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Environmental and climatic changes in Central Chilean Patagonia since the Late Glacial (Mallín El Embudo, 44° S)

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Abstract

Multi-millennial environmental and climatic changes in Central Chilean Patagonia (44–49° S) during the Last Glacial–Interglacial cycle have been of particular interest as changes in the position and strength of the Southern Westerlies are the major forcing factor conditioning the environmental dynamics. Recent attempts to reconstruct regional environmental and climatic signals from Central Chilean Patagonia reveal some discrepancies and unclear issues among the records. This paper presents the 13 ka pollen and charcoal records from Mallín El Embudo (44°40′ S; 71°42′ W) located in the deciduous *Nothofagus* forest in the middle Río Cisnes valley. The paper aims to (1) establish the timing and magnitude of local vegetation changes and fire activity since the Late Glacial and (2) integrate these results at the regional scale in order to discuss the discrepancies and depict the Central Chilean Patagonia environmental and climatic dynamics since Late Glacial. Open landscapes dominated by grasses associated with scattered *Nothofagus* forest patches dominated middle Río Cisnes valley between 13–11.2 ka suggesting low effective moisture but also reflecting that landscape configuration after glacial retreat was still ongoing. At 11.2 ka, a sudden development of an open and quite dynamic *Nothofagus* forest probably associated to the synchronous high fire activity occurred suggesting a rise in effective moisture. Since 9.5 ka, the record reflects the presence of a closed *Nothofagus* forest related to higher/similar effective moisture conditions than before but under an unmarked precipitation seasonality. The forest experienced a slight canopy opening since 5.7 ka, probably due to slightly drier conditions than before followed by a sudden change around 4.2 ka associated with fire and volcanic disturbances. The recovery of an open *Nothofagus* forest related to slight wetter conditions (similar to present) occurred around 2 ka and persisted under highly variable climatic conditions up to 0.1 ka when massive forest burning and logging due to European settlements occurred. Central Chilean Patagonian climatic and environmental changes at millennial-centennial time scales since Late Glacial were driven by changes in the Southern Westerlies latitudinal shift and/or intensity but during the Late

Holocene fire, volcanism and humans arise as major forcings contributing to environmental dynamics.

1 Introduction

Past environmental and climatic variability of Patagonia (40–55° S) since Late Glacial has been a major research topic because changes in the position and strength of the Southern Westerlies (SW) are the major forcing factor conditioning environmental trends. Sensitive-to-precipitation proxies from appropriately located records along Patagonia allow to indirectly trace SW past dynamics since a positive correlation between zonal wind speeds and local precipitation exists throughout the Pacific coast and inland areas on the lee side of the Andes ($r = 0.8$ to 0.4; Garreaud et al., 2013).

Patagonian records indicate that during the Late Glacial Maximum (∼ 21 ka; calendar thousand years before present, here in), the SW core was shifted equatorwards its modern position, centered on 41° S (e.g. Villagrán, 1990; Moreno et al., 1999). Later on, the SW would have shifted southwards to their present position around 14.3 ka and even southwards around 12.5 ka followed by a weakening after 11 ka (Markgraf et al., 1992). The onset of the Mid-Holocene (8 ka) was characterized by an increase in the intensity of the SW, whereas after 5 ka (Moreno et al., 2010a), palaeorecords reflect a regional, zonal and meridional heterogeneity. Palaeoclimate archives from Southern South America indicate an increase in westerly wind intensity during the last 2 ka that culminates between 0.4 and 0.05 ka (Moy et al., 2009). A recent hemispheric view of SW dynamics proposed that they have changed in a zonally symmetric manner at multi-millennial scale between 14 and 5 ka driven by intra-seasonal insolation changes. However, after 5 ka, a breakdown of this symmetry occurred, implying that changes in the strength and latitudinal position of the Southern Westerlies were modulated at seasonal to interannual timescales by large-scale climate phenomena such as ENSO and/or SAM (Moreno and Fletcher, 2011).

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Current understanding of palaeoclimatic dynamics from Central Chilean Patagonia (44–49° S) is scarce, compared to Northern and Southern Chilean Patagonia. Despite the small number of available palaeoecological records, their broad geographical distribution, their extended chronologies and high quality and resolution have allowed to infer Central Chilean Patagonia multi-millennial palaeoclimatic dynamics during the Last Glacial–Interglacial cycle (de Porras et al., 2012). Nevertheless, there are some issues that need to be addressed in order to achieve a unified regional picture. On one hand, opposite precipitation trends have been proposed for Eastern Central Chilean Patagonia during early deglaciation stages (de Porras et al., 2012; Markgraf et al., 2007; Villa-Martinez et al., 2012). According to Markgraf et al. (2007) and de Porras et al. (2012), grass-shrub steppe development at Eastern Central Chilean Patagonian sites after LGM termination indicates drier conditions whereas Villa-Martinez et al. (2012) inferred the local presence of evergreen forest which would suggest higher precipitation than present. On the other hand, Late Holocene environmental dynamics in Central Chilean Patagonia appears highly variable when comparing eastern palaeoclimatic records, but whether this variability is climatically driven or related to other forcings such as fire, volcanism and/or human activities remains unclear.

According to this issues, this paper presents the 13 ka pollen and charcoal records from Mallín El Embudo (44°40′ S; 71°42′ W) located at the Río Cisnes valley in order to establish the timing and magnitude of changes of local vegetation and fire regime since Late Glacial. Besides, local inferences from Mallín El Embudo are then integrated at the regional scale in order to discuss the above mentioned discrepancies or unclear issues and depict the Central Chilean Patagonia palaeoenvironmental and climatic dynamics since Late Glacial.

2 Modern environmental setting

Río Cisnes valley (RCv, 44°40′ S; Fig. 1a) is a west–east oriented valley that was occupied by a former glacier lobe of the Patagonian Ice Sheet during the Last Glacial

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Maximum (LGM) (Glasser et al., 2008) (Fig. 1b). Therefore, RCv landscape has been mainly shaped by glacial erosion presenting an LGM morainic complex in the upper part of the valley which constitutes the current Chile–Argentina international border (Caldenius, 1932; Glasser et al., 2008; Quensel, 1910; Steffen, 1909), a frontal moraine product of a Late-Glacial glacial readvance, and several paleolake shorelines related to former ice-dammed lake that flooded the upper and middle RCv after the LGM and at the Late-Glacial, respectively (Fig. 1b).

The main climate feature along RCv is the abrupt west-to-east precipitation gradient which is the consequence of the rain shadow effect produced by the forced subsidence of the Southern Westerlies over the Andes (Fig. 1c). Annual precipitation ranges from 3400 mm on the west coast (Puerto Cisnes; 44°55′ S; 72°70′ W) to 450 mm (Río Cisnes Ranch; 44°30′ S; 71°24′ W) close to the Chile–Argentina international border whereas mean annual temperatures range between 3.9 °C and 9.0 °C (Fig. 1c) (Luebert and Pliscoff, 2006).

Present-day vegetation physiognomy and composition in the RCv follows the decreasing west–east precipitation gradient (Fig. 1c). Thus, on the west slope of the Andes, plant communities ranges from the coastal evergreen forest of *Pilgerodendron uviferum* and *Astelia pumila*, the evergreen forest of *Nothofagus betuloides* and *Desfontainia spinosa*, and the deciduous forest of *Nothofagus pumilio* and *Ribes cucullatumm* (Fig. 1c). On the lee side of the Andes, plant communities includes the deciduous forest of *Nothofagus pumilio* and *Berberis illicifolia*, the shrubland of *N. antarctica* and *Berberis microphylla* whereas the *Festuca pallescens* grass steppe with *Mulinum spinosum* is present on the Patagonian plateau (Fig. 1c) (Luebert and Pliscoff, 2006).

Mallín El Embudo (44°40′ S; 71°42′ W, 686 m a.s.l.) is a small (0.6 ha) ombrotrophic fen of Cyperaceae (*mallín*, hereafter) located at the middle Río Cisnes valley (mRCv) in the *Nothofagus pumilio* and *Berberis illicifolia* deciduous forest (Fig. 1b). The arboreal stratum is dominated by *Nothofagus pumilio* often associated with *N. betuloides* and accompanied by shrubs like *Berberis illicifolia*, *Escallonia alpina*, *Berberis serrato-dentata*, *Myoschilos oblonga*, *Maytenus disticha*, herbs including *Valeriana la-*

pathifolia, *Macrachaenium gracile*, *Viola reichei*, *Adenocaulon chilense* and *Dysopsis glechomoides* and ferns (*Blechnum penna-marina*). The deciduous forest diversity decreases towards the east so that *N. pumilio* associated with *Chiliotrichum rosmarinifolium* and *Poa alopecurus* dominates (Luebert and Pliscoff, 2006).

Deciduous *Nothofagus pumilio* forest dynamics is controlled by medium-to-large scale disturbances such as fires, volcanism, logging and herbivory (Veblen et al., 1995, 1996).

Fires break the *Nothofagus pumilio* forest balance between canopy and understory, providing higher light conditions and bare soils to be colonized by soil-stored seed plants belonging to the forest or/and other plants from adjacent communities (Vidal and Reif, 2011). Post-fire *Nothofagus pumilio* deciduous forest regeneration is really slow (20 to 40 yr to flourish and fructify) and restricted to a narrow band at the forest margin where conditions are amenable, with adequate seed sources, shelter and proper soil conditions (Kitzberger et al., 2005; Veblen et al., 1996).

The main volcanic disturbance that could affect the deciduous *Nothofagus* forest from RCv may be pyroclastic deposition (ash fallouts) given its distance (> 100 km) to the closest volcanoes (e.g. Hudson, Mentolat, Melimoyu; Fig. 1a). Volcanic disturbances produce forest defoliation, canopy openings and burial of understory plants (Tsuyuzaki, 1995). Therefore, similar to fire, volcanic disturbances generate optimal conditions for the establishment and proliferation of fast-growing shade-intolerant plants at the expense of the tree stratum (del Moral and Grishin, 1999; Foster et al., 1998).

Native human occupation at the Río Cisnes valley has been recorded since 11.5 ka. Archaeological evidence indicates that hunter-gatherer groups inhabited the upper RCv (grass steppe) since 11.5 ka as suggested by a series of ^{14}C-dated redundant, though non-permanent occupations (Méndez et al., 2011). However, current data suggests that the middle and lower RCv were not occupied until 2.8 ka where a series of short human incursions were detected at selected sites (Méndez and Reyes, 2008). European settlement at the RCv occurred at the beginning of the 20th century (1904) when the Río Cisnes Ranch, a sheep breeding farm (~ 50 000 animals), was established

(Martinic, 2005). Since then, massive intentional fires and logging were conducted in order to clear the *Nothofagus* deciduous forest and shrubland and broaden grazing areas. According to historical chronicles, mRCv human settlements (around La Tapera village, Fig. 1b) were not established until 1930, so strong human induced landscape changes were actually late around Mallín El Embudo area (Martinic, 2005).

3 Material and methods

Two sediment cores (EE0110A/B) were recovered from Mallín El Embudo using a modified Livingstone piston corer.

Lithological description, X-radiographs and preliminary tephra analysis were performed to characterize the stratigraphy of the cores. Subsamples were separated for loss-on-ignition (LOI), tephra, pollen and macroscopic charcoal analysis. LOI was performed at 1 cm intervals along the sediment core in 1 cm^3 of material to determine organic and inorganic (carbonates and clastic fraction) contents (Bengtsson and Enell, 1986; Heiri et al., 2001).

Preliminary tephra analysis performed by C. Stern (University of Colorado) consisted of washing the samples in water to remove organics and clay followed by examination under petrographic microscope to determine glass color and mineral content.

The chronology of Mallín El Embudo record was constrained by nine radiocarbon dates (Table 1) which were calibrated using CALIB 6.1.0 program (Stuiver et al., 2005). Dates younger than 9720 yr ^{14}C BP were calibrated with the Southern Hemisphere curve (SHCal04) (McCormac et al., 2004) whereas the three oldest dates were calibrated applying the Northern Hemisphere curve (Reimer et al., 2004). An age-depth model based on eight of the nine AMS radiocarbon dates and assigning a modern age (2010 AD) to the surface of the *mallín* was performed using TILIA software (Grimm, 2012) applying a cubic smoothing spline interpolation. The 1200 ± 30 ^{14}C yr BP date was excluded because it forces the model age, thereby producing an abrupt change in sedimentation rate, without any sedimentological counterpart. Tephra layers were

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not subtracted to perform the age-depth model given that the preliminary analysis revealed that they were not pure volcanic ash but mixed with peat, so that instantaneous sedimentation could not be assumed.

Pollen analysis was performed on 1 cm^3 of sediment samples taken at 8 cm intervals. Pollen extraction from the sediments was done following standard laboratory techniques including KOH 10 %, sieving (120 µm mesh), hot HF 40 % (80 °C), and acetolysis, followed by ultrasonic treatment (Faegri and Iversen, 1989). Tablets of the exotic spore *Lycopodium clavatum* were added to each sample to calculate pollen concentration (grains cm^{-3}) (Stockmarr, 1971). The basic pollen sum for each level includes at least 300 terrestrial pollen grains. Pollen percentages of terrestrial taxa were based on the sum of trees, shrubs, herbs and grasses. Cyperaceae (paludal) and Pterydophytes (*Blechnum* type) taxa percentages were calculated from a supersum that included the basic pollen sum and the sum paludal taxa or the sum ferns, respectively. CONISS cluster analysis (Grimm, 1987) was performed to divide the sequence in zones of similar pollen composition, considering all local terrestrial pollen taxa > 2 %.

Macroscopic charcoal particles were analyzed to reconstruct the local fire regime at Mallín El Embudo. Two cm^3 of sediment at contiguous 1 cm intervals were sieved through 125 and 250 µm mesh following methods outlined by Whitlock and Larsen (2001). Both charcoal fractions (125 and 250 µm) were tallied in gridded Petri dishes and identified at 10–40× magnification under stereomicroscope. Grass particles were differentiated from wood charcoal based on the reference charcoal samples from the study area and published references (Umbanhowar and Mcgrath, 1998; Enache and Cumming, 2006). Charcoal concentration (particles cm^{-3}) was calculated from raw data and then interpolated to 16 yr bins (median temporal resolution of the record; yr $sample^{-1}$) using the Charanalysis Software (Higuera et al., 2009, 2010) to calculate charcoal accumulation rate (CHAR; particles $cm^{-2}\,yr^{-1}$). Two components from the charcoal series were distinguished: the background component (Cback; extra-local or regional fire signal and secondary charcoal deposited in years without fires) and the peak component (Cpeak; local fire episode signal) (Long et al., 1998; Higuera et al., 2007). The Cback was calculated applying a regression method of locally weighted scatterplot smoothing (LOWESS) robust to outliers considering a window width of 1000 yr which allowed to maximize the signal to noise index and the goodness-of-fit (*P* value) between the empirical and modeled noise distributions (Higuera et al., 2009, 2010). The Cpeak was calculated as the difference between Cback and the CHAR interpolated. Given that the Cpeak presents a noise component, a Gaussian mixture model was used to identify the noise of the distribution choosing the 95th percentile. The 95th percentile is more suitable to detect small peaks in charcoal records from *mallines* given that otherwise they would be included within the background component (e.g. Holz et al., 2012). Besides, the fire-episode magnitude (cm^{-2} $peak^{-1}$) based on a 1000 yr moving window and the fire-episode frequency were calculated. A grass-to-total charcoal ratio based on the CHAR values was calculated to analyze the severity of fires. High ratio values (low severity, > 0.5) reflect surface fires whereas low grass-to-total charcoal ratio values (high severity, < 0.5) indicate crown fires (Whitlock et al., 2006).

4 Results

4.1 Stratigraphy and chronology

An 844 cm-long composite sediment core from Mallín El Embudo was obtained by overlapping cores EE0110B1 and EE0110A2-A10 (Fig. 2) based on the LOI data correlation. The composite core consists of grey clays (817–844 cm) related to an ice-dammed lake, gyttja (813–817 cm) associated with organic lacustrine sedimentation and peat from 813 cm to the top associated with the development of a *mallín*. Seven clastic layers are intermingled within the peat: four tephra layers (a, 170–176 cm; b, 246–274 cm; h, 552–553 cm; j, 741–742 cm) and three siliciclastic (sandy-silt) layers (c–f, 384–407 cm; g, 525–532 cm; l, 686–687 cm) (Fig. 2). Microscopic volcanic particle analysis together to the stratigraphic/chronologic position of tephra layers indicates the likely possible

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tephra source volcanoes and eruptions are Melimoyu (MEL 2 < 1750 ± 80 ^{14}C yr BP, layer a), Hudson (H_2 ∼ 3600 ± 200 ^{14}C yr BP; Naranjo and Stern, 1998; layer b) Mentolat (MEN 1, layer h) and some volcano from the Liquiñe-Ofqui fault zone (layer j) (Stern, personal communication, 2013).

Loss-on-ignition data mirror the lithological changes from Mallín El Embudo core (Fig. 2). Organic percentages show a major change from 5 % associated with the grey clays (817–844 cm) and 15 % corresponding to gyttja to values relatively constant over 85 % associated with peat (0–813 cm). Significant decrease of organic percentages ranging from 5 to 60 % and represented as maximum peaks of inorganic content (g cm^{-3}) reflect the clastic (tephra and siliciclastic) layers intermingled with the peat.

The age-depth model of Mallín El Embudo (Fig. 3) suggests a continuous deposition since 13 ka but some sedimentation rate variations are found along the core. The highest sedimentation rates (1.3 and 0.6 cm yr^{-1}) are recorded around 11.2 and 0.1 ka whereas the lowest (0.03 cm yr^{-1}) at 2 ka. On the contrary, the record resolution varies between 3 yr cm^{-1} at 11.2 ka and 0.1 ka to 36 yr cm^{-1} around 2 ka.

4.2 Pollen record

The pollen record from Mallín El Embudo is presented in Fig. 4 showing the dominant taxa percentages. Pollen zones (EE1–6) were defined by CONISS results and ecological criteria.

Zone EE1 (13–11.2 ka; 813–720 cm depth) is dominated by Poaceae (90–40 %) along with Valerianaceae (*Valerianella* type, 30–5 %), *Empetrum rubrum* (< 5 %), Asteraceae subf. Asteroideae (*Chiliotrichum* included, < 5 %) and *Acaena* (< 5 %). Local forest taxa percentages such as *Nothofagus dombeyi* type, *Misodendron* and *Escallonia* as well as long distance taxa such as *Podocarpus* remain below 25 %. Cyperaceae percentages range between 80–30 % whereas Polypodiaceae (*Blechnum* type) shows its maximum percentages around 80 %, towards the top of this zone.

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Zone EE2 (11.2–9.5 ka; 720–580 cm depth) is characterized by a major increase of *Nothofagus dombeyi* type over 35 % that reach maximum values (75 %) around 11.1 and 10.2 ka. Simultaneously, a concomitant decrease of Poaceae (45–10 %) and Valerianaceae (*Valerianella* type, < 10 %) is recorded. Other forest taxa such as *Misodendron*, *Escallonia* and *Podocarpus* remain below 10 % whereas percentages of shrubs like Asteraceae subf. Asteroideae (*Chiliotrichum* included, < 10 %) and herbs represented by Rubiaceae (*Galium* type, < 20 %) and *Gentianella magellanica* (< 5 %) increase. Cyperaceae values are the highest for the whole record fluctuating from 30 to 90 %, whereas Polypodiaceae (Blechnum type) values abruptly decrease below 30 %.

Zone EE3 (9.5–4.2 ka; 580–260 cm depth) shows relatively constant percentages of *Nothofagus dombeyi* type (85–55 %) associated with other forest taxa such as *Misodendron* (< 10 %), *Escallonia* (< 15 %), *Podocarpus* (< 10 %). Poaceae values decrease up to 25–5 % whereas Asteraceae subf. Asteroideae (*Chiliotrichum* included, < 10 %) and *Gentianella magellanica* (< 5 %) percentages remain similar to Zone EE2. A slight decrease of *Nothofagus dombeyi* type (~ 70 %) and increase of Escallonia, Poaceae and Asteraceae subf. Asteroideae (*Chiliotrichum* included) is recorded since 5.7 ka. Cyperaceae shows a gradual decreasing trend from the base to the top of EE3, whereas Polypodiaceae (*Blechnum* type) diminishes to minimum values around 9 ka increasing again at the end of this zone around 5.7 ka.

Zone EE4 (4.2–2.1 ka; 260–173 cm depth) exhibits a major decrease of *Nothofagus dombeyi* type (55–35 %) coupled with an increase of Poaceae (55–25 %) and Rubiaceae (*Galium* type, < 10 %) and a discrete peak of *Escallonia* up to 25 % (3.9 ka). *Misodendron* (< 5 %), *Podocarpus* (< 5 %) and Asteraceae subf. Asteroideae (*Chiliotrichum* included, < 5 %) remain steady. Cyperaceae values increase at 3.9 ka from 20 % up to 60 % around 2.8 ka and decrease (25 %) to the end of the zone whereas Polypodiaceae (*Blechnum* type) declines to minimum percentages at the base of EE4.

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Zone EE5 (2.1–0.1 ka; 173–7 cm depth) is characterized by an increase of *Nothofagus dombeyi* type (85–55 %) associated with a Poaceae (20–5 %) decrease. Gunnera (< 5 %), Escallonia (< 15 %), Asteraceae subf. Asteroideae (*Chiliotrichum* included, < 5 %), Rubiaceae (*Galium* type, < 10 %) values increase since 0.4 ka whereas *Misodendron* (< 5 %) and *Podocarpus* (< 5 %) percentages diminish to the top of this zone. Cyperaceae values fluctuate between 40–10 %, showing minimum values around 1.9 and 0.5 ka.

Zone EE6 (0.1 ka–present; 7–0 cm depth) presents a prominent decrease of *Nothofagus dombeyi* type (30–20 %) coupled with an increase of Poaceae (~ 60 %). No major changes of minor accompanying taxa such as *Misodendron* (< 5 %), *Escallonia* (~ 10 %), *Podocarpus* (< 5 %) occur whereas Cyperaceae percentages peak reaching up to 50 %.

4.3 Charcoal record

Mallín El Embudo record shows millennial-scale trends with highly variable total Charcoal Accumulation Rates (CHAR) and low background charcoal values (Fig. 5). A high signal-to-noise index (global SNI = 10.3) allowed to separate the noise from the fire episodes (49 events) with a high confidence level.

From 13 up to 10.5 ka BP, the record suggests high magnitude of fires and maximum fire episode frequency (up to seven fires/1000 yr). Low grass-to-total charcoal ratio indicates high severity episodes related to crown fires.

The number of fire peaks decreases between 10.5 and 8.2 ka BP but the magnitude remains still high whereas fire-episode frequency declines to less than 3 events/1000 yr. The grass-to-total charcoal ratio increases moderately remaining below 0.5 and suggesting the prevalence of crown fires.

From 8.2 to 3.8 ka BP, the record is characterized by an increasing CHAR trend showing high fire-episode frequency (> 4 fires/1000 yr) and high fire magnitude cen-

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tered around 4.5–3.8 ka. A moderate grass-to-total charcoal ratio rises towards 3.8 ka suggesting surface fires increment.

Between 3.8 and 0.4 ka BP, the fire-episode frequency and magnitude decline except for the 3 ka peak. After 1.5 ka, the grass-to-total-charcoal ratio increases showing highly variable values that suggest a transition from high to low severity fires.

The last 0.4 yr are characterized by high CHAR values and high fire-episode frequency; however variable peak magnitudes and higher grass-to-total charcoal ratio suggest surface fires (low severity).

5 Discussion

5.1 Mallín El Embudo

5.1.1 Environmental reconstruction

The sedimentary and local pollen taxa record of Mallín El Embudo (Figs. 2 and 4) reveals three different depositional environments: (1) grey clays associated with low organic percentages reflect that Mallín El Embudo basin was flooded by a proglacial lake that would have occupied the mRCv before 13 ka; (2) lacustrine organic mud (gyttja) related to an increase in organic percentages together with a rise in Cyperaceae values and the absence of aquatic taxa between 13–12.8 ka indicate the brief development of a shallow lake phase and; (3) the presence of decomposed peat associated with maximum organic percentages and the continuous presence of Cyperaceae suggest the development of a *mallín* similar to the present one since 12.8 ka.

5.1.2 Vegetation and fire dynamics

Mallín El Embudo pollen record reflects a highly dynamic history of vegetation in the middle Río Cisnes valley (mRCv) since 13 ka (Fig. 4).

Open landscapes dominated by grasses (Poaceae) accompanied by herbs (Valerianaceae) and shrubs (Asteraceae subf. Asteroideae (Chiliotrichum included), *Empetrum*) and isolated *Nothofagus* patches prevail in the mRCv between 13 and 11.2 ka (Fig. 4). Modern pollen surveys at Southern Patagonia (50° S) show that similar pollen assemblages reflect grass steppe presence under mean annual precipitation lower than 500 mm (Mancini et al., 2012). *Nothofagus* percentages would reflect pollen locally produced within the forest patches but also long distance transport from the deciduous and evergreen *Nothofagus* forest located to the west, along the Pacific coast or at Chonos Archipelago (Montade et al., 2013; Haberle and Bennett, 2004; Bennett et al., 2000). *Acaena* presence indicates ground soil conditions under still unstable postglacial landscapes in the mRCv by this time (Fig. 4). These pollen assemblages point out therefore lower effective moisture (drier and colder conditions) than present under but also reflect that landscape configuration after glacial retreat in the RCv was still ongoing. On the other hand, ferns (Pteridophytes, *Blechnum* type) peak and the concomitant decrease of paludal taxa (Cyperaceae) towards 11.2 ka suggest a trend towards drier local conditions in Mallín El Embudo (Fig. 4). It is probable that higher summer temperatures would have produced short term oscillations in the *mallín* water table level thus exposing larger shore areas and favoring ferns colonization at expense of paludal taxa. Besides, an increase in fire frequency around 11.2 ka (Fig. 5) supports the latter given that fire occurrence in *Nothofagus* deciduous forest at North Central Chilean Patagonia is mainly dependent today of summer droughts (Veblen et al., 2008).

A major increase of both, *Nothofagus* and its specific parasite *Misodendron*, along with a rise of understory taxa percentages like *Escallonia*, Asteraceae subf. Asteroideae (*Chiliotrichum* included), Rubiaceae (*Galium* type) and *Gentianella magellanica* (Fig. 4), indicate the development of an open *Nothofagus* forest in the mRCv between 11.2–9.5 ka. These pollen assemblages suggests an effective moisture increase but still below modern values. Cyperaceae increase and ferns sharply decrease also support the later (Fig. 4). However, highly fluctuating values of *Nothofagus* and understory taxa in this period point out a quite dynamic forest. High frequency and magnitude

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of crown fires peaking around 11.2 ka (Fig. 5) would be related to this postglacial development of the forest and hence fuel availability coupled with the establishment of seasonal climatic conditions. Thus, wet winters may have promoted the forest development whereas dry summers might have favored the drying of the fuel to be burned. High percentages of Rubiaceae (*Galium* type; Fig. 4) support the forest disturbance due to fire activity given that are known as soil-stored seed plants from the forest understory that sprout after frequent fire events (Vidal and Reif, 2011).

Between 9.5–4.2 ka, high *Nothofagus* percentages associated with low values of understory taxa and Poaceae values indicate the development of a closed forest that shifted to a more open one at 5.7 ka (Fig. 4). Simultaneously, the charcoal record indicates the occurrence of high frequency and low magnitude fires (Fig. 5). Therefore, pollen assemblages and charcoal record suggest an increase in effective moisture under seasonal equable climatic conditions. It is probable that the development of a closed forest (high fuel availability) together with a gentle dry season may have triggered persistent but low magnitude crown fires that did not severely affect the forest. Around 5.7 ka, a decrease in *Nothofagus* percentages associated with increased values of *Escallonia*, Poaceae and Asteraceae subf. Asteroideae (*Chiliotrichum* included) suggest a slight opening of the forest canopy concomitant with a decrease of Cyperaceae values and increased ferns percentages that peak around 4.2 ka (Fig. 4). Thus, *mallín* local indicators trends associated to an increase of understory forest taxa at the expense of trees which suggest a more open forest canopy indicate a slight decrease of effective moisture between 5.7–4.2 ka.

A major *Nothogafus* and *Misodendron* percentage decrease together with the increase of understory taxa such as Asteraceae subf. Asteroideae (*Chiliotrichum* included), Rubiaceae (*Galium* type) and Poaceae between 4.2–2 ka (Fig. 4) indicates a sudden vegetation change to open forest conditions. This change is concomitant with an increase in the frequency of high magnitude of severe fires (crown fires; Fig. 5) and is preceded by the H_2 eruption tephra layer deposition. Even though this vegetation change would have actually begun around 5.7 ka and climatically driven (as explained

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above), the high fire activity and the tephra deposition may have enhanced its magnitude. However, the relative contribution of climate, fire and volcanism is really difficult to identify since the slight trend towards drier conditions, high fire activity and ash fall deposition would result in a similar forest change. Vegetation changes related to ash fall deposition around Patagonia have been recorded as canopy opening (death of the tree stratum) concomitant with the appearance of different understory pioneer taxa that point out first successional stages (Fesq-Martin et al., 2004; Jara and Moreno, 2012; Haberle and Bennett, 2004; Markgraf et al., 2007). Volcanic disturbances effect (up to total environment recovery) appear to last from 80 (Jara and Moreno, 2012) to 2000 yr (Kilian et al., 2006) since the ash fall and seem to be related to the magnitude of the volcanic deposit and the forest dynamics.

A trend to less severe fires in the mRCV between 4.2–3 ka (Fig. 5) would respond to a major development of understory vegetation at expenses of the tree stratum highly affected by crown fires during the previous millennium. Since 2 ka, *Nothofagus* percentages increase pointing out the presence of a closed forest but more open from that of the early/mid-Holocene as indicated by the higher percentages of *Escallonia* and Poaceae (Fig. 4). These pollen assemblages suggest the establishment of modern climatic conditions but probably associated with interannual or interdecadal fluctuations in moisture given that the increased occurrence of less severe fires (surface fires) is conditioned by short-term fluctuations in moisture favoring fuel growing and later desiccation to be burned (Veblen et al., 2003). On the other hand, hunter-gatherer occupations have been recorded at different locations along the whole RCv since 2.8 ka (Méndez and Reyes, 2008), thus fire regime changes by this time may have been also associated with human agency. Since 0.4 ka, a quite dynamic forest occurred (open to close forest shift and vice versa) represented by highly variable *Nothofagus* percentages as well as the presence of understory taxa and grasses related to an increase in the frequency of less severe fires (Fig. 4).

The last 0.1 ka are characterized by an abrupt decline of *Nothofagus* at expense of Poaceae (Fig. 4) reflecting the clearance of the forest during the European colonization.

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Historical chronicles indicate that permanent settlements at the mRCv, close to Mallín El Embudo area did not establish until 1930 but logging and burning would have begun at the early 20th century when Río Cisnes Ranch was established (Martinic, 2005).

5.2 Regional environmental and palaeoclimatic dynamics since the Late Glacial

5.2.1 LGM termination

An early deglaciation timing (ca. 23–16 ka) characterizes Eastern Central Chilean Patagonia (CCP) (Douglass et al., 2006; Kaplan et al., 2004; Hein et al., 2010) if compared to the proposed age for the Patagonian Ice Cap deglaciation onset after the first warming pulse around 17.5 ka (McCulloch et al., 2000). Thus, the basal ages and the beginning of organic sedimentation from Lago Shaman (19 ka; de Porras et al., 2012) and Mallín Pollux (18 ka; Markgraf et al., 2007) evidence that Eastern CCP areas were free of ice by 19–18 ka whereas glacial retreatment associated with a proglacial lake at Lago Augusta area (47° S; Fig. 1a) occurred ∼2 ka later (16 ka) probably due to its southern location. Ice retreat at Western CCP (Chonos Archipelago and Taitao Peninsula; Haberle and Bennet, 2004) occurred around 17.5–16.5 ka.

Pollen records from Eastern CCP (Lago Shaman, de Porras et al., 2012; and Mallín Pollux, Markgraf et al., 2007) indicate the development of grass-shrub steppes between 19–15 ka (Fig. 6). On the contrary, the pollen record of Lago Augusta was interpreted as showing local scattered low-density populations of evergreen *Nothofagus* (probably *N. betuloides*) in an open landscape dominated by Poaceae and Ericaceae between 16–15.6 ka (Fig. 6; Villa-Martínez et al., 2012). These authors discussed that the evergreen forest signal is local and not attributable to long-distance transport from forests located at Western CCP and proposed that similar pollen assemblages found at Mallín Pollux record (and interpreted as extra-local signal by Markgraf et al., 2007) would also reflect local development isolated patches of evergreen forest. However, modern pollen assemblages from the evergreen *Nothofagus* forest (Haberle and Bennet, 2001) and a transect along the Río Cisnes valley (44°30′ S; Maldonado, unpublished

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data) indicate that the percentages of evergreen forest taxa (< 10 %) found in Lago Augusta, Mallín Pollux and Lago Shaman records during early deglaciation stages may reflect long-distance transport, probably from forest refugia located along the Pacific coast (Montade et al., 2013; Haberle and Bennett, 2004; see discussion below). Besides, pollen assemblages of Lago Augusta dominated by Poaceae associated with steppe taxa like Ericaceae, *Acaena*, Asteraceae subf. Asteroideae, Caryophyllaceae and *Perezia*-type between 16–15.6 ka are quite similar to those recorded at Mallín Pollux and Lago Shaman (Fig. 6) and interpreted as grass-shrub steppes.

In Western CCP, Taitao Peninsula and Chonos Archipelago (Bennett et al., 2000) pollen records show the development of Ericaceae heathlands and grasslands after deglaciation whereas the pollen record from a marine core offshore Taitao Peninsula (MD07-3088, Fig. 1a) reflects the predominance of scatter vegetation (parkland like) dominated by *Nothofagus* associated with Poaceae, *Gunnera*, Asteraceae and Ranunculaceae along the Chilean coast around 22–17.6 ka (Fig. 6; Montade et al; 2013). A rapid expansion of forest after deglaciation in Taitao Peninsula and Chonos Archipelago and the pollen signal of *Nothofagus* parkland up to 17.6 ka at MD07-3088 record suggest the presence of forest refugia during the LGM along the western coastal margin probably partially free of ice (Haberle and Bennett, 2004; Montade et al; 2013).

Vegetation in CCP reflects therefore colder and drier climatic conditions than present during LGM termination. These palaeoecological inferences coincide with the low values of the Smectite/Illite + Chlorite index from MD07-3088 marine core which suggest lower precipitation than present between 19–15 ka (Fig. 6; Siani et al., 2010). Taken together, the palaeoecological and glaciological data from CCP support the hypothesis of an equatorward Southern Westerlies (SW) LGM position around 41° S (e.g. Markgraf, 1989; Rojas et al., 2009).

5.2.2 Deglaciation

Evidence of cold reversal events like Antarctic Cold Reversal (ACR; 14.5–12.8 ka) and Younger Dryas (YD; 13–11.2 ka) at Central Chilean Patagonia is scarce and inconclusive. A late glacial readvance represented by the Menucos moraine at Lago Buenos Aires/Lago General Carrera (46° S, Fig. 1a) around 14 ka (Fig. 6; Douglass et al., 2006) and a frontal moraine at the middle Río Cisnes Valley (Fig. 1b) indirectly dated ~ 13 ka occur simultaneously with the ACR. However, recent results of glacial geomorphology at the Eastern North Patagonian Icefield (47° S) point out glacier advances synchronously with the YD chronozone (Fig. 6; Glasser et al., 2012).

ACR or YD signal are not reflected by terrestrial pollen records at Central Chilean Patagonia (Fig. 6; Bennett et al., 2000; de Porras et al., 2012; Markgraf et al., 2007; Villa-Martínez et al., 2012). Eastern CCP records point out steppe-dominated vegetation with scattered *Nothofagus* trees whereas the rain-forest development with Nothofagus, Pilgerodendron and Podocarpus occurred in Western CCP (Haberle and Bennett, 2004). CCP vegetation suggests an increase in precipitation under the warming trend that characterized deglaciation. However, a magellanic moorland expansion between 14.5–12.8 ka reflected in MD07-3088 pollen record and an Smectite/Illite + Chlorite index increase (Fig. 6) were interpreted as an increase in precipitation and slight cooling (or a pause of warming) that is synchronic to the ACR (Montade et al., 2013; Siani et al., 2010).

In summary, the inconclusive evidence regarding ACR or YD reflection at CCP pin points a new issue that needs further multi-proxy research. Based on the terrestrial and marine pollen records evidence, two possible SW scenarios were stated. On one hand, terrestrial records support the idea of a southward migration of SW up to its modern position about 1.5 ka after LGM termination (Markgraf et al., 1992). On the other hand, marine record changes would reflect a northward shift of SW or a latitudinal broadening of its latitudinal influence (Montade et al., 2013).

5.2.3 Early Holocene

Around 11.5 ka, Central Chilean Patagonia records show a trend towards similar to modern environments pointing out the onset of the Holocene. Eastern CCP records show the gradual development of *Nothofagus* deciduous forest (Mallín El Embudo;

Mallín Pollux, Markgraf et al., 2007; Lago Augusta, Villa-Martínez et al., 2012) or the *Nothofagus* forest- grass steppe ecotone (Lago Shaman) whereas evergreen *Nothofagus* forest with *Podocarpus*, *Pilgerodendron* and *Tepualia* established at Taitao Peninsula and Chonos Archipelago in Western Central Chilean Patagonia (Fig. 6). The development of these plant communities suggests an increase in precipitation but still under modern values. The increase of *Tepualia* and *Weinmannia* (heliophytic taxa) at expense of cold-tolerant taxa at Taitao Peninsula and Chonos Archipelago forest, also recorded at MD07-3088 core (Fig. 6), suggests warmer conditions since ~ 11.7 ka. Besides, simultaneous local changes at Eastern CCP records reflected as a fern peak (Mallín El Embudo), sudden dominance of paludal over aquatic taxa (Lago Shaman and Mallín Pollux) and the presence of laminated carbonates (higher evaporation rates; Lago Augusta) point out increased summer temperatures around 11.5 ka.

Charcoal data indicate that the early Holocene was characterized by a high fire-episode frequency at Eastern (Mallín El Embudo, Mallín Pollux, Lago Shaman) or Western (Taitao Peninsula) CCP (Fig. 6). This pattern correlates to that found at most Patagonian charcoal records south of 40° S which show a widespread fire-activity (positive anomalies) between 12–8 ka that was related to climatic drivers (Fig. 6; Whitlock et al., 2006; Moreno et al., 2010b; Power et al., 2008). However, the widespread presence of humans at the eastern flank of the Andes during this period (Méndez, 2013) implies that they should be also considered as a possible ignition agent contributing to the increased fire activity.

In combination, vegetation and charcoal records point out a slight increase in precipitation and increased summer temperatures. This climatic scenario would be due to weaker and poleward shifted SW as a consequence of a reduction in the latitudinal temperature gradient driven by higher-than-present insolation in southern high latitudes (de Porras et al., 2012; Liu et al., 2003; Whitlock et al., 2006).

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5.2.4 Mid-Holocene

The Mid-Holocene was characterized by the establishment of similar-to-modern vegetation (de Porras et al., 2012) at CCP. Eastern CCP sites show the easternmost position of the *Nothofagus* forest-steppe ecotone (Lago Shaman) and the closest deciduous forest development (Mallín El Embudo and Mallín Pollux) during the whole Holocene (Fig. 6). Evergreen forest of *Nothofagus*, *Pilgerodendron* and *Tepualia* established around 7.6 ka at Chonos Archipelago and Taitao Peninsula and persisted until the present (Fig. 6; Haberle and Bennett, 2004).

Charcoal records from Eastern CCP sites point out low-to-moderate frequency of fires but characterized by low magnitude episodes during the Mid-Holocene. As explained for Mallín El Embudo (see Sect. 5.1.2), fuel availability would have been abundant but a gentle dry season (wet summers) may have trigger persistent but low magnitude fires that did not severely affect the forests.

Taken together, pollen and charcoal records from CCP suggest wetter conditions than present coupled to seasonally equable conditions which match with increasing values of the Smectite/Illite + Chlorite index (MD07-3088 core) that also suggest a slight gradual increase of precipitation (Fig. 6; Siani et al., 2010).

The synchronous increase in precipitation in CCP as well as in Northern (e.g. Abarzúa et al., 2004; Moreno, 2004; Moreno and León, 2003) and Southern Patagonia (e.g. Moreno et al., 2010a) reflects an intensification of the Southern Westerlies during the mid-Holocene that will be due to a steepening of the pole-equator ocean gradient around 6 ka according to climate modeling results (Rojas and Moreno, 2009).

5.2.5 Late Holocene

The Late Holocene (5 ka to the present) was characterized by an apparent breakdown in synchronicity of vegetation and fire dynamics between Western and Eastern CCP records (except for Lago Augusta) (Fig. 6). Whilst western records do not show major changes since the mid-Holocene, eastern sites reflect a quite dynamic picture

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(Fig. 6). A sudden opening of the deciduous forest canopy occurred synchronously around ~ 4.2–4.0 ka at Mallín El Embudo and Mallín Pollux (Markgraf et al., 2007) apparently climatically driven (due to a trend to drier conditions since 5.7 ka) but probably enhanced by the H_2 tephra deposition and high fire activity. The combined effect of climate, ash deposition and fire on vegetation seems to have lasted up to 2 ka when both records show the recovery of the deciduous forest. A retraction of the forest-steppe ecotone is recorded at Lago Shaman record between 3–1.3 ka and associated to high fire activity.

High fire activity characterized most Eastern CCP records during the Late Holocene although asynchronies among records are evident (Fig. 6). This asynchronies could be related to the complex climate–fire–vegetation relationships occurring at the different vegetation units, but also as a consequence of widespread and recurrent human activity recorded at Central Chilean Patagonia through the late Holocene (Méndez and Reyes, 2008; Méndez et al., 2011, 2012; Mena and Stafford, 2006). CCP high fire occurrence during the Late Holocene does not match to the regional fire pattern (Fig. 6; Power et al., 2008) but is consistent with the fire dynamics regionalization proposed by Whitlock et al. (2006).

In summary, terrestrial and marine (Smectite/Illite + Chlorite index) records suggest the establishment of slightly drier conditions than during the Mid-Holocene around 5 ka (de Porras et al., 2012; Siani et al., 2010). About 2 ka, the recovery of the deciduous forest at CCP (Mallín El Embudo and Mallín Pollux records, Fig. 6) suggests a shift to slightly wetter conditions than before and similar to the present ones under interannual or decadal climatic variability evidenced by the occurrence of surface fires which are actually conditioned by short scale moisture variability (Veblen et al., 2003).

The Late Holocene high climatic variability at CCP has been attributed to the effect of short climatic variability sources such as El Niño Southern Oscillation (ENSO) or the Southern Annular Mode (SAM) (Markgraf et al., 2007; Haberle and Bennett, 2004; de Porras et al., 2012). Both of them play a role in altering temperatures and precipitation amount and distribution at seasonal to interannual timescales through changes in the

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strength and latitudinal position of the Southern Westerlies (Garreaud et al., 2009). Even though palaeorecords from CCP show a high variability during the late Holocene, they fail to show environmental and climatic changes in such short scale given their millennial-centennial scale resolution.

Finally, during the last century (0.1 ka), major vegetation changes are recorded at almost all sites at Central Chilean Patagonia associated with the European settlement (Fig. 6; Martinic, 2005). Forest clearance to widen grazing areas through burning and/or logging like recorded in Mallín El Embudo (Szeicz et al., 2003; Haberle and Bennett, 2004; Markgraf et al., 2007) or irreversible succesional processes at grasslands characterized by the replacement of perennial grasses by shrubs due to overgrazing as inferred from Lago Shaman record (de Porras et al., 2012) are recorded across Central Patagonia.

6 Conclusions

Mallín El Embudo pollen and charcoal records demonstrate that vegetation changes at millennial scale since Late Glacial are mainly climatically driven but fire and volcanic disturbances play also a central role in the forest dynamics during the Holocene. Open landscapes dominated by grasses associated with scattered *Nothofagus* forest patches dominated middle Río Cisnes valley up to 11.2 ka when the development of an open *Nothofagus* forest related to high fire activity began. At 9.5 ka, the presence of a closed forest that experimented a slightly canopy opening since 5.7 ka followed by a sudden change around 4.2 ka associated to fire and volcanic disturbances occured. The recovery of an open *Nothofagus* forest related to slight wetter conditions was present around 2 ka and persisted under highly variable climatic conditions up to 0.1 ka when massive forest burning and logging due to European settlements occurred.

The regional integration of terrestrial and marine records allowed to shed light onto the unclear issues and provided a unified view of the environmental and climatic dynamics Central Chilean Patagonia since the Late Glacial.

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In our view, eastern records reflect grass-shrub steppes indicating cold and dry conditions at LGM termination. Evergreen forest element values indicate long dispersal transport from western areas such as free-ice continental areas along the Pacific coast. Therefore, lower effective moisture than present is inferred based on terrestrial pollen records from Mallín Pollux, Lago Shaman and Lago Augusta and supported by the pollen and geochemical record from marine core MD07-3088.

On the other hand, Late Holocene environmental dynamics seems to be mainly climatically driven but disturbances such as volcanic activity, fire and humans (as ignition agents) emerge as crucial to complete the picture. However, high pollen resolution (centennial, decadal, annual scales) records from appropriately located sites at Eastern Central Chilean Patagonia are needed to better address the magnitude, direction and timing of vegetation changes due to the different drivers. Besides, Late Holocene fire asynchronies across CCP should be carefully compared to the archaeological record given that the "random" fire patterns could be more related to human behavior than to the variable relationships between climate–vegetation–fire.

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Table 1. AMS radiocarbon dates from composite core EE0110 from Mallín El Embudo.

Lab Code	Sample	Material	Accumulated depth (cm)	Age (^{14}C yr BP $\pm 1\sigma$ error)	δ^{13}C (‰)	Age (cal yr BP)
UGAMS 13761	EE0110BT1 25–26	seeds	25	140 ± 20	−26.6	94
UGAMS 13756	EE0110AT2 9–10	seeds	62	1200 ± 30	−27.2	1043
UGAMS14918	EE0110AT3 5–6	charcoal	154	1610 ± 40	−26,4	1453
UGAMS 13757	EE0110AT3 13–14	plant macroremains	162	1860 ± 20	−28.7	1743
AA96425	EE0110AT4 27–28	peat	266	4076 ± 40	−30.3	4492
UGAMS 13759	EE0110AT7 69–70	wood	585	8670 ± 30	−27.7	9567
UGAMS 13760	EE0110AT8 86–87	peat	699	9720 ± 30	−27.9	11 179
AA96426	EE0110AT9 27–28	bulk sediment	740	9879 ± 69	−26.9	11 302
UGAMS 8375	EE0110At9 96–97	gyttja	809	11 100 ± 35	−28.6	12 997

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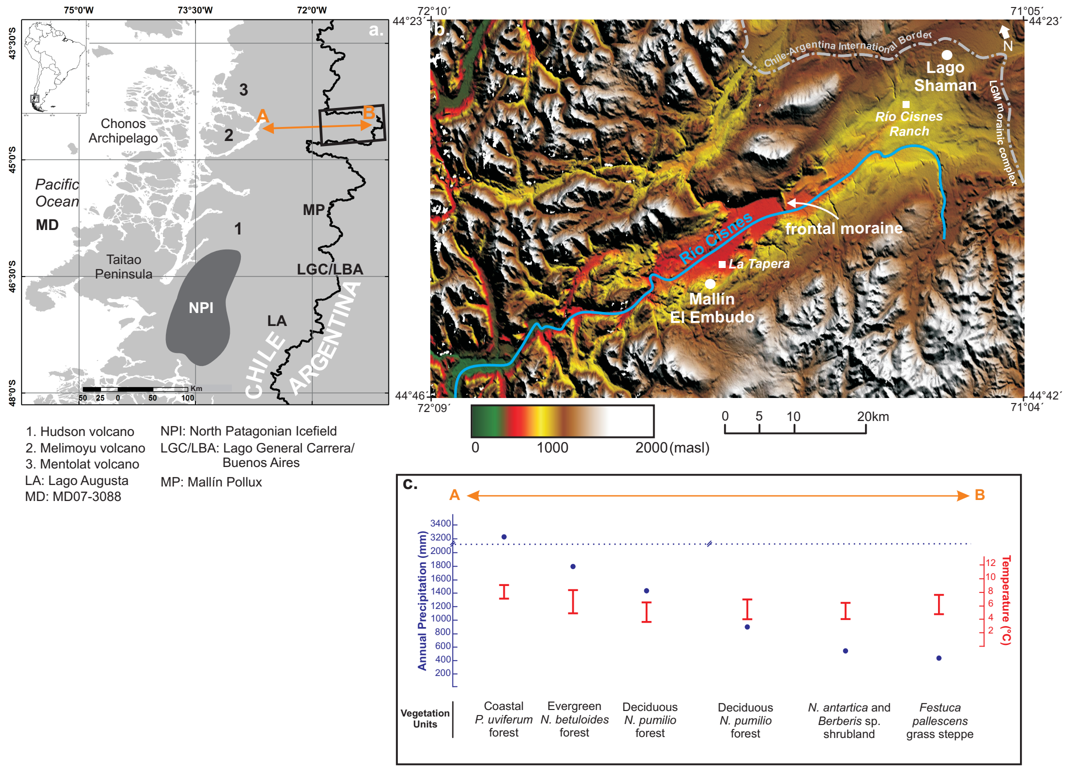

Fig. 1. (a) Map showing location of Río Cisnes valley (black square) and sites mentioned in the text; **(b)** upper and middle Río Cisnes valley Digital Elevation Model (DEM) showing location of Mallín El Embudo and major geomorphological features; **(c)** mean annual precipitation, mean temperature and major vegetation along a west–east transect within the Río Cisnes valley (A–B).

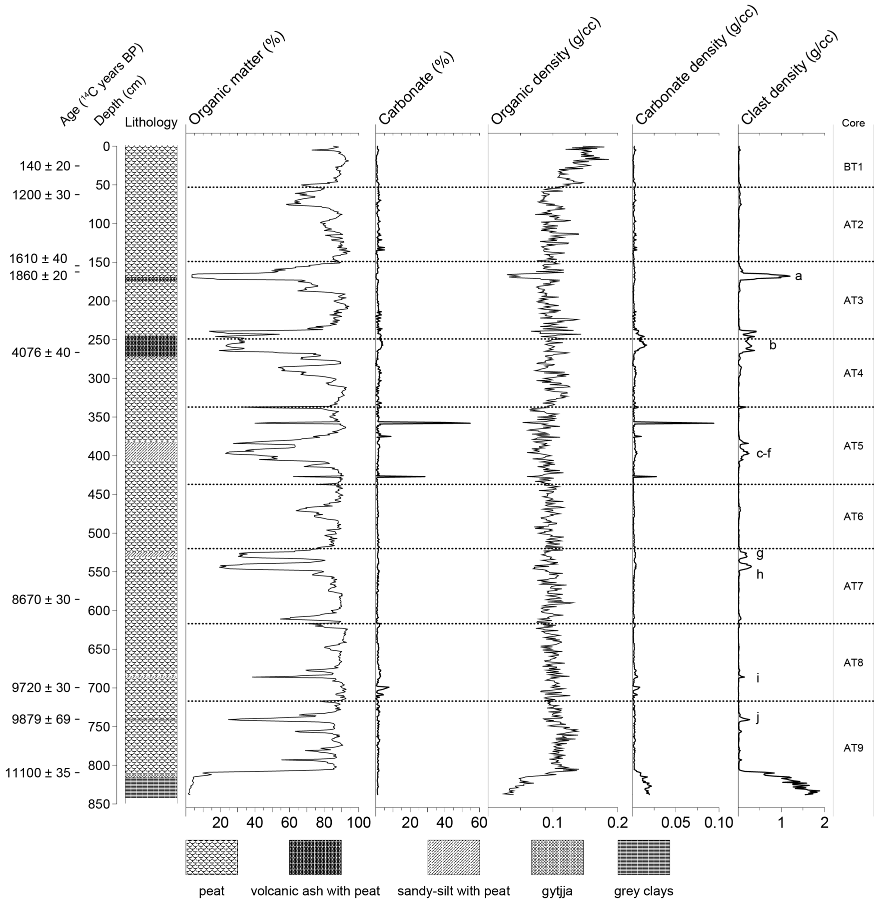

Fig. 2. Stratigraphic column of Mallín El Embudo composite core, radiocarbon dates and loss on ignition results. Letters represent clastic layers and dashed horizontal lines indicate the core segment boundaries.

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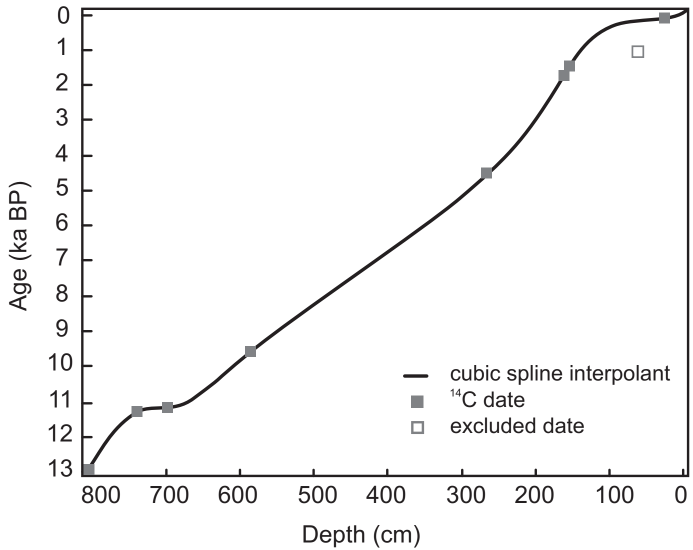

Fig. 3. Age-depth model from Mallín El Embudo based on eight calibrated AMS radiocarbon dates. Date excluded from the age-depth model is represented as an open square.

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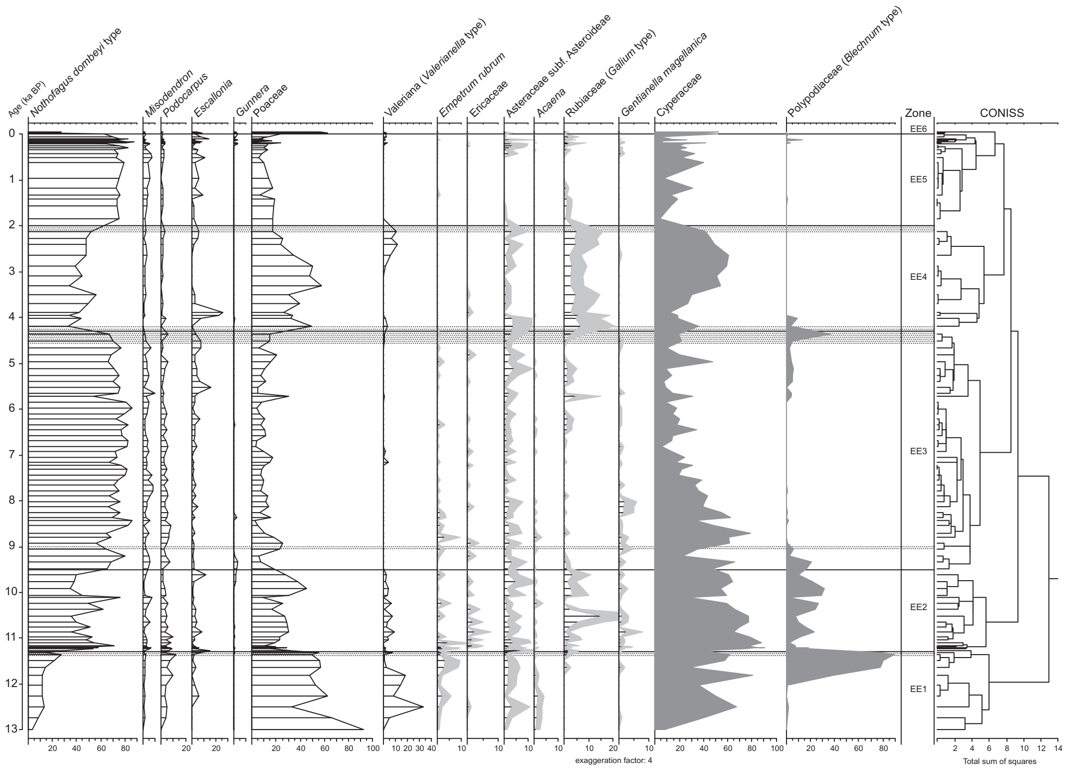

Fig. 4. Percentage pollen diagram of Mallín El Embudo showing dominant taxa and CONISS. Grey horizontal bands represent tephra layers.

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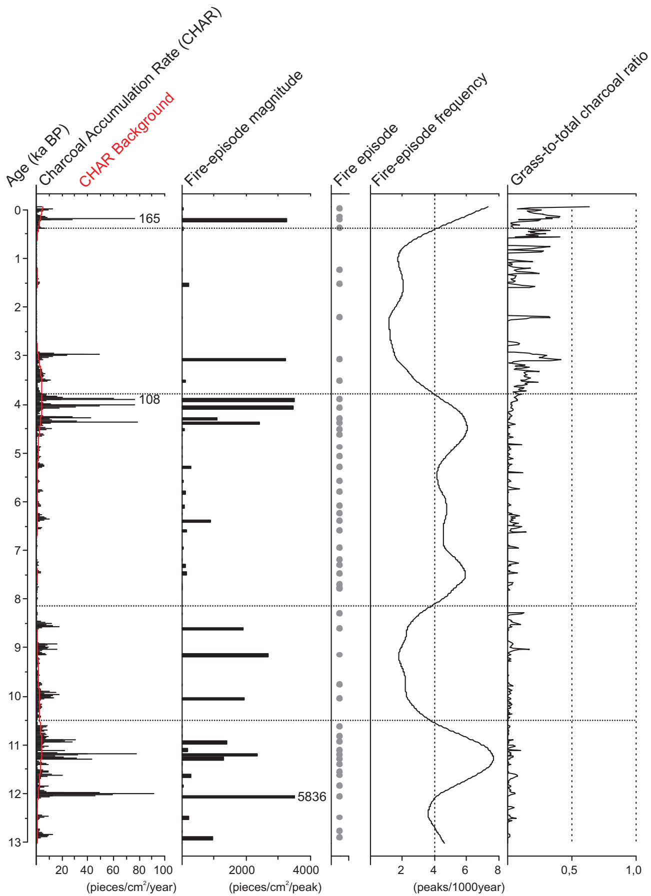

Fig. 5. Charcoal record from Mallín El Embudo including Charcoal Accumulation Rates (CHAR), magnitude, fire episodes, frequency and grass-to-total charcoal ratio. The horizontal lines show the division of the record according to fire regime changes.

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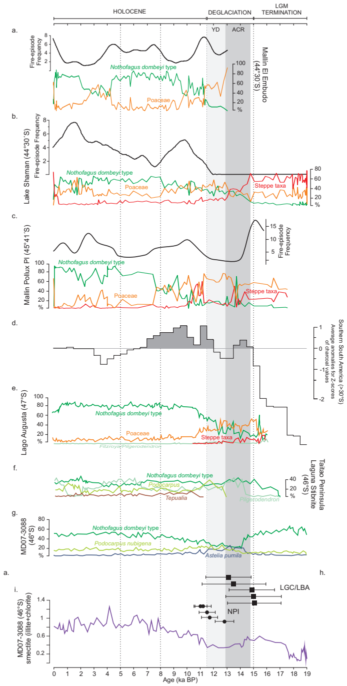

Fig. 6. Integration of selected palaeoenvironmental data from Central Chilean Patagonia since Late Glacial showing fire-episode frequency curve and summarized pollen diagram (%) from **(a)** Mallín El Embudo, **(b)** Lago Shaman (de Porras et al., 2012) and **(c)** Mallín Pollux (Markgraf et al., 2007); **(d)** summary of palaeofire activity in Western South America (> 30° S, Power et al., 2008); summarized pollen diagram (%) from **(e)** Lago Augusta (Villa-Martinez et al., 2012); **(f)** Laguna Stibnite (Bennett et al., 2000) and **(g)** MD07-3088 marine core (Montade et al., 2013); **(h)** surface exposure ages of Late Glacial moraines at LBA/LGC (Douglass et al., 2006) and NPI (Glasser et al., 2012); **(I)** Smectite/(Illite + Chlorite) index from MD07-3088 marine core (Siani et al., 2010). Grey vertical lines represent ACR and YD chronozones.

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