned to advances of the LIA (<1,000 cal BP) based on their fresh, uneroded forms, proximity to existing ice, and similarity of their positions to moraines in the vicinity that had already been assigned to the LIA (Menounos et al. 2013). Also, two glacial advances, the early and late LIA, have been reported in the Glaciar Ema valley, one at around 695 ^{14}C BP (619 cal BP) and the other between 335 ^{14}C (373 cal BP) and 60 years BP (Strelin et al. 2008). Our pollen data show low frequency and concentration values of *Nothofagus* pollen by ca. 400 cal BP that correlate well with these glacial events. Furthermore, a decline of *Nothofagus* forest between 680 and 300 cal BP has been reported from the Las Cotorras peat core, located in a high Andean valley. Evidence of cooler and wetter climate conditions has been recognized by a multi-proxy record in the inner low Andean valleys (Mauquoy et al. 2004). In the Lago Fagnano record (~54°S), the LIA is represented by high Fe levels at 50 cm which are linked to the intensification of the Southern Westerlies and humidity increase (Waldmann et al. 2010). Palaeoclimate studies from southwestern Patagonia (51°–52°S) showed a correspondence of the LIA event with *Nothofagus* dominance under cold and wet environmental conditions (Huber et al. 2004; Villa-Martínez and Moreno 2007; Moreno et al. 2009, 2014). Comparison between palaeoclimate records from Tierra del Fuego and southwestern Patagonia reveals differences in the direction of changes in the forest communities during the LIA chronozone. Dendrochronological studies on *N. pumilio* populations in Tierra del Fuego (Massaccesi et al. 2008) and southern Chile at 55°S (Aravena et al. 2002) indicate that the radial growth of the trees is positively correlated with summer temperatures. It is likely that the low temperatures associated with the LIA event increased the incidence of frosts and favoured more extended snowfall seasons, restraining the development of the *Nothofagus* forest.

Conclusions

The La Correntina mire records palaeoenvironmental changes from the central part of Tierra del Fuego during the late Pleistocene and Holocene. Our pollen data show that:

1. The area to the east of Lago Fagnano was free of ice by 15,400 cal BP and covered by pioneer vegetation dominated by dwarf shrub heath, grasses and herbs with sparsely distributed *Nothofagus* trees, under dry conditions.
2. After 13,000 cal BP, an increase in the total pollen concentration values and *Nothofagus* expansion indicate moister and milder conditions than before. During this time, the minimal frequency record of the beech hemiparasite *Misodendrum* suggests the presence of small groups of trees surrounding the mire.
3. The geochemical signature of a tephra layer with an interpolated age of 12,845 cal BP indicates an eruption from Volcán Hudson, in southern Patagonia. This material constitutes the first evidence of a late Pleistocene eruption of this volcanic centre.
4. *Nothofagus* forest started to spread by about 10,000 cal BP, and the forest-steppe ecotone was established after 9,400 cal BP. Increases in temperature and precipitation probably drove this vegetation change.
5. Closed-canopy forest dominated the landscape between 5,000 and 3,000 cal BP, suggesting cold and wet environmental conditions.
6. After 3,000 cal BP, *Nothofagus* forest became more open, accompanied by development of mesic grasslands.

7. The landscape displayed a physiognomy of a closed-canopy forest after ca. 400 cal BP. Human disturbance is reflected by the record of *Rumex acetosella*, an introduced plant.

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