Review of Palaeobotany and Palynology 246 (2017) 242–250

Contents lists available at ScienceDirect

Review of Palaeobotany and Palynology

journal homepage: www.elsevier.com/locate/revpalbo

Palaeohydric balance variations in eastern Andean environments in southern Patagonia (48°–52.5° S): Major trends and forcings during the last ca. 8000 cal yrs BP

Marcos Emanuel Echeverria [a], Florencia Paula Bamonte [a,b,c,*], María Alejandra Marcos [a,b,c], Gonzalo David Sottile [a,b,c], María Virginia Mancini [a,b]

[a] *Laboratorio de Paleoecología y Palinología, Departamento de Biología, Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Mar del Plata, Funes 3250, 7600 Mar del Plata, Argentina.*
[b] *Instituto de Investigaciones Marinas y Costeras – IIMyC – CONICET, Rodríguez Peña 4046, 7600 Mar del Plata, Argentina.*
[c] *Consejo Nacional de Investigaciones Científicas y Técnicas –CONICET, Argentina.*

ARTICLE INFO

Article history:
Received 8 May 2017
Received in revised form 3 July 2017
Accepted 20 July 2017
Available online 24 July 2017

Keywords:
Palaeohydric balance variations
South Patagonia
Last 8000 cal yrs BP
West to east palaeohydric gradient

ABSTRACT

The core of the storm track flow intersects the landmass of Southern Patagonia providing a unique opportunity for palaeo-reconstructions. Most of the palaeo-reconstructions are based on records from sites where the relationship between precipitation and wind flow intensity, can be reconstructed from the impact on vegetation communities. Seven sites were selected for this study. The importance relies on their location in relation to vegetation communities; two sites lie within forest communities, two are from the forest-steppe ecotone and the other three from steppe communities in Southern Patagonia, Argentina, between 48° and 52.5° S and between 70° and 72° W. To compare the past palaeohydric balance based on the seven pollen records from these different vegetation communities along the precipitation gradient, we constructed a Palaeohydric Balance Index (PBI). The PBI is based on the water requirement of the main plant taxa represented by the pollen types analyzed in the records. The information provided by this index improves the understanding of the hydric balance variability in relation to the storm track behavior. During the last 8000 cal yrs BP we observed out-of-phase behavior in PBI variations between forest, forest-steppe ecotone and steppe PBIs, a greater amplitude of forest versus steppe environments and low amplitude of the forest-steppe ecotone variability. This out-of-phase behavior appears to have been replaced by in-phase palaeohydric changes between 700 and 500 cal yrs BP interpreted as related to an equatorward migration of the storm tracks.

1. Introduction

Southernmost South America is of particular interest for palaeoclimate reconstructions because it is the only land-mass intersecting the core of the Southern Hemisphere storm tracks related to mid-latitude atmospheric circulation. The zonal atmospheric flow and moist air masses from the Pacific are a main component of the climate system at hemispheric and global scale, given their influence on precipitation patterns in the middle latitudes of the southern hemisphere (Prohaska, 1976; Shulmeister et al., 2004; Toggweiler et al., 2006; Rojas et al., 2009). The topography of the Andes generates precipitations over the western slope and dry conditions in eastern Patagonia, although the potential advection of eastern moisture produces heterogeneities in the precipitation–atmospheric circulation relationship (Moy et al., 2009).

Years with higher precipitation correspond to periods of enhanced westerly flow at 850 hPa over the Southern hemisphere (Moreno et al., 2009). The positive correlation, between precipitation and westerly flow, results in the highest values of precipitation on the top of the mountain range where the stream flow intensity is high, which means that the precipitation increases where there exists an intensified westerly flow on the western side of the Andes (Garreaud et al., 2013). The correlation becomes less significant on the lee side of the Andes and turns negative towards the forest-steppe ecotone with intensified westerly flow which causes lower precipitation (Garreaud et al., 2009; Moy et al., 2009; Moreno et al., 2010; Garreaud et al., 2013). Several studies have analyzed the relationship between precipitation and westerly flow on the lee side of the Andes and their relation with the distribution of the vegetation during the Holocene (Mancini, 2009; Tonello et al., 2009; Bamonte and Mancini, 2011; de Porras et al., 2012; Sottile et al., 2012; Echeverria et al., 2014; Bamonte et al., 2015). Variations in the migratory surface cyclones moving to the east along the Southern

* Corresponding author at: Laboratorio de Paleoecología y Palinología, Departamento de Biología, Universidad Nacional de Mar del Plata, Funes 3250, 7600 Mar del Plata, Argentina.
E-mail address: bamonte@mdp.edu.ar (F.P. Bamonte).

http://dx.doi.org/10.1016/j.revpalbo.2017.07.006
0034-6667/© 2017 Published by Elsevier B.V.

Hemisphere storm tracks associated with changes in precipitation regimes have an influence on the distribution of the Patagonian vegetation (Berbery and Vera, 1996). Palaeoclimate records from Patagonia have illustrated differences in timing, direction, and magnitude of precipitation regimes throughout the Holocene (Heusser, 1995; Markgraf et al., 2003; Moreno, 2004; Gilli et al., 2005; Mayr et al., 2007; Moreno et al., 2009; Tonello et al., 2009; Markgraf and Huber, 2010; Lamy et al., 2010; Fletcher and Moreno, 2011; Moreno et al., 2012; Villa-Martínez et al., 2012, Iglesias et al., 2016; among others).

The aim of this study is to reconstruct the palaeohydric balance variations for the last ca. 8000 cal yrs BP from fossil pollen sequences located in both, Andean and extra-Andean communities in Southern Patagonia (Fig. 1). We focus on palaeohydric balance variations of the forest, forest-steppe ecotone and steppe communities from our seven records and compare our data with other pollen records from Southern Patagonia (46°–52.5° S; 70°–72° W).

2. Characteristics of the present day climate and vegetation

The vegetation types are primarily linked to the west–east precipitation gradient in Southern Patagonia (Fig. 1.a, b). The uplift of westerly air masses over the western slopes of the Andes produces orographic precipitation with maximum values of 4000 mm/yr, whereas the subsidence over the eastern side of the Andes in the Central Plateau produces dry conditions with precipitation lower than 200 mm/yr (Fig. 1.a; Garreaud and Aceituno, 2007; Garreaud et al., 2009; Moy et al., 2009).

On the western side of Patagonia, the climate is characterized by the presence of snow and rain, over 800 mm of annual rain fall as a result of the dominance air masses coming from the Pacific and the annual average temperature oscillates between 8 and 5.5 °C (Fig. 1.a, Oliva et al., 2001; González and Rial, 2004). The Andean vegetation is characterized by the Subantarctic forests of *Nothofagus* between 1200 and 800 mm/yr. Evergreen forests of *Nothofagus betuloides* and *Drymis winteri* grow where precipitations are close to 1000 mm/yr with a poor understory community dominated by shade-tolerant species as *Adenocaulon chilensis*, *Viola* spp. and *Blechnum penna-marina*, whereas in less humid sites *Nothofagus pumilio* patches prevail; in drier areas the deciduous *N. pumilio* and *Nothofagus antarctica* forest dominates with mean annual precipitation between 650 and 450 mm/yr. Deciduous forests are replaced by open *N. antarctica* woodlands, as precipitation decreases to 500–350 mm/yr at the forest–steppe ecotone. The forest clearings are characterized by *Poa pratensis*, *Deschampsia* sp. and *Agrostis* sp., with exotic species such as *Trifolium repens* and *Plantago lanceolata*. Slopes and high mountains are covered with grasslands of *Festuca pallescens*. *Empetrum rubrum* and *Gaultheria pumila* develop on high altitude forests and open areas (Fig. 1.b; Oliva et al., 2001).

Further towards the east, the precipitation decreases to 200 mm/yr annual (Fig. 1.a) and a grass and shrub steppe expands. The grass steppe grows between 500 and 300 mm/yr precipitation (Fig. 1.a, b). Along the Andes, *Festuca pallescens* predominates with increased presence of cushion plants (Movia et al., 1987). A grass steppe of *Festuca pallescens* develops eastward and between *N. pumilio* and *Nothofagus antarctica* forest patches. Shrub species such as *Embothrium coccineum*, *Gaultheria mucronata*, *Escallonia rubra*, *Mulinum spinosum* and *Senecio* spp. grow in open forest and eastwards where precipitation is close to 400 mm/yr. The west grass steppe is characterized by *Festuca pallescens* accompanied by mesic herbs species as *Carex andina*, *Poa ligularis*, *Cerastium arvense*, *Calceolaria lanceolata* and *Relbunium richardianum*, between other herbs. Whereas wetlands areas are dominated by *Festuca pallescens* accompanied by some herbs such as *Carex magellanica*, *Carex canescens*, *Gunnera magellanica*, *Empetrum rubrum*, *Juncus* sp., *Triglochin* sp., *Ranunculus* sp. and *Acaena magellanica* (León et al., 1998; Roig, 1998).

In areas closer to Subantarctic forest, the mesic shrub steppe is represented by *Maytenus magellanica*, *Embothrium coccineum*, *Ribes magellanicum*, *Gaultheria mucronata*, *Empetrum rubrum* and *Escallonia rubra*. In rocky areas *Adesmia boronoides* and *Mulinum spinosum* develops. The shrub steppe distribution is primarily related to the water availability where the predominant climate is cold arid, which is actually controlled by unpredictable precipitation inputs lower than 400 mm/yr, runoff redistribution and edaphic composition. (Fig. 1.a, b; Mancini et al., 2012). *Nassauvia glomerulosa* is a small xerophytic shrub that characterizes the shrub steppes that cover most of the area together with *Ephedra frustillata*.

In the southeast of Santa Cruz the climate presents oceanic features, since the southern sector of the Andes is lower and allows the entrance

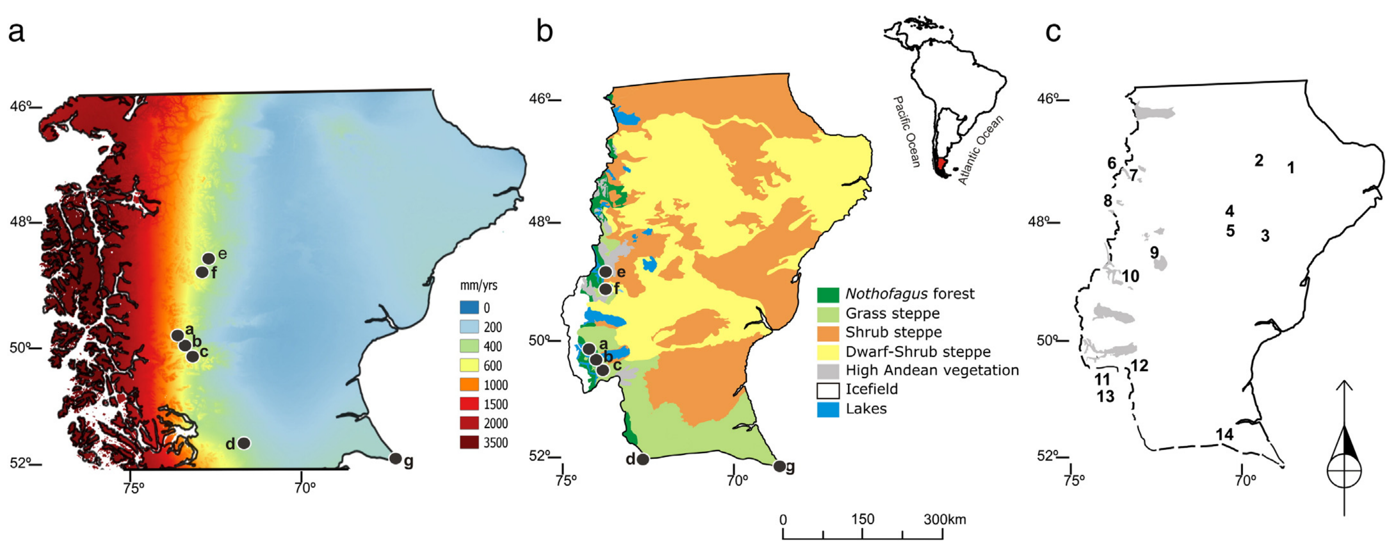

Fig. 1. (a) Distribution of annual precipitation (mm); (b) main vegetation units in South Patagonia Argentina (modified from Mazzoni and Vázquez, 2004). Black circles correspond to pollen sequences used to construct Palaeohydric Balance Indices (PBIs): a — Península Avellaneda Alto (PAA), b — Península Avellaneda Bajo (PAB), c — Cerro Frías (CF), d — Río Rubens (RR), e — Mallín Paisano Desconocido (MPD), f — Mallín La Tercera (MLT), and g — Cabo Vírgenes (CV), see references in Table 1. (c) South Patagonia sites locations used for regional integration: 1 — Piedra Museo (Borromei, 2003); 2 — Los Toldos (Páez et al., 1999; de Porras, 2010); 3 — La María (de Porras, 2010); 4 — La Martita (Mancini, 1998); 5 — La Gruta (Mancini et al., 2013; Brook et al., 2013, 2014); 6 — Lago Augusta (Villa-Martínez et al., 2012); 7 — Cueva Milodón Norte 1 (Horta et al., 2016); 8 — CCP7, CCP5, ADO, ADG (Pardiñas, 1998; Mancini et al., 2002; Mancini, 2007b); 9 — Lago Cardiel (Markgraf et al., 2003); 10 — Cueva Paisano Desconocido (Bamonte, 2012; Bamonte et al., 2013; Espinosa et al., 2013); 11 — Brazo Sur (Wille and Schäbitz, 2009); 12 — Chorrillo Malo 2 (Mancini, 2002); 13 — Lago Guanaco, Vega Ñandú (Villa-Martínez and Moreno, 2007; Moreno et al., 2009); 14 — Laguna Potrok Aike (Haberzettl et al., 2005; Zolitschka et al., 2006; Wille et al., 2007; Schäbitz et al., 2013).

of humid winds from the Pacific. Eastward, the precipitation varies between 200 and 300 mm/yr by marine influence from the Atlantic ocean (Oliva et al., 2001). In the wetter southeastern areas of Santa Cruz, *Festuca gracillima* is dominant, accompanied by grasses such as *Agropyron fuegianum*, *Deschampsia flexuosa* and *Rytidosperma virescens* and sedges of the genus *Carex*. Whereas the xeric grass steppe is characterized by *F. gracillima* accompanied by *Nardophyllum bryoides* and *Nassauvia ulicina*. Among the shrubs *Chiliotrichum diffusum* and *Berberis buxifolia* are present (Fig. 1; León et al., 1998; Oliva et al., 2001).

3. Water availability and vegetation formations relationship

Different conditions often produce differences in vegetation patterns. Water availability is the main component of vegetation differences in southernmost Patagonia. However, other factors such as the topography, slope orientation and edaphic characteristics also play an important role in determining the vegetation composition and distribution.

The strong precipitation gradient (Fig. 1.a) has a profound influence on vegetation distribution (Fig. 1.b). In flat landscapes, spatial changes in water availability depend mainly on precipitation, which has a continuous variation in space generating homogeneous gradients. In mountainous landscapes water availability is also influenced by slope and altitude. Consequently, water availability gradients in mountainous landscapes are heterogeneous (Jobbágy et al., 1996).

Low availability of water and nutrients, low temperature, and high speed and frequency of winds are the physical factors that determine the structure and functioning of the Patagonian communities and the morpho-physiological characteristics of its species (Bucci et al., 2011). Generally, trees require relatively high amounts of water availability; however, when the minimum requirements are not available, they are replaced by other types of vegetation such as thickets and steppes. In ecotones areas some trees usually have a special resistance to drought periods that allows them to survive, such as *Nothofagus antarctica* (Donoso et al., 2004). In extra-Andean Patagonia, the rainfall regime is low and variable, coupled with high evaporative demand, strong and persistent winds and low temperature, which in winter can generate negative balances in the capacity of water use. Due to this scenery, the maintenance of the hydric balance can be particularly critical for the species whose radical systems are relatively superficial, therefore, more exposed to the consequences that these physical factors have on the soil water availability. Thereby, the temporal variability of precipitation has significant control on the composition of the vegetation and the physiological behavior of plants (Chesson et al., 2004).

The analysis of species traits dominance in different plant communities to assess functional structure of ecosystems, lead to the classification of Plant Functional Types (PFTs), which has provided an alternative approach to disentangle how multiple processes (micro and macroclimatic conditions or disturbances) affect ecosystems attributes (Prentice and Webb, 1998; Díaz and Cabido, 2001; Mouillot et al., 2012). Annual precipitation controls vegetation distribution and functional characteristics of the ecosystems of Andean and extra-Andean Patagonia (Paruelo et al., 2004; Tonello et al., 2009), whereas mean annual temperature in conjunction with strong winds producing high evaporation rates have a strong effect on plant growth (Paruelo et al., 2001). At the landscape scale, several authors have demonstrated that plant species are also limited by hydric balance conditions determined by top-down processes (tree canopy in forested areas, Sottile et al., 2015b) or geomorphological characteristics (Golluscio and Sala, 1993; Jobbágy et al., 1996). Thus, reconstructing past species abundances for the last eight millennia between 48°–52.5° S would allow us to hypothesize about past regional hydric balance changes and relate them with possible changes in the frequency of the storm tracks affecting southern Patagonia.

4. Materials and methods

4.1. Scale analysis and vegetation representation

Pollen assemblages reflect general patterns in vegetation, thus they are a valuable tool for reconstructing past ecosystem behavior in terms of past hydric balance. Nevertheless, pollen representation is biased by several factors such as differences in pollen production, dispersal or preservation (Prentice, 1988; Faegri and Iversen, 1992). According to Jacobson and Bradshaw (1981) sedimentary deposits from depositional areas <~2 ha present pollen mainly from local to extralocal vegetation and minor representation of regional vegetation, especially by highly productive and anemophilous species. Studies about pollen dispersal carried out by Pérez et al. (2009) demonstrate that anemophilous pollen presents long trajectories from western Andean slopes to eastern Andean and extra-Andean environments related to synoptic scale processes. *Nothofagus* is the main genus of Patagonian forest trees and has been extensively used as a forest indicator at local and extralocal scale (e.g. Markgraf et al., 2007; Mancini, 2009; Bianchi and Ariztegui, 2012; Sottile et al., 2012) in late Quaternary pollen records. Nonetheless, *Nothofagus* pollen has been reported to reach more than a thousand kilometers beyond its source area (Gassmann and Pérez, 2006). However, the analysis of *Nothofagus*/Poaceae ratio has been used effectively to infer changes in forest/steppe cover at regional scales (e.g. Wille et al., 2007). Sottile (2014), and Sottile et al. (2016) correlated *Nothofagus* pollen percentages from surface pollen samples with *Nothofagus* cover estimated from satellite images. The authors inferred for the first time the "*Nothofagus* pollen source area" applying regression functions of increasing concentric areas which are oriented according to the dominant wind direction at the location of the surface pollen samples. The authors concluded that 87–80% of *Nothofagus* pollen represented a forest area of 1500 m diameter oriented along the main wind direction and 20–13% of *Nothofagus* pollen represented a regional source with an $r^2 = 0.7–0.75$. Marcos and Mancini (2012), highlighted the representation of main taxa of Patagonian and Monte steppe shrubs and herbs at local scales. The authors demonstrated that most herb and shrub pollen vegetation representation was associated at local scales due to the high degree of entomophily of the steppe species. Bamonte et al. (2015) showed that the fossil pollen reconstruction from a sequence located in the steppe about 1 km to the east of the forest is probably influenced by local (herbs and shrubs, usually less dispersed) and extra-local (*Nothofagus* pollen type) pollen input. Linking both, Andean (extra-local) and extra-Andean (local) vegetation dynamics allowed them to compare the synchronicity and phase or antiphase variability of past moisture regimes.

4.2. Site selection criteria

In order to reconstruct the past 8000 years of environmental changes and variability in different landscapes of eastern Andean Patagonia, continuous pollen records we selected from (Table 1): (1) peatbogs located between 48° and 52.5° S, including those that were previously published and available in Neotoma Paleoecology Database (http://www.neotomadb.org); and (2) pollen records from the Paleoecology and Palynology Lab database (UNMdP-IIMyC, CONICET). In order to be included, proxy data series must have a chronology based on more than 2 dates for the last 5000 cal yrs and more than 2 dates for the last 2300 yrs BP (see Table 1).

Southern Patagonian pollen dataset was classified into two categories (local and regional, sensu Jacobson and Bradshaw, 1981) in response to the pollen source area and the variables selected to calculate Palaeohydric Balance Index (PBI). The local dataset category involves pollen records that register past local vegetation variations. These records present a high relationship between the surrounding vegetation of the deposition site (<1500 m ratio) and recent pollen samples assemblages (Península Avellaneda Alto — PAA, Península Avellaneda Bajo —

Table 1
Sites selected for eastern Andean environmental synthesis to calculate Palaeohydric Balance Indices (PBIs).

Site	Coordinates	Modern hydric balance (mm/yr)	Vegetation unit	References
a — Península Avellaneda Alto (PAA)	−50.26°S; −72.85°W	104.5	*N. pumilio* forest	Sottile (2014), Sottile and Mancini (2015) and Sottile et al. (2015a). This work, Supplementary material (Section 3)
b — Península Avellaneda Bajo (PAB)	−50.26°S; −72.84°W	67.2	*N. pumilio* forest and *N. antarctica*/steppe	Echeverria et al. (2014)
c — Cerro Frías (CF)	−50.41°S; −72.71° W	−65	Forest/steppe ecotone	Mancini (2009) and Sottile et al. (2012)
d — Río Rubens (RR)	−52.06°S; −71.51°W	−189.8	Forest steppe/ecotone	Huber et al. (2004) and Markgraf and Huber (2010).
e — Mallín Paisano Desconocido (MPD)	−48.95°S; −72.23°W	−163.2	Grass-shrub steppe ecotone	Bamonte (2012) and Bamonte et al. (2015)
f — Mallín La Tercera (MLT)	−49.182°S; −72.37°W	−146.6	Grass steppe	Bamonte and Mancini (2011), Bamonte (2012) and Sottile et al. (2012)
g — Cabo Vírgenes (CV)	−52.32°S; −68.38°W	−303.7	Grass steppe	Mancini (2007a) and Mancini and Graham (2014)

PAB, Mallín Paisano Desconocido — MPD, Mallín La Tercera — MLT, Cabo Vírgenes — CV). Regional category includes records that in recent pollen samples presented higher amounts of pollen types from larger distances (>3 km southwestward) than pollen from the vegetation surrounding the deposition site (Cerro Frías — CF, Río Rubens — RR).

4.3. Modern hydric balance index and Palaeohydric Balance Indices (PBIs) estimation

The modern hydric balance index was calculated for each site as the ratio between annual precipitation and potential evapotranspiration. Potential evapotranspiration values were estimated according to Thornthwaite (1948). Precipitation and temperature values were imported from WorldClim database to calculate the modern hydric balance (http://www.worldclim.org/current.htm: Hijmans et al., 2005) into GIS software (QGis 2.6.187). Monthly values were obtained from interpolating the data by kriging method; afterwards mean values were calculated for the selected sites. The modern hydric balance of every site was compared to palaeohydric values in reference to the pollen samples with an age of ca. 1900 AD of every record (preventing possible changes on pollen spectra related to European settlement).

We have selected pollen taxa indicators specific for local and extralocal vegetation. Then we constructed past pollen based PBI from seven continuous pollen sequences from Andean and extra-Andean communities (Table 1) for the last ca. 8000 cal yrs BP. Main pollen taxa suggest above/below hydric availability at every site, following palaeoecological and modern pollen–vegetation calibrations highlighted in previous published works and field observations (Mancini, 2007a, 2009; Bamonte and Mancini, 2011; Mancini et al., 2012; Sottile et al., 2012; Echeverria et al., 2014; Sottile, 2014; Bamonte et al., 2015, see Supplementary material, Sections 1 and 2 for details). Each PBI was calculated as the standardized ratio between the sum (in percentages) of positive hydric availability taxa and the sum of negative hydric availability taxa (see Supplementary material, Section 1 for details). The standardization of every ratio was calculated by subtracting the mean and dividing it by the standard deviation.

Finally, the selected sites were grouped into the three major vegetation communities (forest, forest-steppe ecotone and steppe), which are sensitive to infer and discuss possible major trends in palaeohydric balance at the west–east hydric balance gradient during the last 8000 cal yrs BP. In order to highlight the general trend of every site group, a locally weighted scatterplot smoothing spline was applied (with a smoothing factor of 0.2) (Cleveland, 1979, 1981) and the 95% confidence band was plotted based on a 999 bootstrap replicate technique.

The major palaeohydric trends at forest, forest-ecotone and steppe communities inferred from this research were compared with a compilation of pollen records from South Patagonia (Fig. 1.c).

5. Results

5.1. Palaeohydric Balance Indices (PBIs) trends for the last 8000 cal yrs BP

The interpretation of the PBIs from local dataset category sites (PAA; PAB; MPD; MLT; CV) may be indicative of local conditions changes since these records show a high relationship between the surrounding vegetation and recent pollen samples assemblages. On the other hand, PBIs from the regional category sites (CF; RR) we interpreted not as changes in the local hydric balance at a single site but as representatives of the forest-ecotone region from these two sites.

Forest areas (PAA; PAB; Fig. 2) experienced major PIBs changes during the last 8000 cal yrs BP. Above average hydric availability characterized this area between 8000 and 4000 cal yrs BP, decreasing to negative values by 1200 cal yrs BP. The highest values were three times the modern values. A slight increase in positive hydric values took place around 1000 cal yrs BP, doubling modern hydric balance values (PAA: 104 mm/yr and PAB 67 mm/yr).

The forest-steppe ecotone PBI (CF; RR; Fig. 2) variability showed lower amplitude of change than the forest PBI curve. PBIs at the forest-steppe ecotone present some differences between maximum palaeohydric positive values during the middle Holocene: RR peaks ~-6000 cal yrs BP and CF peaks ~4500–5000 cal yrs BP. When grouping these two sites, the resulting curve shows positive values between 6000 and 2500 cal yrs BP. The mean highest paleohydric values occur ~5000–3500 in this environment. The forest-steppe ecotone PBI curve around 1000 cal yrs BP shows a similar trend to the forest curve but is shifted a thousand years to the present.

The steppe curve (MPD; MLT; CV; Fig. 2) showed wider amplitude of PBI change than the forest-steppe ecotone, similar to the forest PBIs amplitude. The steppe paleohydric balance variability showed the opposite trend than forest palaeohydric variability between 8000 and 1000 cal yrs BP. Between 8000 and 3000 cal yrs BP steppe BPIs were similar to modern negative palaeohydric balance values. Since then, positive palaeohydric values prevailed up to ~1200 cal yrs BP.

The PBI of the three environments along the west–east moisture gradient between 700 and 500 cal yrs BP, shows negative values. The negative PBI values are lower than modern values at forest and forest-steppe ecotone sites (PAA; PAB; CF; RR; Fig. 2). After this period, forest and forest-steppe ecotone curves show a slight increase in palaeohydric values, but still below average values in comparison to the last 8000 cal yrs BP. Subsequently there is a minor decrease in PBI values

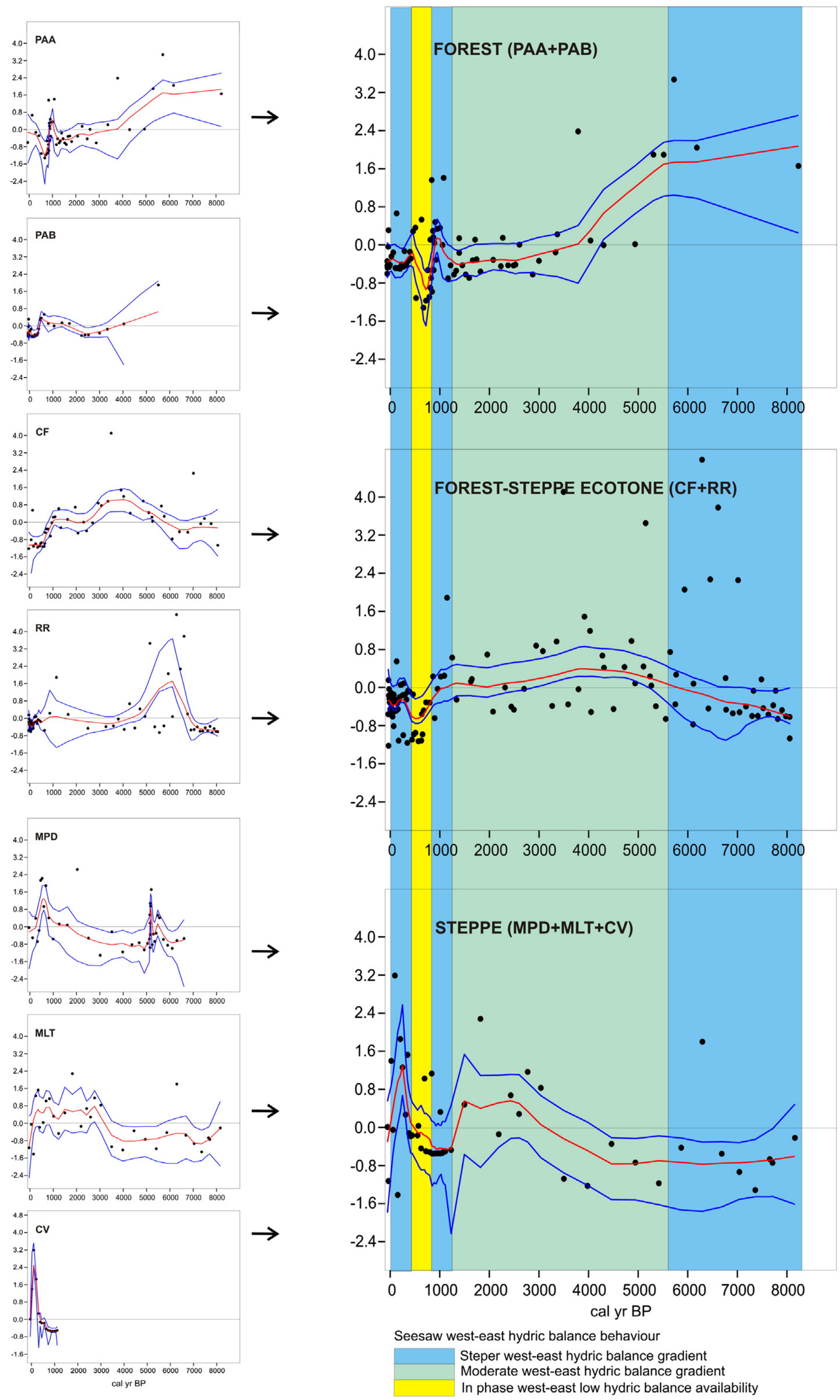

Fig. 2. Palaeohydric Balance Indices (PBIs) calculated from pollen data sequences studied in the forest (PAA and PAB), forest-steppe ecotone (CF and RR) and steppe communities (MPD, MLT and CV).

in forest and forest-steppe ecotone environments coinciding with an opposite trend at steppe environments. During the last 500 cal yrs BP, the palaeohydric curves from the three major environments might have reduced their out-of-phase behavior, which represents a much shorter time lag than the out of phase experience during the middle Holocene-last millennia.

The comparison of the three major trends in PBIs suggests an intense west–east palaeohydric balance gradient between 8000 and 5500 cal yrs BP, followed by a slow weakening of the gradient reaching moderate values between 5500 and 3500 cal yrs BP. The weakest west–east palaeohydric gradient occurred between 2500 and 1200 cal yrs BP. There was a slight intensification of the longitudinal moisture gradient

~1000 cal yrs BP, producing more humid conditions in forest environments, although the positive palaeohydric values were above modern values, they were half the values reached during the early to mid-Holocene (Fig. 2).

During the last millennium, the PBIs showed two different types of behavior. Synchronic PBIs decreased in all eastern environments between 700 and 500 cal yrs BP, and increases around 300–250 cal yrs BP up to modern values in forest areas similar to that experienced at ~1000 cal yrs BP. This slight increase is shown some decades later in the forest-steppe ecotone and later on in steppe environments with a sharp increase during the last centuries.

6. Discussion

6.1. Comparison with other palaeoclimatic records

The PBIs reconstruction of the last 8000 cal yrs BP between 48° and 52.5° S allowed us to hypothesize about possible changes in the intensity of the storm tracks affecting Southern Patagonia. By comparing the PBIs from our records (Fig. 2) with other pollen records from Southern Patagonia (Fig. 1.c) we present a regional hydric balance variability for different time windows (Fig. 3).

6.1.1. Between 8000 and 5500 cal yrs BP

The PBI for the steppe sequences are shown negative values on this period (Figs. 2; 3). Sites from the eastern part[2,3,4,5] of Southern Patagonia and Lago Cardiel[9] show synchronous changes mainly related to variations in shrubby communities. The dwarf-shrub/grass communities with low shrubs have been replaced by shrub/grass communities with taller shrubs indicating a progressive temperature increase and drier conditions through this period (de Porras, 2010). In Chorrillo Malo 2[12] an increase in shrub taxa started at ca. 8500 cal yrs BP (Mancini, 2002). These conditions are also registered in Laguna Potrok Aike[14], where a shrub steppe increase by ca. 8700 cal yrs BP and during the middle Holocene suggests dry conditions in extra-Andean communities (Wille et al., 2007). Fluctuations in geochemical parameters were interpreted in terms of lake levels fluctuations under overall drier conditions by 6300 cal yrs BP (Haberzettl et al., 2005).

Palaeoenvironmental reconstructions from Lago San Martin basin, MPD[e] (Bamonte et al., 2015), the archeological site Cueva Paisano Desconocido[10] (Bamonte et al., 2013), and MLT[f] (Bamonte and Mancini, 2011) showed a shrub steppe suggesting low moisture availability until ca. 6000 cal yrs BP.

Slightly increases are reflected in the PBI in forest-steppe ecotone records during this period (Figs. 2; 3). Similarly, higher moisture availability was recorded from sequences located in the forest-steppe ecotone in Cueva Milodon Norte 1[7] (Horta et al., 2016) and in the Parque Nacional Perito Moreno (CCP7[8], CCP5[8]; Mancini et al., 2002) interpreted from forest expansion in the Andes and grass steppe development to the east. At Lago Augusta[6] little variations in *Nothofagus* occurred during the last ca. 8000 cal yrs BP suggesting continuous forest (Villa-Martínez et al., 2012). The high precipitation values in the Andean zone have also been evidenced by the dominance of *Nothofagus* forest in Brazo Sur[11] and Vega Ñandú[13] since ca. 7500 cal yrs BP (Huber et al., 2004; Moreno et al., 2009; Wille and Schäbitz, 2009). CF[c] pollen record suggest a *Nothofagus* forest developed between 8000 and 7000 cal yrs BP.

Positive PBI values of forest curve are registered up to ca. 6000 cal yrs BP (Figs. 2; 3), most likely related to an increase in precipitations through an intensification of the storm tracks flow. PAA[b] (Sottile, 2014; Sottile and Mancini, 2015; Sottile et al., 2015a) peatbog, record located in the forest, suggests abundance of *Nothofagus* forest up to ca. 7000 cal yrs BP.

The palaeohydric balance integration show for the period between 8000 and 5500 cal yrs BP a strong west to east palaeohydric gradient;

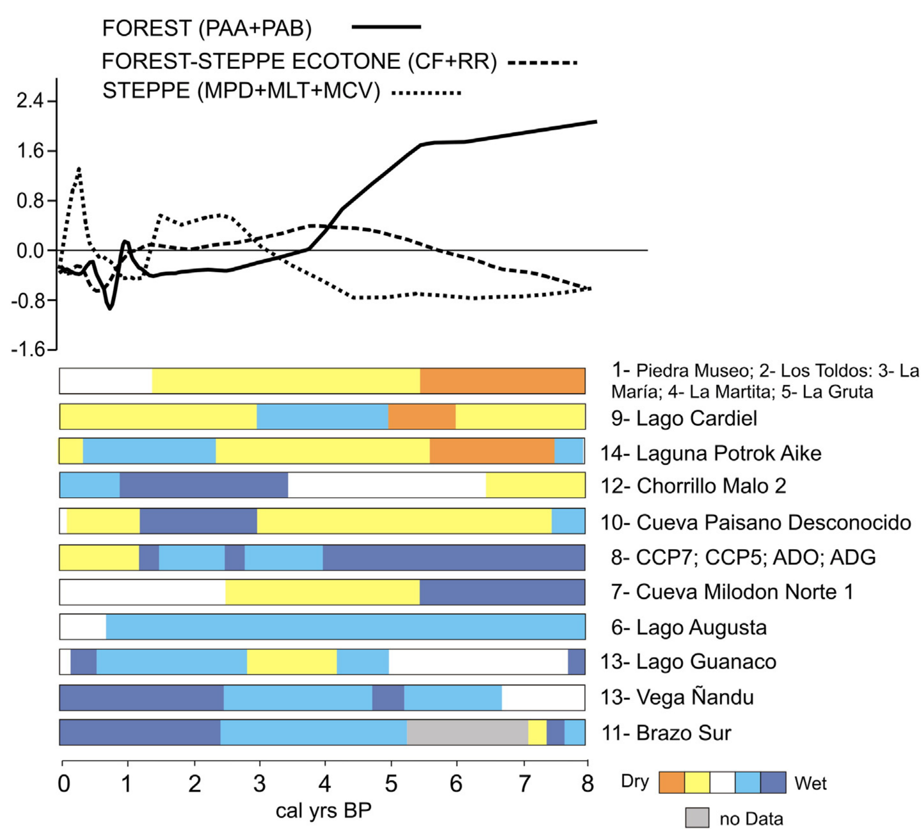

Fig. 3. Palaeohydric balance integration since ca. 8000 cal yrs BP, from South Patagonia pollen records (46°–52.5° S). At the top of the figure is shown the PBI from forest, forest-steppe ecotone and steppe.

this maybe associated to an intensification in the storm tracks flow, generating dense forest in the Andes and steppes in the eastern areas.

6.1.2. Between 5500 and 1200 cal yrs BP

PBI from the steppe showed a slight positive trend towards ca. 2000/1500 cal yrs BP (Figs. 2; 3), related to a smooth increase in precipitation. The shrubs communities development on sites located in the east of Southern Patagonia (Los Toldos[2], La María[3], La Martita[4], La Gruta[5]) (Mancini, 1998; Páez et al., 1999; de Porras, 2010; Mancini et al., 2013; Brook et al., 2014) and Lago Cardiel[9] (Markgraf et al., 2003) suggest similar conditions as the modern ones, regarding communities composition and temperature. The lake levels fluctuations during the middle to late Holocene show environmental variability during this period (Markgraf et al., 2003).

In Chorrillo Malo 2[12] the shrub taxa increase was recorded until 4000 cal yrs BP, followed by an increase in grasses, suggesting an increase in the moisture availability (Mancini, 2002). The moisture levels registered from Laguna Potrok Aike[14] increased, the grass steppe expanded and the forest signal from the Andean zone decreased (Wille et al., 2007).

From MPD[e], *Nothofagus* increased at ca. 4500 cal yrs BP, suggesting a wet pulse in the Andean zone (Bamonte et al., 2015). Whereas at ca. 2000 cal yrs BP, MLT[f] and MPD[e] (Bamonte and Mancini, 2011; Bamonte et al., 2015) showed an increase in the moisture availability based on expansion of grass steppe and a decrease in forest taxa.

Forest and forest-steppe ecotone records showed a negative trend in the PBIs up to ca. 2000 cal yrs BP (Figs. 2; 3). After ca. 2000 cal yrs BP, the trend in the PBI started to increase. The development of shrub steppe continued in Cueva Milodon Norte 1[7] (Horta et al., 2016), whereas in CCP7[08] and CCP5[08] a discontinuous forest was inferred between ca. 2800 and 1000 cal yrs BP for the Andean zone (Mancini et al., 2002). These results suggest a fluctuation in the moisture availability.

In sequences located in the forest, PAB[b] (Echeverria et al., 2014), and forest-steppe ecotone, CF[c] (Mancini, 2009), high abundance of *Nothofagus* pollen values were registered between 5800 and 3200 cal yrs BP. Furthermore, PAB[b], PAA[a], and CF[c] indices show an increase at ca. 4500/4000 cal yrs BP. Tonello et al. (2009) have placed the Holocene Pann maximum at ca. 4000–3500 cal yrs BP. Glacier advances have been documented at ca. 4500 cal yrs BP (Wenzens and Wenzens, 1998; Wenzens, 1999; Aniya, 2013). Later, in the southwestern Andean communities (PAB[b], CF[c], Brazo Sur[11], Lago Guanaco[13] and Vega Ñandú[13]) pollen records suggested lower moisture availability from ca. 4500/4000 cal yrs BP to ca. 2000 cal yrs BP (Villa-Martínez and Moreno, 2007; Mancini, 2009; Moreno et al., 2009; Wille and Schäbitz, 2009; Echeverria et al., 2014). A decrease in precipitation of westerly origin between ca. 3000 and 2000 cal yrs BP has been reconstructed by Tonello et al. (2009). In addition, several authors postulated low temperatures for ca. 2500 cal yrs BP (Mercer, 1982; Wenzens and Wenzens, 1998; Wenzens, 1999; Moreno et al., 2009; Aniya, 2013). Apparently, in the Andean areas precipitation decreased between ca.4000–2000 cal yrs BP, which maybe associated to a weakening of the storm tracks flow. Villa-Martínez and Moreno (2007) and Wille and Schäbitz (2009) suggested an increase in moisture availability after ca. 2500 cal yrs BP due to an increase in dense forest development. Tonello et al. (2009) have proposed an increase of precipitation up toca. 1000 cal yrs BP. In conclusion, dry conditions characterized this period, from 4000 to 2000 cal yrs BP; and a wetter environment began to establish towards 1000 cal yrs BP in Andean communities.

These comparisons of records show that during the period between 5500 and 1200 cal yrs BP the reconstructed vegetation of more humid steppes to the east and open forest in the west indicate a low west–east palaeohydric gradient. Nevertheless, high variability in hydric conditions was registered, and were reflected in the vegetation distribution.

6.1.3. The last 1200 cal yrs BP

Steppe PBI curve shows a positive trend in the hydric balance (Figs. 2; 3) between ca. 1000 and 400 cal yrs BP, most likely related to a precipitation increase from ca. 1000 to 400 cal yrs BP. The high palaeoenvironmental variability during the last millennium is related to events such as Medieval Climate Anomaly (MCA, 950–750 cal yrs BP) and Little Ice Age (LIA, 380–50 cal yrs BP). However, the magnitude, timing and nature of these events have not been clearly defined in southern South America (Moy et al., 2009).

Sites located in the East of South Patagonia (Piedra Museo[1], Los Toldos[2], La María[3], La Martita[4], La Gruta[5]) (Mancini, 1998; Páez et al., 1999; Borromei, 2003; de Porras, 2010; Mancini et al., 2013; Brook et al., 2014) showed a trend of increasing moisture up to the present. The shrubby communities of these sites reflect conditions similar to the modern ones (de Porras, 2010).

Eastern communities such as Laguna Potrok Aike[14] and CV[g] sequences, showed an increase in grass vegetation associated with an increase in the moisture levels at the end of this period (Wille et al., 2007; Mancini and Graham, 2014).

In the Lago San Martín area (MPD[e] and MLT[f]) a change from grass to shrubby communities was recorded at ca. 400 cal yrs BP, which could be related to the beginning of the LIA; whereas the last century was characterized by dry conditions evidenced by an increase of shrubs (Bamonte and Mancini, 2011; Bamonte et al., 2015).

Horta et al. (2016) have suggested from the Cueva Milodon Norte 1[7] sequence the existence of a shrub steppe during the last millennium. These interpretations proposed lower moisture conditions with wet pulses for sites located at 47° S. In CCP7[8]and CCP5[8], from ca. 1200/800 to 250 cal yrs BP, the records showed a shrub steppe development suggesting a trend from wet to dry conditions. From ca. 250 cal yrs BP to present a grass steppe dominance associated with an increase in moisture was registered in this area (Mancini et al., 2002).

A positive to negative trend in PBI for forest and forest-steppe ecotone sequences is shown in the Figs. 2 and 3. In southwestern Andean communities, pollen records suggest the development of open forests up to present, which may be related to lower moisture availability. A significant physiognomic change has occurred within this period, the replacement of the forest by grass steppe at ca. 400 cal yrs BP (Echeverria et al., 2014). A trend from wet to dry conditions towards the end of this period was registered from ca. 1000 to 400 cal yrs BP. This lower moisture availability at ca. 400 cal yrs BP has also been pointed out in Vega Ñandú[13] (Villa-Martínez and Moreno, 2007) based on a reduction in forest pollen signal of forest. In contrast, Wille and Schäbitz (2009) showed wet conditions at that time in their sequences from Brazo Sur[11]. This may be due to variations found by the mosaic distribution of vegetation in these forest-steppe ecotone areas. The re-establishment of an open landscape suggests decreasing precipitation values in Andean areas until ca. 400 cal yrs BP.

The low temperature postulated for the last ca. 450 cal yrs BP (Wenzens and Wenzens, 1998; Wenzens, 1999; Luckman and Villalba, 2001; Villalba et al., 2003; Masiokas et al., 2009; Neukom et al., 2010;Aniya, 2013) might have enabled glacier advances and restricted the water availability, triggering a decrease in *Nothofagus* cover in southwestern Patagonia. Thus, the last millennium can be interpreted as a climatic period with sub-century variability, with moist/dry pulses, with different responses according to the geographical location.

During the last 1200 cal yrs BP high variability in the hydric conditions has been observed for each site. The out-of-phase behavior described for the previous periods is not evidenced. There is a slight intensification of the longitudinal moisture gradient ~1000 cal yrs BP, producing more humid conditions in forest environments. Then, PBIs show a synchronic decrease in all eastern environments between 700 and 500 cal yrs BP, may be related to a northward displacement of the storm tracks, producing lower precipitation between 48° and 52.5° S. An increase in PBIs values around 300–250 cal yr BP up to modern values in forest areas. This slight increase is shown a number of decades later in the forest-steppe ecotone and later on in steppe environments. This out-of-phase variability between sites along the longitudinal humid gradient may suggest a reestablishment of a fluctuating behavior between forest and steppe environments. This different behavior may be due to high climatic variability registered for this period (LIA, MCA, equatorward migration of the storm tracks).

7. Conclusion

The use of PBI and the comparison between sequences located in Andean and extra-Andean communities of South Patagonia, offer the possibility to hypothesize about past moisture availability related to storm tracks variations from ca. 8000 cal yrs BP. The inference of a seesaw behavior in PBIs variations during most of the last 8000 cal yrs BP is supported by: a) the out of phase between forest, forest-steppe and steppe ecotone PBIs curves and b) the greater amplitude of forest versus steppe environments and the low amplitude of the forest-steppe ecotone variability. This out-of-phase behavior might have been replaced by a synchronous and equal direction of palaeohydric changes in eastern Andean environments between 700 and 500 cal yrs BP. These changes could be related to equatorward migration of the storm tracks affecting equally to forest and steppe environments between 48° and 52.5° S.

We present a scenario with several intervals for the last 8000 cal yrs BP:

- Between ca. 8000–5500 cal yrs BP, intense west to east palaeohydric balance gradient.
- Between ca. 5500–1200 cal yrs BP, slow weakening to the west to east palaeohydric balance gradient, being the weakest between 2500 and 1200 cal yrs BP.
- Around ca. 1000 cal yrs BP, slight intensification of hydric gradient.
- Between 700 and 500 cal yrs BP the synchronic decrease in the hydric balance in all environments may be related to equatorward storm tracks displacement.
- During most of the last 8000 cal yrs BP, the PBIs variations correspond to out-of-phase behavior, with the exception of the two hundred years between 700 and 500 cal yrs BP.

Acknowledgements

This research was supported by PIP-CONICET 1265; UNMdP-EXA 642/12 and EXA 602/13. We are grateful to Parque Nacional Los Glaciares, Prefectura Lago Argentino, Ea. La Federica and Ea. 9 de Julio for allowing us to work in their fields and offering us logistic support. To Vera Markgraf for her comments which helped to improve the manuscript and helping us in the English version.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.revpalbo.2017.07.006.

References

Aniya, M., 2013. Holocene glaciations of Hielo Patagónico (Patagonia Icefield), South America: a brief review. Geochem. J. 47, 97–105.
Bamonte, F.P., 2012. Cambios paleoecológicos y su posible relación con las ocupaciones humanas durante el Holoceno en el SO de Santa Cruz. Argentina, (Ph.D. Thesis). 142. Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Mar del Plata.
Bamonte, F.P., Mancini, M.V., 2011. Palaeoenvironmental changes since Pleistocene–Holocene transition: pollen analysis from a wetland in Southwestern Patagonia (Argentina). Rev. Palaeobot. Palynol. 165 (1–2), 103–110.
Bamonte, F.P., Mancini, M.V., Belardi, J.B., Espinosa, S., 2013. Inferencias paleoambientales a partir del análisis polínico de sitios arqueológicos del área del Lago San Martín (Santa Cruz, Argentina). Magallania 41 (1), 205–220.
Bamonte, F.P., Mancini, M.V., Sottile, G.D., Marcos, M.A., Gogorza, C., 2015. Vegetation dynamics from Lago San Martín area (Southwest Patagonia, Argentina) during the last 6500 cal B.P. Veg. Hist. Archaeobotany 24, 267–277.
Berbery, E.H., Vera, C.S., 1996. Characteristic of the Southern Hemisfere winter storm track with filtered and unfiltered data. J. Atmos. Sci. 53 (3), 468–481.
Bianchi, M.M., Ariztegui, D., 2012. Vegetation history of the Río Manso superior catchment area, Northern Patagonia (Argentina), since the last deglaciation. The Holocene 22, 1283–1295.
Borromei, A.M., 2003. Palynology at Piedra Museo locality, Santa Cruz Province, Argentina. In: Miotti, L., Salemme, M., Flegenheimer, N. (Eds.), Where the South Winds Blow: Ancient Evidence of Paleo South Americans. Center for Studies of the First Americans (CSFA). Texas A&M University Press, pp. 113–119.
Brook, G., Mancini, M.V., Franco, N., Bamonte, F.P., Ambrústolo, P., 2013. An examination of possible relationships between paleoenvironmental conditions during the Pleistocene-Holocene transition and human occupation of southern Patagonia (Argentina) east of the Andes, between 46° and 52° S. Quat. Int. 305, 104–118.
Brook, G., Franco, N.V., Ambrústolo, P., Mancini, M.V., Wang, L., Fernández, P., 2014. Evidence of the earliest humans in the Southern Deseado Massif (Patagonia, Argentina), Mylodontidae, and changes in water availability. Quat. Int. 363, 107–125.
Bucci, S.J., Scholz, F.G., Iogna, P.A., Goldstein, G., 2011. Economía del agua de especies arbustivas de las Estepas Patagónicas. Ecol. Austral 21, 43–60.
Chesson, P., Gebauer, R.L.E., Schwinning, S., Huntly, N., Wiegand, K., Ermest, S.K., Sher, A., Novoplansky, A., Weltzin, J.F., 2004. Resource pulses, species interactions, and diversity maintenance in arid and semi-arid environments. Oecologia 141, 236–253.
Cleveland, W.S., 1979. LOWESS: a program for smoothing scatterplots by robust locally weighted regression. J. Am. Stat. Assoc. 35:54. http://dx.doi.org/10.2307/2683591.
Cleveland, W.S., 1981. Robust locally weighted fitting and smoothing scatterplots. J. Am. Stat. Assoc. 74, 829–836 (1979).
de Porras, M.E., 2010. Dinámica de la Vegetación de la Meseta Central de Santa Cruz Durante los Últimos 11,000 Años: Forzantes Bióticos y Abióticos. (Ph.D. Thesis). Facultad de Ciencias Exactas y Naturales. Universidad Nacional de Mar del Plata, p. 137.
de Porras, M.E., Maldonado, A., Abarzúa, A.M., 2012. Postglacial vegetation, fire and climate dynamics at Central Chilean Patagonia (Lake Shaman, 44°S). Quat. Sci. Rev. 50, 71–85.
Díaz, S., Cabido, M., 2001. Vive la differénce: plant functional diversity matters to ecosystem processes. Trends Ecol. Evol. 16, 646–655.
Donoso, C., Premoli, A., Gallo, L., Ipinza, R., 2004. Variación Intraespecífica en las Especies Arbóreas de los Bosques Templados de Chile y Argentina. Edit. Universitaria, Santiago, Chile.
Echeverria, M.E., Sottile, G.D., Mancini, M.V., Fontana, S.L., 2014. *Nothofagus* forest dynamics and palaeoenvironmental variations during the mid and late Holocene, in southwest Patagonia. The Holocene 24 (8), 957–969.
Espinosa, S.L., Belardi, J.B., Barrientos, G., Carballo, M., 2013. Poblamiento e intensidad de uso del espacio en la cuenca del Lago San Martín (Patagonia argentina): nuevos datos desde la margen norte. Comechingonia 105–121.
Faegri, K., Iversen, J., 1992. In: Faegri, K., Kaland, P.E., Krywinski, K. (Eds.), Texbook of pollen analysis, 4th edition Wiley, Copenhagen (328 pp.).
Fletcher, M.S., Moreno, P.I., 2011. Zonally symmetric changes in the strength and position of the Southern Westerlies drove atmospheric CO_2 variations over the past 14 k.y. Geology 39 (5), 419–422.
Garreaud, R.D., Aceituno, P., 2007. Atmospheric circulation over South America: mean features and variability, Chapter 2. In: Veblen, T., Young, K., Orme, A. (Eds.), The Physical Geography of South America. Oxford University Press.
Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American Climate. Palaeogeogr. Palaeoclimatol. Spec. Issue LOTRED S. Am. 281 (3–4), 180–195.
Garreaud, R., Lopez, P., Minvielle, M., Rojas, M., 2013. Large scale control on the Patagonia climate. J. Clim. 26, 215–230.
Gassmann, M.I., Pérez, C.F., 2006. Trajectories associated to regional and extra-regional pollen transport in the southeast of Buenos Aires province, Mar del Plata (Argentina). Int. J. Biometeorol. 635 (50), 280–291.
Gilli, A., Ariztegui, D., Anselmetti, F.S., McKenzie, J.A., Markgraf, V., Hajdas, I., McCulloch, R.D., 2005. Mid-Holocene strengthening of the Southern Westerlies in South America sedimentological evidences from Lago Cardiel, Argentina (49°S). Glob. Planet. Chang. 49, 75–93.
Golluscio, R.A., Sala, O.E., 1993. Plant functional types and ecological strategies in Patagonian forbs. J. Veg. Sci. 4, 839–846 (625).
González, L., Rial, P., 2004. Guía Geográfica Interactiva de Santa Cruz. Estación Experimental Agropecuaria Santa Cruz. Convenio INTA-Santa Cruz-UNPA, Santa Cruz, Argentina.
Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G., Wille, M., Zolitschka, B., 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). J. Paleolimnol. 33, 283–302.
Heusser, C.J., 1995. Three Late Quaternary pollen diagrams from southern Patagonia and their palaeoecological implications. Palaeogeogr. Palaeoclimatol. Palaeoecol. 118, 1–24.
Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution 20 interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.
Horta, L.R., Marcos, M.A., Bozzuto, D.L., Mancini, M.V., Sacchi, M., 2016. Paleogeographic and paleoenviromental variations of Pueyrredón Lake Posadas — Salitroso area during the Holocene and their relationship to occupational dynamics. Palaeogeogr. Palaeoclimatol. Palaeoecol. 449, 541–552.
Huber, U.M., Markgraf, V., Schäbitz, F., 2004. Geographical and temporal trends in late Quaternary fire histories of Fuego-Patagonia, South America. Quat. Sci. Rev. 23, 191–198.
Iglesias, M.V., Markgraf, V., Whitlock, C., 2016. 17,000 years of vegetation, fire and climate change in the eastern foothills of the Andes (lat. 44°S). Palaeogeogr. Palaeoclimatol. Palaeoecol. 457, 195–208.

Jacobson Jr., G.L., Bradshaw, R.H.W., 1981. The selection of sites for paleovegetational studies. Quat. Res. 16, 80–96.
Jobbágy, E., Paruelo, J.M., León, R.J.C., 1996. Vegetation heterogeneity and diversity in flat and mountain landscapes of Patagonia (Argentina). J. Veg. Sci. 7, 599–608.
Lamy, F., Kilian, R., Arz, H.W., Francois, J.-P., Kaiser, J., Prange, M., Steinke, T., 2010. Holocene changes in the position and intensity of the southern westerly wind belt. Nat. Geosci. 3, 695–699.
León, R.J.C., Bran, D., Collantes, M., Paruelo, J.M., Soriano, A., 1998. Grandes unidades de vegetación de la Patagonia extra andina. Ecol. Austral 8, 125–144.
Luckman, B.H., Villalba, R., 2001. Assessing the synchroneity of glacier fluctuations in the western Cordillera of the Americas during the last millennium. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, New York, NY, USA, pp. 119–140.
Mancini, M.V., 1998. Vegetational changes during Holocene in the extra-Andean Patagonia, Santa Cruz Province, Argentina. Quat. Sci. Rev. 138 (1–4), 207–219.
Mancini, M.V., 2002. Vegetation and climate during the Holocene in Southwest Patagonia, Argentina. Rev. Palaeobot. Palynol. 122, 101–115.
Mancini, M.V., 2007a. Variabilidad climática durante los últimos 1000 años en el área de Cabo Vírgenes, Argentina. Ameghiniana 44 (1), 173–182.
Mancini, M.V., 2007b. Cambios paleoambientales en el ecotono bosque-estepa: análisis polínico del Sitio Casa de Piedra 7, Santa Cruz (Argentina). In: Morello, F., Martinic, M., Prieto, A., Bahamonde, G. (Eds.), Arqueología de Fuego-Patagonia, Edic. CECUA, Punta Arenas, pp. 89–93.
Mancini, M.V., 2009. Holocene vegetation and climate changes from a peat pollen record of the forest-steppe ecotone, Southwest of Patagonia (Argentina). Quat. Sci. Rev. 28, 1490–1497.
Mancini, M.V., Graham, M., 2014. Registros polínicos de depósitos del Holoceno en el Sudeste de Patagonia, Argentina: su aplicación en la reconstrucción paleoambiental. Ameghiniana 51 (3), 194–208.
Mancini, M.V., Páez, M.M., Prieto, A.R., 2002. Cambios paleoambientales durante los últimos 7000 ^{14}C años en el ecotono bosque-estepa, 47°–48° S, Santa Cruz, Argentina. Ameghiniana 39 (2), 151–162.
Mancini, M.V., de Porras, M.E., Bamonte, F.P., 2012. Southernmost South America Steppes: vegetation and its modern pollen-assemblages representation. In: Germanno, D. (Ed.), Steppe Ecosystem Dynamics, Land Use and Conservation. Nova Science Publishers, Nueva York, pp. 141–156.
Mancini, M.V., Franco, N.V., Brook, G., 2013. Palaeoenvironment and early human occupation of Southernmost South America (South Patagonia, Argentina). Quat. Int. 299, 13–22.
Marcos, M.A., Mancini, M.V., 2012. Modern pollen and vegetation relationships in northeastern Patagonia (Golfo San Matías, Río Negro). Rev. Palaeobot. Palynol. 171, 19–26.
Markgraf, V., Huber, U.M., 2010. Late and postglacial vegetation and fire history in Southern Patagonia and Tierra del Fuego. Palaeogeogr. Palaeoclimatol. Palaeoecol. 293 (2), 351–366.
Markgraf, V., Bradbury, J.P., Schwalb, A., 2003. Holocene paleoclimates of southern Patagonia: limnological and environmental history of Lago Cardiel, Argentina. The Holocene 13, 581–591.
Markgraf, V., Whitlock, C., Haberle, S.G., 2007. Vegetation and fire history during the last 18,000 cal yr B. P. in southern Patagonia: Mallin Pollux, Coyhaique, Province Aisén (45° 410 3000 S, 71° 500 3000 W), 640 m elevation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 254, 492–507.
Masiokas, M.H., Luckman, B.H., Villalba, R., Delgado, S., Skvarca, P., Ripalta, A., 2009. Little Ice Age fluctuations of small glaciers in the Monte Fitz Roy and Lago del Desierto areas, south Patagonian Andes, Argentina. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 351–362.
Mayr, C., Wille, M., Haberzettl, T., Fey, M., Jansen, S., Lücke, A., Ohlendorf, C., Oliva, G., Schäbitz, F., Scleser, G.H., Zolitschka, B., 2007. Holocene variability of the Southern Hemisphere westerlies in Argentinean Patagonia (52° S). Quat. Sci. Rev. 26, 579–584.
Mazzoni, E., Vázquez, M., 2004. Ecosistemas de mallines y paisajes de la Patagonia Austral (Provincia de Santa Cruz). INTA. 63 pp.
Mercer, J.H., 1982. Holocene glacier variations in southern South America. Striae 18, 35–40.
Moreno, P.I., 2004. Millennial-scale climate variability in northwest Patagonia over the last 15,000 yr. J. Quat. Sci. 19, 35–47.
Moreno, P.I., François, J.P., Villa-Martínez, R.P., Moy, C.M., 2009. Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia. Quat. Sci. Rev. 28 (1–2), 25–38.
Moreno, P.I., François, J.P., Villa-Martínez, R.P., Moy, C.M., 2010. Covariability of the Southern Westerlies and atmospheric CO_2 during the Holocene. Geology 38 (8), 727–730.
Moreno, P.I., Villa-Martínez, R., Cárdenas, M.L., Sagredo, E.A., 2012. Deglacial changes of the southern margin of the southern westerly winds revealed by terrestrial records from SW Patagonia (52°S). Quat. Sci. Rev. 41, 1–21.
Mouillot, D., Graham, N.A.J., Villéger, S., Mason, N.W.H., 2012. A functional approach reveals community responses to disturbances. Trends Ecol. Evol. 28 (3), 167–177.
Movia, C.P., Soriano, A., León, R.J.C., 1987. La vegetación de la cuenca del Río Santa Cruz (Provincia de Santa Cruz, Argentina). Darwin 28, 9–78.
Moy, C.M., Dunbar, R.B., Moreno, P., Francois, J.P., Villa-Martinez, R., Guilderson, T.P., Garreaud, R.D., 2009. Isotopic evidence for hydrologic change related to the westerlies in SW Patagonia, Chile, during the last millennium. Quat. Sci. Rev. 27 (13–14), 1335–1349.
Neukom, R., Luterbacher, J., Villalba, R., Küttel, M., Frank, D., Jones, P.D., Grosjean, M., Wanner, H., Aravena, J.C., Black, D.E., Christie, D.A., D'Arrigo, R., Larra, A., Morales, M., Soliz-Gamboa, C., Srur, A., Urrutia, R., von Gunten, L., 2010. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. Clim. Dyn. 37 (1–2), 35–51.
Oliva, G., González, L., Rial, P., Livraghi, E., 2001. Áreas ecológicas de Santa Cruz y Tierra del Fuego. In: Borrelli, P., Oliva, G. (Eds.), Ganadería Ovina Sustentable en la Patagonia Austral. Instituto Nacional de Tecnología Agraria, Santa Cruz.
Páez, M.M., Prieto, A.R., Mancini, M.V., 1999. Fossil pollen from Los Toldos locality: a record of the Late-Glacial Transition in the extra-Andean Patagonia. Quat. Int. 53–54, 69–75.
Pardiñas, U.F., 1998. Roedores holocénicos del sitio Cerro Casa de Piedra 5 (Santa Cruz, Argentina): tafonomía y paleoambientes. Palimpsesto. Rev. Arqueol. 5, 66–89.
Paruelo, J.M., Jobbagy, E.G., Sala, O.E., 2001. Current distribution of ecosystem functional types in temperate South America. Ecosystems 4, 683–698.
Paruelo, J.M., Garbulsky, M.F., Guerschman, J.P., Jobbágy, E.G., 2004. Two decades of NDVI in South 807 America, identifying the imprint of global changes. Int. J. Remote Sens. 25, 2793–2806.
Pérez, C.F., Castañeda, M.E., Gassmann, M.I., Bianchi, M.M., 2009. A statistical study of *Weinmannia* pollen trajectories across the Andes. Adv. Geosci. 22, 79–84.
Prentice, I.C., 1988. Records of vegetation in time and space: the principles of pollen analysis. In: Huntley, B., Webb III, T. (Eds.), Vegetation History. Kluwer, The Hague, pp. 17–42 (809).
Prentice, I.C., Webb III, T., 1998. BIOME 6000: reconstructing global mid-Holocene vegetation 811 patterns from palaeoecological records. J. Biogeogr. 25, 997–1005.
Prohaska, F., 1976. The climate of Argentina, Paraguay and Uruguay. In: Schwerdtfeger, W. (Ed.), Climates of Central and South America. Elsevier, Amsterdam, pp. 13–112.
Roig, F., 1998. La vegetación de la Patagonia. In: Correa, M.N. (Ed.), Flora Patagónica. Coleccion Cientifica del Instituto Nacional de Tecnologia Agropecuaria, pp. 48–166.
Rojas, M., Moreno, P., Kageyama, M., Crucifix, M., Hewitt, C., Abe-Ouchi, A., Ohgaito, R., Brady, E., Hope, P., 2009. The Southern Westerlies during the last glacial maximum in PMIP2 simulations. Clim. Dyn. 32, 525–548.
Schäbitz, F., Wille, M., Francois, J.P., Haberzettl, T., Quintana, F., Mayr, C., Lücke, A., Ohlendorf, C., Mancini, V., Paez, M.M., Prieto, A.R., Zolitschka, B., 2013. Reconstruction of palaeoprecipitation based on pollen transfer functions - the record of the last 16 ka from Laguna Potrok Aike, southern Patagonia. Quat. Sci. Rev. 71, 175–190.
Shulmeister, J., Goodwin, I., Renwick, J., Harle, K., Armand, L., McGlone, M.S., Cook, E., Dodson, J., Hesse, P.P., Mayewski, P., Curran, M., 2004. The Southern Hemisphere westerlies in the Australasian sector over the last glacial cycle: a synthesis. Quat. Res. 118–119, 23–53.
Sottile, G., 2014. Historia de la vegetación vinculada a disturbios de incendios durante el Holoceno en el ecotono bosque-estepa de Santa Cruz, Argentina. (Ph. D. Thesis). Facultad de Ciencias Exactas y Naturales. Universidad Nacional de Mar del Plata, p. 144.
Sottile, G.D., Mancini, M.V., 2015. Avances y retrocesos de las comunidades de bosque de la Península Avellaneda vinculado a la dinámica glacial y otros disturbios desde la transición Pleistoceno-Holoceno. VI Congreso Argentino del Cuaternario y Geomorfología. Ushuaia, Argentina.
Sottile, G., Bamonte, F.P., Mancini, M.V., Bianchi, M.M., 2012. Insights into Holocene vegetation and climate changes at the southeast of the Andes: *Nothofagus* forest and Patagonian steppe fire records. The Holocene 22 (11), 1201–1214.
Sottile, G.D., Echeverria, M.E., Mancini, M.V., Bianchi, M.M., Marcos, M.A., Bamonte, F.P., 2015a. Eastern Andean environmental and climate synthesis for the last 2000 years BP from terrestrial pollen and charcoal records of Patagonia. Clim. Past 11, 2121–2157.
Sottile, G.D., Meretta, P.E., Tonello, M.S., Bianchi, M.M., Mancini, M.V., 2015b. Disturbance induced changes in species and functional diversity insouthern Patagonian forest-steppe ecotone. For. Ecol. Manag. 353, 77–86.
Sottile, G.D., Tonello, M.S., Mancini, M.V., 2016. Potentiality of past vegetation land cover reconstruction in forest-high Andean steppe ecotone of Southern Patagonia, Argentina. First results. XIV International Palynological Congress, X International Organisation of Palaeobotany Conference; Salvador, Brasil.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.
Toggweiler, J.R., Russell, J.L., Carson, S.R., 2006. Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages. Paleoceanography 21, PA2005.
Tonello, M., Mancini, M.V., Seppä, H., 2009. Quantitative reconstruction of Holocene precipitation changes in southern Patagonia. Quat. Res. 72, 410–420.
Villalba, R., Lara, A., Boninsegna, J.A., Masiokas, M., Delgado, S., Aravena, J.C., Roig, F.A., Schmelter, A., Wolodarsky, A., Ripalta, A., 2003. Large-scale temperature changes across the southern Andes: 20th-century variations in the context of the past 400 years. Clim. Chang. 59, 177–232.
Villa-Martínez, R., Moreno, P.I., 2007. Pollen evidence for variations in the southern margin of the westerly winds in SW Patagonia over the last 12,600 years. Quat. Res. 68, 400–409.
Villa-Martínez, R., Moreno, P.I., Valenzuela, M.A., 2012. Deglacial and postglacial vegetation changes on the eastern slopes of the central Patagonian Andes (47°S). Quat. Sci. Rev. 32, 86–99.
Wenzens, G., 1999. Fluctuations of outlet and valley glaciers in the Southern Andes (Argentina) during the past 13,000 years. Quat. Res. 51, 238–247.
Wenzens, G., Wenzens, E., 1998. Late glacial and Holocene glacier advances in the area of Lago Viedma (Patagonia, Argentina). Zbl. Geol. Paläontol. 1, 593–608.
Wille, M., Schäbitz, F., 2009. Late-Glacial and Holocene climate dynamics at the steppe-forest ecotone in southermost Patagonia, Argentina: the pollen record from a fen near Brazo Sur, Lago Argentino. Veg. Hist. Archaeobotany 18 (3), 225–234.
Wille, M., Maidana, N.I., Schäbitz, F., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schleser, G.H., Zolitschka, B., 2007. Vegetation and climate dynamics in southern South America: the microfossil record of Laguna Potrok Aike, Santa Cruz, Argentina. Rev. Palaeobot. Palynol. 146, 234–246.
Zolitschka, B., Schäbitz, F., Lücke, A., Corbella, H., Ercolano, B., Fey, M., Haberzettl, T., Janssen, S., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike Volcanic Field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia. Argentina. J. S. Am. Earth Sci. 21, 294–309.