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Pollen evidence for variations in the southern margin of the westerly winds in SW Patagonia over the last 12,600 years

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Abstract

We report pollen and charcoal records from Vega Ñandú (~51°0′S, 72°45′W), a small mire located near the modern forest-steppe ecotone in Torres del Paine National Park, southern Chile. The record shows an open landscape dominated by low shrubs and herbs between 12,600 and 10,800 cal yr BP, under cold and relatively humid conditions. *Nothofagus* experienced frequent, large-amplitude oscillations between 10,800 and 6800 cal yr BP, indicating recurrent transitions between shrubland/parkland environments, under warm and highly variable moisture conditions. A sustained increase in *Nothofagus* started at 6800 cal yr BP, punctuated by step-wise increases at 5100 and 2400 cal yr BP, implying further increases in precipitation. We interpret these results as indicative of variations in the amount of precipitation of westerly origin, with prominent increases at 6800, 5100, and 2400 cal yr BP. These pulses led to peak precipitation regimes during the last two millennia in this part of SW Patagonia. Our data suggest variations in the position and/or strength of the southern margin of the westerlies, most likely linked to variations in the extent and/or persistence of sea ice and sea-surface temperature anomalies in the Southern Ocean. Over the last two centuries the record shows a forest decline and expansion of *Rumex acetosella*, an exotic species indicative of European disturbance.

Keywords: Paleoclimate; Holocene; Torres del Paine; Southern Westerlies; SW Patagonia

Introduction

The westerly wind belt is an important component of the atmospheric circulation of the Southern Hemisphere, supplying the winter- or year-round precipitation from subtropical to subantarctic latitudes, respectively. Variations in the latitudinal position and intensity of the westerlies at seasonal and interannual scales cause important changes in the precipitation at the western coast of South America. These variations are controlled by high-latitude conditions and the strength and/or position of the Subtropical Anticyclone in the SE Pacific sector (Miller, 1976; Aceituno et al., 1993). South America is the only landmass in the Southern Hemisphere that intersects the entire westerly wind belt continuously. Within this region, the western coast and Andean regions of Patagonia (40°–54°S) are the only areas affected by the permanent influence of the westerly wind belt, which constitutes the primary control on the composition and distribution of the regional biota (Pisano, 1974; Miller, 1976; Weischet, 1985; Endlicher and Santana, 1988).

Previous discussion on the glacial–interglacial history of the southern westerlies in the Pacific coast of South America has centered on paleoclimate records located at or near its northern margin (Veit, 1996; Lamy et al., 2001; Jenny et al., 2002; Villa-Martínez et al., 2003; Moreno, 2004). Paleoclimatic reconstructions based on pollen and chironomid records from small, closed-basin lakes in NW Patagonia (41°–46°S) have documented changes in the latitudinal position of the northern margin of westerlies (Moreno, 2004; Massaferro et al., 2005). These studies found a multi-millennial trend in westerly activity, which includes a southward displacement of the westerlies between ~10,500 and 7500 cal yr BP, followed by a northward shift and intensification after ~7000 cal yr BP. Seismic stratigraphy, sedimentology, and geomorphological studies in Lago Cardiel (49°S), located in the eastern Andean

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slopes of central Patagonia, indicate a transgressive lake sequence that led to a deep lake with prominent shorelines 55 m above the modern elevation between ~10,800 and 7500 cal yr BP, followed by a lake-level drop and onset of an oscillatory trend with moderate high stands over the last 7000 years (Gilli et al., 2001, 2005). Because Lago Cardiel is located east of the Andean range, it is likely that past lake-level fluctuations resulted from multiple factors, including enhanced moisture from westerly, Atlantic, and polar outbreak sources. The large size of the lake and its catchment area (370 and 4500 km^2, respectively) pose an additional difficulty when deciphering the paleoclimate history based on fossil pollen data, as palynological records from large lakes integrate multiple signals of past vegetation change across geographic and climatic space, and thus yield a blurred picture of vegetation changes at fine- and meso-scales (Markgraf et al., 2003).

Because very few paleoclimate records from SW Patagonia have attempted to reconstruct the deglacial and postglacial history of the southern margin of the westerly winds, we set out to investigate this problem by means of paleovegetation records in the Torres del Paine area of SW Patagonia. Detailed pollen analysis on sediment cores obtained from a small, closed-basin site in an area affected solely by precipitation of westerly origin provides an interesting means of exploring past changes at a climate-sensitive vegetation boundary: the forest-steppe ecotone. Thus, it is expected that past variations in the strength and/or position of the southern westerlies drove changes in this important vegetation and climate benchmark. Because small closed-basin sites maximize the local environmental signal, they yield palynological/paleoclimate data with high spatial and temporal resolution that minimize the averaging or integration of extralocal signals. Small lakes and bogs are ideal for examining the temporal evolution of specific vegetation and climatic settings, in particular the highly sensitive forest-steppe ecotone in SW Patagonia.

The data from Vega Ñandú allow assessment of the following questions: What were the timing and direction of vegetation changes in SW Patagonia throughout the Holocene? Did vegetation changes occur in a gradual or abrupt manner? How did the southern margin of the westerlies vary during the Holocene? Did the southern margin of the westerlies vary in concert (timing, direction) with its northern margin during the Holocene?

Study area

The climate of southern Patagonia (50°–54°S, Fig. 1) is characterized by the permanent dominance of the westerly winds and the strong west–east precipitation gradient resulting from the rain shadow of the Andes cordillera. Annual precipitation at sea level on the Pacific coast reaches 7000 mm, while on the eastern Andean slopes precipitation declines abruptly to 350 mm within ~100 km (Miller, 1976; Romero, 1985). The distribution of plant communities in southern Patagonia closely follows this precipitation gradient (Fig. 1); consequently, the western side of the Andean Range is dominated by Magellanic Moorland communities and Magellanic evergreen forest, whereas east of the Andes the vegetation is characterized by winter-deciduous *Nothofagus* forests, which merge with the Patagonian steppe towards the east.

Vega Ñandú (50°55′58″S; 72°45′55″W; 200 m elevation) is a small mire located in the NE sector of Torres del Paine National Park, between Laguna Amarga and L. Azul (Fig. 1). The mire lies on a narrow E–W oriented ravine that runs perpendicular to the Río Paine valley, about 50 m above the valley floor, near the ecotone between *Nothofagus*-dominated forests and the Patagonian steppe. The climate in Torres del Paine has been described as transandean (Pisano, 1974), which corresponds to a transition between the extremely wet oceanic climates on the western coast and the arid, strongly continental climates east of the Andes. The principal characteristic of this climate is the abrupt eastward decline of the mean annual precipitation from 1000 to 400 mm (Fig. 1). The mean annual temperature in the Torres del Paine area is 6 °C (Pisano, 1974).

The distribution of the vegetation reflects the transitional character of the local climate in the Torres del Paine area. The following plant communities were described and mapped by Pisano (1974) along a west–east transect:

(1) Magellanic Deciduous Forests correspond to a low-density forest dominated almost exclusively by the winter-deciduous *Nothofagus pumilio* (Nothofagaceae) and occur where the annual precipitation is >750 mm. In humid sectors (>850 mm/yr), *N. pumilio* forms mixed forests with the evergreen tree *N. betuloides.* In areas with impeded drainage, *N. pumilio* commonly intermingles with *N. antarctica*. The species-poor shrub stratum develops only near the forest edges; dominant taxa are *Berberis ilicifolia* (Berberidaceae), *Ribes magellanicus* (Saxifragaceae), *Chiliotrichum diffusum* (Asteraceae), *Escallonia serrata, E. rubra* (Escalloniaceae), *Maytenus disticha* (Celastraceae), and *Embothrium coccineum* (Proteaceae). The herbaceous understory is dominated by *Acaena ovalifolia* (Rosaceae), *Ozmorhiza obtusa* (Apiaceae), *Cardamine glacialis* (Brassicaeae), and the fern *Blechnum penna-marina* (Blechnaceae).

(2) Pre-Andean shrublands are considered transitional communities between the forest and the steppe. These shrublands occur where the mean annual precipitation ranges between 400 and 700 mm. Arid sections are dominated by *Mulinum spinosum* (Apiaceae), *Anarthrophyllum desideratum*, *Adesmia boronoides* (Papilionaceae), *Ribes cucullatum, Discaria serratifolia* (Rhamnaceae), *Nardophyllum obtusifolium, Baccharis magellanica*, *Senecio patagonicus* (Asteraceae), and *Berberis buxifolia* (Berberidaceae). Other herbs associated with this unit are *Acaena intergerrima*, *Festuca gracillima* (Poaceae), *Gamochaeta nivalis* (Asteraceae), and *Valeriana carnosa* (Valeraniaceae). Humid areas (~700 mm/yr) are dominated by mesophytic shrublands featuring *Escallonia rubra*, *Adesmia boronoides*, *Discaria serratifolia*, *Berberis empetrifolia*, and *Pernettya mucronata* (Ericaceae), along with small trees such as *Embothrium coccineum*, *Maytenus*

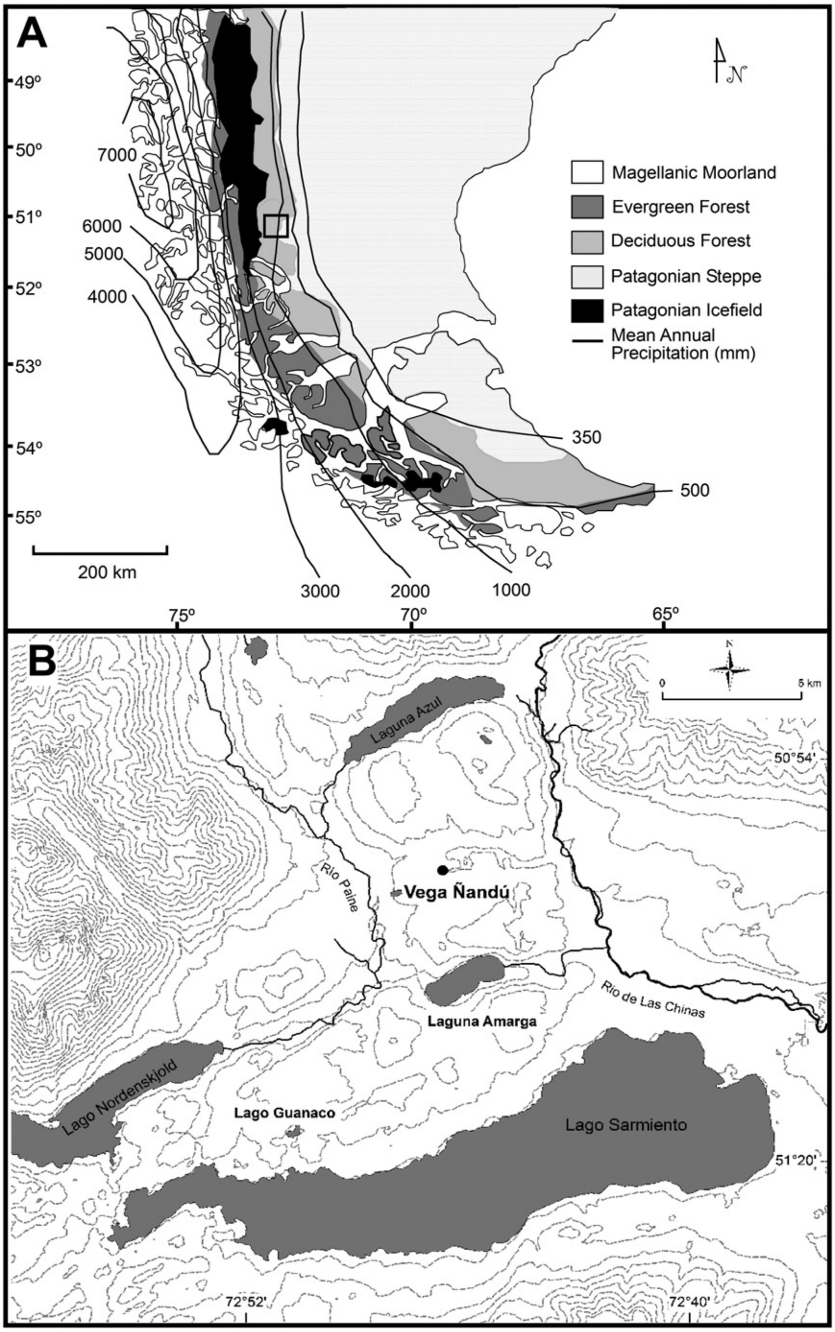

Figure 1. (A) Map of southern Patagonia showing the spatial distribution of major vegetation units (modified after Gajardo, 1993; Luebert and Pliscoff, 2006; Pisano, 1992), and isohyets (modified after Miller, 1976; Romero, 1985). The open square shows the location of Torres del Paine National Park. (B) Topographic map of study area showing the location of Vega Ñandú in Torres del Paine National Park. The contour interval is 100 m.

magellanica, and *N. pumilio*. Common herbs are *Acaena lucida*, *Adesmia pumila*, *Apium australe* (Apiaceae), *Phacelia magallanica* (Hydrophyllaceae), *Cerastium arvense* (Caryophyllaceae), *Festuca gracillima*, *Azorella caespitosa* (Apiaceae), and *Valeriana carnosa*.

(3) Patagonian steppe occurs in lowland areas where the mean annual precipitation is <400 mm. The dominant species is *Festuca gracillima*, along with *F. magallanica*, *Stipa brevipes*, *Bromus unioloides* (Poaceae), *Acaena argentea*, *A. intergerrima*, *A. pinnatifida* (Rosaceae), *Adesmia pumila* (Papilionaceae), and *Arjona patagonica* (Santalaceae). *Adesmia boronoides*, *B. buxifolia, B. empetrifolia* (Berberidaceae), *C. diffusum, Baccharis magallanica* (Asteraceae), *Mulinum spinosum*, and *Verbena tridens* (Verbenaceae) are common shrubs in this unit.

(4) Andean desert is found above the *Nothofagus* forests; it includes small patches of *N. pumilio* and dwarf shrubs, such as *Escallonia rubra* and *Ribes cucullatum*. The herbaceous understory is dominated by *Acaena magallanica*, *Pernettya pumila* (Ericaceae), *Empetrum rubrum* (Empetraceae), *Senecio skottbergii* (Asteraceae), *Leuceria leonthopodioides* (Asteraceae), *Perezia megalantha*

(Asteraceae), *Nassauvia lagascae* (Asteraceae), *Agrostis canina* (Poaceae), and *Festuca pyrogea*.

Methods

We obtained multiple, overlapping sediment cores from the deepest part of the Vega Ñandú mire using a 5-cm-diameter modified Livingstone piston corer (Wright, 1967). A 5-cm-diameter Russian corer was used to retrieve the upper meter of the sedimentary sequence. The stratigraphy of the core was characterized by lithological descriptions, X-radiographs, and loss-on-ignition analysis following overnight drying at 105 °C. Sequential burns at 550 °C (2 h) and 925 °C (4 h) in a muffle furnace were performed to determine organic and carbonate content, respectively (Bengtsson and Enell, 1986; Heiri et al., 2001).

The chronology of the sediment cores is controlled by ten AMS radiocarbon dates and chronostratigraphic correlation of tephra layers also found in nearby sites (Table 1, Fig. 1). Radiocarbon dates were converted to calendar years before present (cal yr BP) using the CALIB 5.01 program (Stuiver et al., 1998). We developed a linear interpolation model based on the calibrated radiocarbon ages to assign interpolated calendar ages to the pollen levels (Fig. 2).

We analyzed 170 palynological levels throughout the sediment cores with a mean deposition time of 34 yr/cm, and an average time resolution of 72 yr between samples. A constant volume (2 cc) of sediment was processed for pollen and charcoal analysis using standard techniques (KOH, HF and Acetolysis; Faegri and Iversen, 1989). *Lycopodium* spore tablets (Stokmarr, 1971) were added to the sediment samples to allow calculation of charcoal accumulation rates. The concentrates were mounted on pollen slides using silicon oil (2000 cs) and were analyzed at 400× and 1000× magnification using a Leica DMLB2 stereomicroscope.

The basic pollen sum for each level includes at least 300 pollen grains of terrestrial origin. Percentages of aquatic and fern taxa were calculated from a supersum that included the basic pollen sum, the sum aquatic/paludal taxa, and the sum Pteridophytes. The pollen zones were defined with the aid of a Constrained Incremental Sum of Squares (CONISS) cluster analysis (Grimm, 1987). The rate-of-change parameter (square-chord distance) was calculated to quantify the magnitude/rapidity of vegetation changes by smoothing the pollen percentage data with a five-point moving average and interpolating pollen samples at regular 75-yr intervals. For the CONISS and the rates-of-change analyses we used all terrestrial pollen taxa ≥2% (excluding Pteridophytes), with percentages recalculated based on that sum (Jacobson et al., 1987). The basal clayey sediments (1088–400 cm) contained extremely low pollen concentrations and, hence, were not suited for high-resolution pollen analysis. Microscopic charcoal particles were counted in pollen slides along with their pollen and spore content. The abundance of charcoal is expressed as accumulation rates, determined by standardizing the concentration data by depositional time.

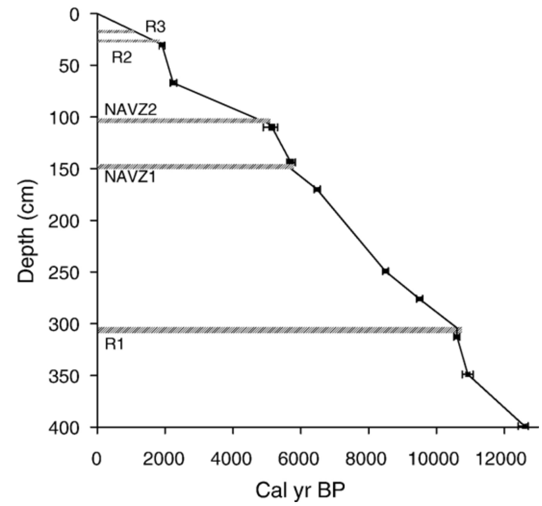

Figure 2. Age-depth curve from cores PS0304A and PS0405RCA1 showing the linear interpolation age model applied to the calibrated radiocarbon dates. Horizontal error bars represent±two standard deviations. The age model includes the dates we obtained for the same tephras in the Lago Guanaco record. The hatched pattern indicates the position of tephra layers. See main text and Figure 4 captions for more details.

Table 1
AMS ^{14}C dates and calibrated ages from core PS0304A

CAMS #	Core	Depth (cm)	^{14}C yr BP±1 S.D.	$\delta^{13}C$	Cal yr BP (median probability)	2σ range
98826 (*)	PS0303AT4	31	2015±30	−27.17	1910	1826–1990
124602	PS0304AT1	67	2305±35	−25	2235	2150–2340
107056 (*)	PS0404AT2	111	4545±50	−26.83	5147	4894–5312
114971	PS0304AT1	144	5035±35	−25	5703	5650–5840
99123	PS0304AT2	170	5750±40	−25	6478	6410–6530
114972	PS0304AT2	249	7770±60	−25	8490	8454–8540
98836	PS0304AT3	276	8530±40	−27	9491	9470–9520
98835	PS0304AT3	313	9310±40	−27	10,426	10,300–10,510
99122	PS0304AT3	313	9430±35	−25	10,601	10,520–10,665
98834	PS0304AT3	349	9615±45	−27	10,923	10,760–11,070
107005	PS0304AT4	399	10,395±45	−25	12,273	12,160–12,380
98833	PS0304AT4	399	10,555±40	−27	12,594	12,400–12,695

The asterisk indicates the radiocarbon dates obtained for the same tephras in the Lago Guanaco record.

Results

Stratigraphy

We selected a 1088-cm-long sediment core (PS0304A and PS0405RCA1) to conduct this study, based on its stratigraphic completeness and optimal recovery (Figs. 3, 4). The basal sediments consist of 688 cm of bluish-gray laminated glaciolacustrine mud between 1088 and 400 cm. An abrupt concordant transition gives way to a 400-m-thick organic unit. This unit consists of organic mud (gyttja) deposited in a lacustrine environment (400–350 cm, 318–296 cm, 280–250 cm, 207–193, and 95–144 cm), peat (350–320 cm and 95–0 cm), and coarse detritus gyttja (250–207 cm and 193–150 cm).

We found five tephras in the organic unit of cores PS0304A-PS0405RCA1 (Figs. 3, 4); they were identified by C. Stern (University of Colorado) by means of ICPMS and petrologic characterizations (Stern, 2007). Three of them were derived from Reclús volcano (312–305, 31–30, and 21–20 cm) and two ashes are related to the Northern Austral Volcanic Zone (NAVZ) (Stern, 2004), probably from the Aguilera volcano (150–144 and 110–108 cm). We found a similar tephrostratigraphy in sediment cores from Lago Guanaco (unpublished data), a site located 12 km SW from Vega Ñandú (Fig. 1). We obtained close maximum ages of 10,430 cal yr BP for the lowermost Reclús tephra and 2000 cal yr BP for the most recent Reclús tephras. The chronology of the NAVZ tephras is constrained by a close minimum age of 5700 cal yr BP for the older tephra and a close maximum age of 5150 cal yr BP for the younger NAVZ tephra (Figs. 2, 4; Table 1).

The organic matter content (Fig. 3) shows an increase beginning at 12,600 cal yr BP, with maximum percentages associated with a 32-cm-thick peat layer at 10,900 cal yr BP. The percent organic content then decreased and varied in concert with the alternating changes between coarse detritus gyttja and muddy peat. A rise in organic content is evident with the deposition of peat during the last 4000 yr. The carbonate content of the sediments is negligible (mean = 1.16 ± 0.4% for the basal glaciolacustrine mud, and 2.3 ± 1.3% for the organic portion). In fact, these low percentages probably represent loss of water molecules retained in the clay lattices during the 925 °C burn (Heiri et al., 2001).

Pollen analysis

We identified five assemblage zones based on conspicuous changes in the pollen stratigraphy and a CONISS ordination (Fig. 5). For each zone we show the three most abundant taxa, with the mean percentage of each taxon in parentheses.

Zone 1

Poaceae–Acaena–*Nothofagus dombeyi*-type (400–330 cm depth, 12,600–10,800 cal yr BP). This zone is dominated by Poaceae (53%), *Acaena* (12%), and Ericaceae (4.3%). *Plantago* (5.8%) has high percentages at the beginning of the zone, followed by its virtual disappearance from the record. *Nothofagus dombeyi*-type has low values (8%) and shows an increasing trend until ~11,300 cal yr BP, followed by a conspicuous decline towards the end of the zone. Cyperaceae (54%) increases rapidly to reach its maximum abundance (93%) at the end of the zone.

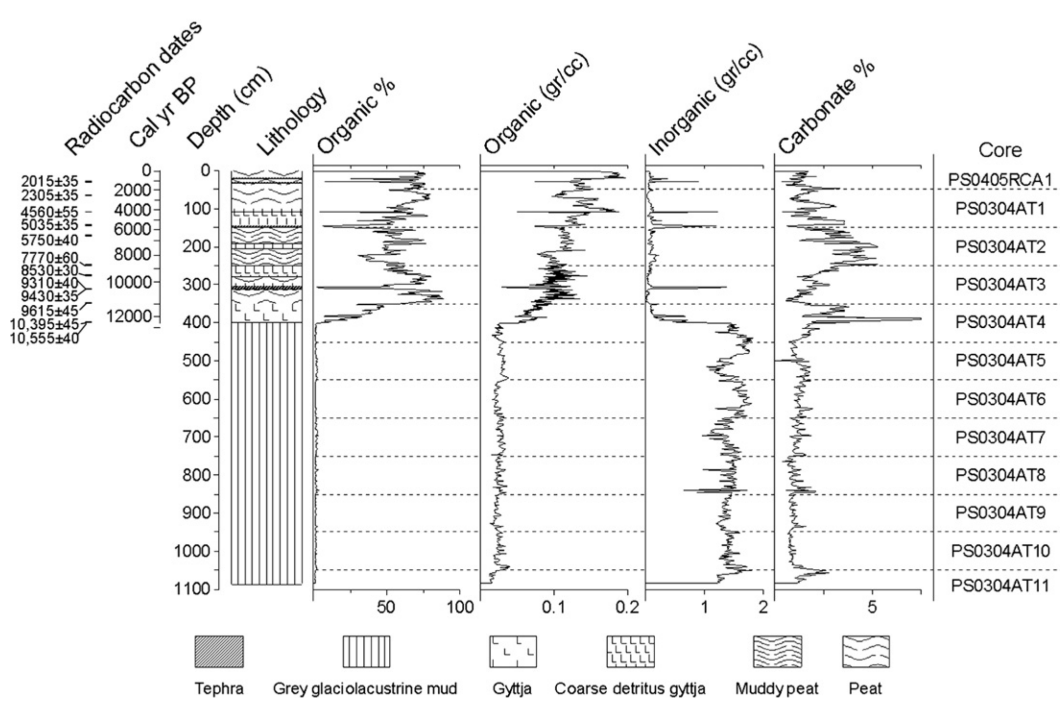

Figure 3. Stratigraphic column of cores PS0304A and PS0405RCA1, along with the corresponding radiocarbon dates and results of the loss-on-ignition analysis. The dashed horizontal lines represent the individual core boundaries.

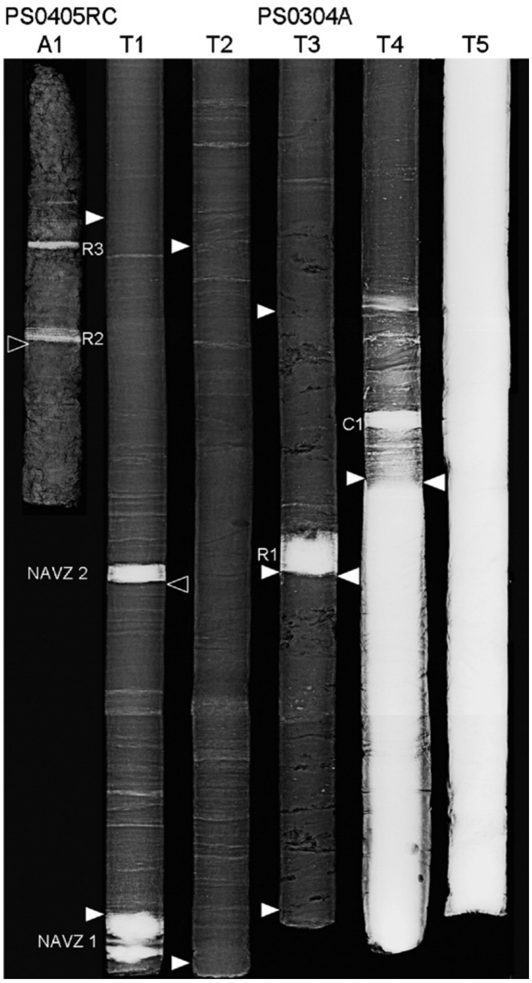

Figure 4. Digital X-radiographs of core PS0405RCA1 (far left) and the upper 500 cm of core PS0304A. The cores are aligned reflecting increasing depth from top to bottom and from left to right. Glaciolacustrine silts and clays predominate in the sediment core located in the far right (PS0304AT5) and the lower half of the overlying core PS0304AT4. An abrupt concordant transition gives way to crudely laminated organic lake sediments with decreasing silt content, a 2-cm-thick clastic layer (C1), and then to a horizontally lain Reclús tephra (R1) in middle portion of PS0304AT3. Several silty laminae are clearly visible in cores PS0304AT1 and PS0304AT2, along with two tephras derived from the Northern Austral Volcanic Zone (NAVZ1 and NAVZ2). Two tephras derived from Volcán Reclús (R2 and R3) are easily distinguishable in core PS0405RC. White triangles indicate the position of radiocarbon-dated levels from Vega Ñandú, open triangles correspond to radiocarbon dates obtained from the Lago Guanaco record.

Zone 2

Poaceae–*Nothofagus dombeyi*-type–Asteraceae (330–185 cm depth, 10,800–6800 cal yr BP). Within this zone, *Nothofagus dombeyi*-type expands abruptly along with increases in *Asteraceae* (8.6%), *Perezia*-type, and *Valeriana*. Poaceae (47%), *Acaena* (5.7%), and Ericaceae (0.8%) show a marked decline relative to the previous zone. Cyperaceae (65%) maintains high percentages and the aquatic *Myriophyllum* (3%) expands during a brief episode between 8700 and 7900 cal yr BP. The most abundant taxa (*N. dombeyi*-type, Poaceae, and Cyperceae) display strong and frequent fluctuations in their abundances during this zone. The percent abundance of *Nothofagus* during this interval is 26.3 ± 1.3 (mean ± S.E.), with peak values (values surpassing the 40% threshold) reaching 44.2 ± 1.1 and minima (values below the 20% threshold) of 14.3 ± 1.0.

Zone 3

Poaceae–*Nothofagus dombeyi*-type–Asteraceae (185–108 cm depth, 6800–5100 cal yr BP). During this time, *Nothofagus dombeyi*-type (22%) shows a sustained increasing trend while Poaceae (23%) exhibits a concomitant decline. Both taxa display strong fluctuations in their abundances. The abundances and fluctuations of shrubs are similar to the previous zone, with the exception of Asteraceae (8.6%), which reaches its highest abundance in the record followed by an abrupt decline toward the end of the zone. Cyperaceae (35%) maintains its decreasing trend with minor fluctuations.

Zone 4

Nothofagus dombeyi-type–Poaceae–*Acaena* (108–70 cm depth, 5100–2400 cal yr BP). *Nothofagus dombeyi*-type (48%) maintains its rising trend with short-lived fluctuations, accompanied by a rise of Apiaceae (2.4%). Poaceae (29%) and Asteraceae (4.5%) decrease in abundance, along with Cyperaceae (48%), which drops abruptly before reaching high percentages near the end of pollen zone. *Acaena* (9.2%) expands abruptly at the beginning of this zone and then decreases to minimum percentages.

Zone 5

Nothofagus dombeyi-type–Poaceae–Apiaceae (70–0 cm depth, 2400–0 cal yr BP). This zone features the dominance of *Nothofagus dombeyi*-type (61%), accompanied by its specific parasite *Misodendron* (0.6%). Poaceae (22. 2%) reaches its minimum values in the record. Other herbs and shrubs maintain the low percentages of the previous zone. Cyperaceae (43%) maintains its decreasing trend, but increase sharply at the end of the zone. During the last ∼200 yr, *N. dombeyi*-type drops abruptly, concurrent with expansions of *Rumex acetosella*, Apiaceae, and Caryophyllaceae.

Charcoal stratigraphy

Charcoal accumulation rates (CHAR) are extremely low from 12,600 cal yr BP until 10,800 cal yr BP, when a marked increase coincides with the first expansion of *Nothofagus* (Fig. 5). The charcoal record then displays frequent fluctuations of increasing magnitude that culminate at 6600 cal yr BP, coeval with the large-amplitude oscillations observed in the dominant pollen taxa (Fig. 5). CHAR remains low following the *Nothofagus* expansion that had started at 6800 cal yr BP, with the exception of two short-lived maxima centered at 5700 and 5200 cal yr BP. CHAR then increased with prominent fluctuations between 5100 and 2700 cal yr BP, followed by a sharp and sustained increase between 2300 and 2000 cal yr BP which probably represents local fires (as suggested by unpublished macroscopic charcoal data). The latter coincides with the final expansion of *Nothofagus* forests in the Vega Ñandú site. After this CHAR

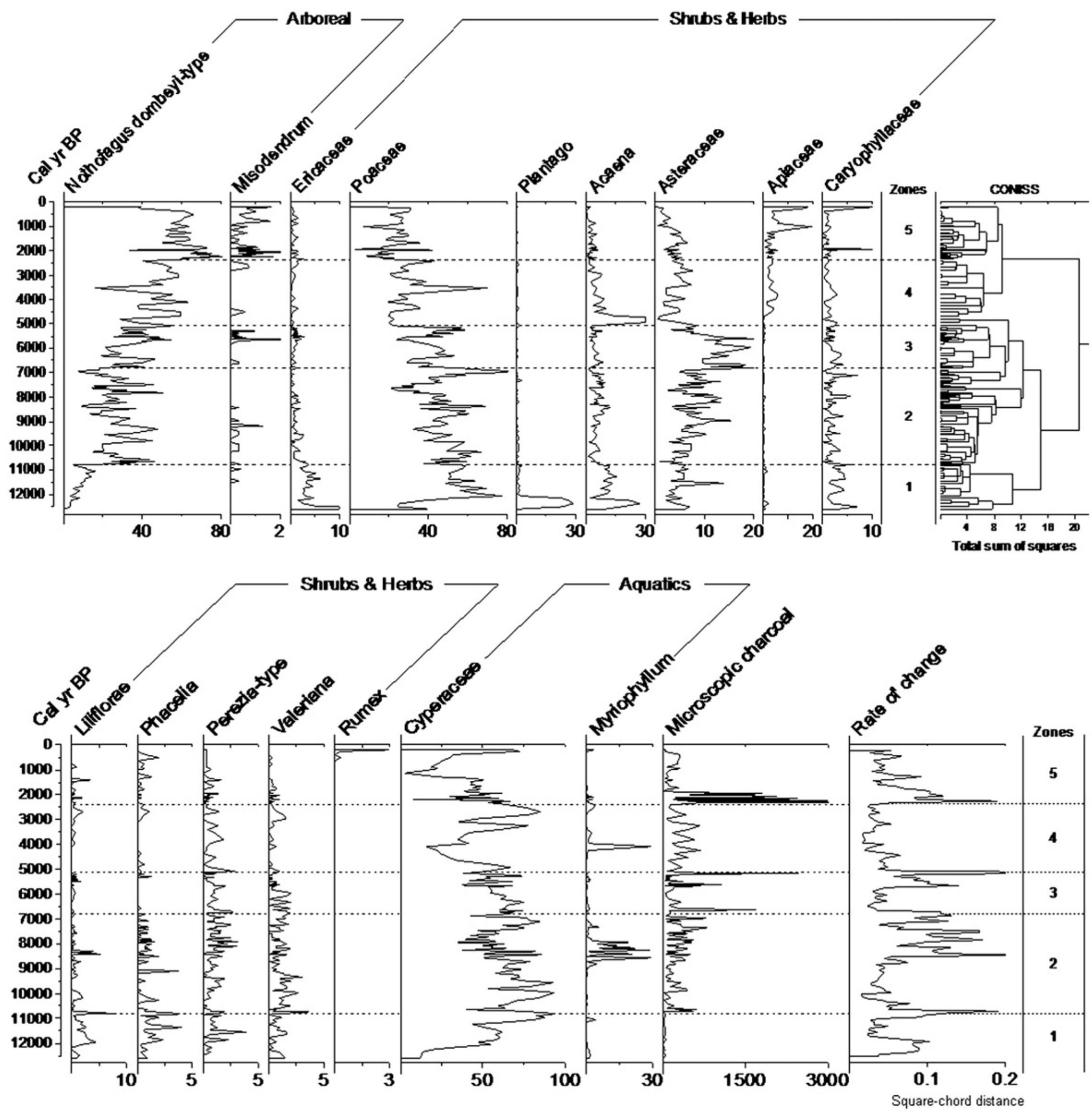

Figure 5. Percent pollen diagram for selected plant taxa from Vega Ñandú, accumulation rate curve of microscopic charcoal particles, and results of the rate-of-change analysis. The dashed lines indicate major changes in pollen stratigraphy.

maximum, the abundance values decrease abruptly and remain low over the last 2000 yr.

Discussion

The pollen record from Vega Ñandú shows the dominance of shrubs (Ericaceae) and herbs (Poaceae, *Acaena*, Asteraceae, *Plantago*, *Valeriana,* and *Phacelia*) and absence of forest indicators between 12,600 and 10,800 cal yr BP. Modern vegetation surveys indicate that Ericaceae and *Valeriana* are common in pre-Andean shrublands, while Poaceae, Asteraceae, and *Acaena* are components both of steppe and pre-Andean shrublands (Pisano, 1974). Although the high percentage values of Poaceae are characteristic of the Patagonian steppe (Mancini, 1993), the presence and significant abundance of Ericaceae, *Valeriana*, and Caryophyllaceae suggest dominance of pre-Andean shrublands. This vegetation unit occurs in areas of Torres del Paine National Park where mean annual precipitation values surpass 400 mm (Pisano, 1974). Hence, we interpret this pollen assemblage as an open landscape dominated by pre-Andean shrubland-type vegetation under relatively humid and cold climate conditions. The prevalence of a lacustrine environment, attested by the deposition of laminated gyttja in the site between 12,600 and 11,000 cal yr BP, is consistent with this interpretation. An increase of organic matter, paludal taxa (Cyperaceae), and deposition of peat between 11,000 and 10,600 cal yr BP suggest a drop in lake level, probably in response to lower effective moisture driven by a rise in temperature. The microscopic charcoal record exhibits extremely low values between 12,600 and 10,800 cal yr BP (Fig. 5), suggesting low fire activity in a sparsely vegetated landscape. Low biomass accumulation and/or fuel discontinuity may have prevented the occurrence of frequent and widespread fires.

An abrupt rise of *Nothofagus* and *Valeriana* occurred at 10,800 cal yr BP, along with a decrease of Ericaceae, Poaceae, Liliflorae, and *Acaena*, suggesting the establishment of a Mesophytic Shrubland (Fig. 5). This vegetation unit, which today includes patches of *Nothofagus* forest, occurs in areas of the Torres del Paine National Park with precipitation ranging between 550 and 700 mm/yr (Pisano, 1974). Dendroecological studies on *N. pumilio* populations found at the upper tree-line along a transect ranging from 51° to 55°S in SW Patagonia indicate a positive correlation between annual temperatures and tree growth (Aravena et al., 2002; Villalba et al., 2003). Thus, the rise of arboreal pollen and the cyclic dominance of Mesophytic Shrubland/Parkland starting at 10,800 cal yr BP suggest high variability in precipitation under warmer conditions. The fact that the charcoal accumulation rate and arboreal cover increased in unison at 10,800 cal yr BP probably reflects the effect of larger biomass accumulation in the system, allowing greater production and delivery of charcoal to the Vega Ñandú site.

The pollen record shows frequent, large-amplitude fluctuations in Poaceae and *Nothofagus* between 10,800 and 6800 cal yr BP, indicating high variability in arboreal cover near Vega Ñandú. The relatively modest expansions of *Nothofagus* during the peak wet phases (mean = 44.2%), nevertheless, suggest overall drier conditions than at present. These fluctuations are associated with similar oscillations in the charcoal content of the sediments and high rate-of-change values (Fig. 5), in particular between 8500 and 6600 cal yr BP. Because the distribution of *Nothofagus* forests in the Torres del Paine area is highly dependent upon the precipitation regime, these fluctuations probably represent strong rainfall variability in the area. Large-amplitude variations in both aquatic taxa (Cyperaceae, *Myriophyllum*) and depositional environments (subaerial to shallow lake deposits) are also consistent with the scenario of strong precipitation variability. A possibility exists that frequent precipitation variations between 10,800 and 6800 cal yr BP led to changes in the fire regime (frequency, magnitude, fire-free intervals), which in turn could have driven transitions between parkland/woodland environments in the areas adjacent to the Vega Ñandú site.

Major changes in the pollen stratigraphy occur at 6800 and 5100 cal yr BP, including a sustained increase of *Nothofagus*, an attenuation of its fluctuations, and a rise in Apiaceae. The latter occurs in pre-Andean shrublands, in the steppe, and in deciduous forests as an understory herb (*Ozmorhiza obtusa*; Pisano, 1974). We interpret the rise of Apiaceae and *Nothofagus* that started at 6800 cal yr BP as indicative of forest expansion under increasingly wetter conditions in the Vega Ñandú area. The charcoal record indicates consistently low values during this interval with two discrete pulses with high charcoal content at 5700 and 5200 cal yr BP. The rates-of-change parameter indicates that each of these events (6800, 5700, and ~5100 cal yr BP) was associated with rapid, large-magnitude changes in the vegetation that surrounded Vega Ñandú (Fig. 5).

An abrupt rise of arboreal taxa occurred at ~2400 cal yr BP, as indicated by the highest percentages in *Nothofagus* and *Misodendron*, a drop of Poaceae, and high values in the rates-of-change curve (Fig. 5). Today, high percentages of *Nothofagus* (~60%) are found only in forested areas with ≥750 mm/yr, as revealed by modern vegetation and pollen rain studies between 50° and 52°S (Pisano, 1974; Mancini, 1993), suggesting the local establishment of a dense forest starting at ~2400 cal yr BP in the Vega Ñandú area. The charcoal record shows prominent peaks following this transition from woodland to forest environments, probably representing the occurrence of frequent fires favored by the local abundance of coarse fuels.

Our data suggest that the establishment of dense *Nothofagus* forests in the Torres del Paine area occurred only when precipitation had reached its maximum level of the last 12,600 yr. This condition ended with the expansion of *Rumex*, Apiaceae, Caryophyllaceae, and Cyperaceae, which indicate severe anthropogenic disturbance and landscape degradation near Vega Ñandú in historical times.

Regional implications

The pollen data suggest cold and relatively humid conditions between 12,600 and 10,800 cal yr BP, followed by warming at 10,800 cal yr BP and the establishment of strongly variable moisture conditions between 10,800 and 6800 cal yr BP. This high variability is also recorded in the pollen record from the Río Rubens site (Huber et al., 2004) but is absent in the Gran Campo Nevado pollen record (Fesq-Martin et al., 2004), a site located within the fjord region of SW Patagonia. The latter pollen record shows little change in the forest composition and predominance during the first half of the Holocene. This contrasting vegetation response raises the possibility that the west–east precipitation gradient in SW Patagonia changed repeatedly, becoming steeper and relaxing during several episodes within the 10,800–6800 cal yr BP interval.

One explanation for these fluctuations is a highly variable position and/or intensity of the westerly winds in SW Patagonia. Some aspects of Haberzettl's (2006) interpretation of the Laguna Potrok Aike geochemical record, a crater lake located in the southern portion of extra-Andean Patagonia, are consistent with our inferences. Because Potrok Aike is susceptible to climatic influences other than the southern westerlies (e.g., advection of Atlantic moisture, polar outbreaks), it is possible that the divergences between paleoclimate records from the windward/leeward side of the Andes might reflect varying degrees of influence of the westerly winds toward the Atlantic coast.

The erratic behavior of the westerlies between 10,800 and 6800 cal yr BP was followed by the establishment of a stronger, more stable influence, as revealed by the onset and persistence of a forest expansion trend starting at 6800 cal yr BP. Precipitation increased further in pulses centered at 5100 and 2400 cal yr BP, ultimately leading to the establishment of closed-canopy forests during the last two millennia. Our data indicate peak forest development under wet conditions during this interval is also revealed by the Río Rubens (Huber et al., 2004), Meseta Latorre (Schäbitz, 1991), Beagle Channel (Heusser, 1998), Magellan Strait (Heusser, 1995), and the Gran Campo Nevado (Fesq-Martin et al., 2004) pollen records.

Paleoclimate data from central Chile (Jenny et al., 2002; Villa-Martínez et al., 2003; Valero-Garcés et al., 2005) and NW

Patagonia (Moreno and León, 2003; Moreno, 2004) show a strong negative anomaly in westerly activity between ~10,500 and 7600 cal yr BP, followed by prominent increases in precipitation in pulses centered at 7600, 6800, and 5700 cal yr BP. On the contrary, lake-level data from Lago Cardiel show a strong positive anomaly between ~11,000 and 7500 cal yr BP, followed by a fluctuating sequence of moderately high lake-level stands over the last ~7000 yr. Gilli et al. (2005) alluded to the onset of a dominant and permanent influence of the westerly winds in Lago Cardiel at 6800 cal yr BP, based on the inference of a dominant lake current system that led to the formation of a sediment drift and conspicuous changes in magnetic susceptibility in several lake sediment cores.

The multi-millennial pattern of westerly activity inferred from Vega Ñandú matches the timing and direction of NW Patagonian paleoclimate records, and is opposite to the timing of maximum lake levels in Lago Cardiel. This emerging pattern of contrasting precipitation anomalies, across and along the Patagonian Andes, poses an interesting paleoclimate puzzle. We propose three likely explanations: (i) the maximum strength of the southern westerlies was focused between 46° and 49°S during the interval between ~11,000 and ~7500 cal yr BP (supplying the moisture to sustain the high lake levels in Lago Cardiel), and then expanded both north- and southward. (ii) The southern westerlies shifted south of 51°S during the same interval, and then expanded northward causing forest expansion at Vega Ñandú, the establishment of a permanent current and sediment drift in Lago Cardiel, and the re-expansion of hygrophilous rainforests in NW Patagonia. Under this scenario, the high lake levels in Lago Cardiel between ~11,000 and ~7500 cal yr BP would be related to moisture sources different from the southern westerlies. (iii) The westerlies generally weakened with no major latitudinal shifts, along with increased advection of humid Atlantic air masses to the eastern Andean slopes of central Patagonia.

Ice core records from Antarctica show various timing, directions, and frequencies of temperature change throughout the Holocene. Despite the vast heterogeneity among individual sites, it is possible to recognize a common cooling trend starting at ~8000 cal yr BP (Masson et al., 2000). Marine records from the Atlantic sector of the Southern Ocean and Palmer Deep, a marine basin adjacent to the Antarctic Peninsula, indicate high sea-surface temperatures and limited sea ice extent/persistence between ~7000 and 5500 cal yr BP (Hodell et al., 2001; Leventer et al., 2002; Sjunneskog and Taylor, 2002; Taylor and Sjunneskog, 2002).These conditions ended at ~6200 cal yr BP or ~5500 cal yr BP with the onset of a cooling trend (Nielsen et al., 2004) and increased discharge of iceberg-rafted detritus in the South Atlantic sector of the Southern Ocean (Hodell et al., 2001). Altogether these data indicate that cooling in the Antarctic interior, along with sea-ice expansion and sea-surface cooling in the Southern Ocean, may have increased the pole-to-equator temperature and pressure gradients, forcing a northward shift or an intensification of the westerly wind belt starting sometime between 8000 and 5500 cal yr BP. A concomitant weakening of the South Pacific Anticyclone over the same interval could have favored the equatorward penetration of the westerly winds up to the subtropical latitudes of central Chile.

Conclusions

The high-resolution pollen record from Vega Ñandú provides evidence for past changes in the position and composition of the forest/steppe ecotone in the Torres del Paine area. Changes in this sensitive boundary in SW Patagonia mainly reflect variations in the amount of westerly moisture that spills eastward through trans-Andean environments. The Vega Ñandú palynological record suggests the following:

(1) Pre-Andean shrubland taxa dominated between 12,600 and 10,800 cal yr BP under cold and relatively humid climate conditions. At the end of this interval *Nothofagus* expanded abruptly, suggesting a warming event at the beginning of the Holocene.
(2) Frequent and large-magnitude fluctuations in *Nothofagus* occurred between 10,800 and 6800 cal yr BP, suggesting repeated transitions between parkland/woodland environments driven by strong changes in westerly precipitation.
(3) A highly variable negative anomaly in westerly precipitation occurred between 10,800 and 6800 cal yr BP. The temporal coherence with paleohydrological estimates from NW and central Patagonia suggests that the westerly wind belt either focused between 46° and 49°S or shifted south of 51°S.
(4) *Nothofagus* started a multi-millennial expansion trend at 6800 cal yr BP, driven by the stabilization and prominent increase in westerly precipitation. Subsequent pulses at 5100 and 2400 cal yr BP led to the establishment of closed-canopy forests during the last two millennia.
(5) An abrupt decline of *Nothofagus* forests and expansion of *Rumex acetosella* started at ~200 cal yr BP in response to landscape degradation caused by European settlers in historical times.

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