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A new record of paleoenvironmental conditions from the northeastern San Martín Lake Basin (Patagonia, Argentina): Vegetation reconstruction from pollen and carbon isotopes since 10,200 cal. years BP

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ARTÍCULO

A NEW RECORD OF PALEOENVIRONMENTAL CONDITIONS FROM THE NORTHEASTERN SAN MARTÍN LAKE BASIN (PATAGONIA, ARGENTINA): VEGETATION RECONSTRUCTION FROM POLLEN AND CARBON ISOTOPES SINCE 10,200 CAL. YEARS BP

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Abstract. In this research, we reconstruct the paleoenvironmental conditions from a sedimentary record of a wetland (*mallín*) located in the Patagonian steppe near to the Subantarctic forest on the northeastern shore of the San Martín Lake basin (SW Santa Cruz, Patagonia, Argentina). The Mallín Ñire (49° 00′ 23.5″ S; 72° 13′ 34.5″ W) presents a basal age of 10,200 cal. years BP and its pollen content, carbon isotopes, and stratigraphy were analyzed. The relationship with modern pollen assemblages from surface sediment samples allows us to interpret changes in the fossil record. Between 10,200 and 9,000 cal. years BP, we can infer a grass-shrub steppe with dwarf-shrubs under arid conditions and between 9,000 and 6,500 cal. years BP, a grass steppe dominated under an increase of moisture availability. Conditions became drier until 4,000 cal. years BP; later, a grass-shrub steppe developed, which suggests an environmental transition like the modern ones. The last 1,400 cal. years BP present high paleoenvironmental variability. The integration with other sequences allowed us to interpret the regional changes during the Holocene related to moisture availability by precipitation changes related to the westerly variations.

Key words. Vegetation communities. Holocene. Pollen analysis. Carbon isotopes. Patagonia. Wetland. Paleoenvironmental reconstruction.

Resumen. UN NUEVO REGISTRO DE CONDICIONES PALEOAMBIENTALES PARA EL NORESTE DE LA CUENCA DEL LAGO SAN MARTÍN (PATAGONIA, ARGENTINA): RECONSTRUCCIÓN DE LA VEGETACIÓN A PARTIR DEL POLEN E ISÓTOPOS DE CARBONO DESDE 10.200 CAL. AÑOS AP. En la presente investigación reconstruimos las condiciones paleoambientales a partir de un registro sedimentario de un humedal (mallín) localizado en la estepa Patagónica cercano al bosque subantártico de la margen noreste de la cuenca del Lago San Martín (SO Santa Cruz, Patagonia, Argentina). A partir del Mallín Ñire (49° 00′ 23,5″ S; 72° 13′ 34,5″ O) se analizó el contenido polínico, los isótopos de carbono y estratigrafía desde los 10.200 cal. años AP. La relación con las asociaciones polínicas de muestras de sedimento superficial nos permitió interpretar cambios en el registro fósil. Entre 10.200 y 9.000 cal. años AP, inferimos una estepa graminosa-arbustiva con sub-arbustos bajo condiciones áridas, y entre los 9.000 y 6.500 cal. años AP dominó una estepa graminosa bajo un incremento en la disponibilidad de humedad. Las condiciones se tornaron más secas hasta los 4.000 cal. años AP y luego se desarrolló una estepa graminosa-arbustiva lo que sugiere un ambiente de transición como los actuales. Los últimos 1.400 cal. años AP presentaron una alta variabilidad paleoambiental. La integración con otras secuencias nos permitió interpretar los cambios regionales durante el Holoceno en relación a la disponibilidad de humedad por cambios en la precipitación relacionada a variaciones en los vientos del oeste.

Palabras clave. Comunidades de vegetación. Holoceno. Análisis polínico. Isótopos de carbón. Patagonia. Humedal. Reconstrucción paleoambiental.

SOUTHERN PATAGONIA is an area of great value for paleoenvironmental studies due to its environmental, topographic, and climatic characteristics. Several studies for vegetation communities reconstructions from different types of deposits in Southern Patagonia were carried out. Changes in the vegetation response related to the precipitation pattern by the position and strength of the westerlies (*e.g.*, Heusser, 2003; Markgraf *et al.*, 2003; Mancini, 2009; Markgraf &

Hubber, 2010; Sottile *et al.*, 2012; Echeverría *et al.*, 2018, 2022; Vilanova *et al.*, 2019; Marcos *et al.*, 2022a), as well as the climatic patterns and the dynamics of the glaciers (*e.g.*, Glasser *et al.*, 2004, 2011; Villa-Martínez & Moreno, 2007; Moreno *et al.*, 2012; Flantua *et al.*, 2016; Lüning *et al.*, 2018; Horta *et al.*, 2019) were analyzed.

The Andes generate west–east precipitation gradients, reflected in the vegetation communities' composition. Southern westerly winds (SWW) are a component of zonal flow in the global atmospheric system that influences the precipitation patterns (Garreaud *et al.*, 2013), making it a susceptible area for the registration of paleoenvironmental changes through the Holocene (Fletcher & Moreno, 2012; Villa Martínez *et al.*, 2012; Moreno *et al.*, 2019). The knowledge of the modern pollen and vegetation relationships allowed us to interpret the vegetation communities' variations by changes in climatic conditions and topographic characteristics (Mancini, 2002; Bamonte *et al.*, 2015; Mancini *et al.*, 2018; Echeverría *et al.*, 2022) in Patagonia since the Pleistocene–Holocene transition. The paleoenvironmental and paleoecological investigations by pollen, charcoal, and macro-fossil analysis in southern Patagonia, provided vital information about vegetation distribution at different scales (*e.g.*, Huber & Markgraf, 2003; Markgraf *et al.*, 2003; Bamonte & Mancini, 2011; Sottile *et al.*, 2012; Echeverría *et al.*, 2018, 2022; Mancini *et al.*, 2018; Mosquera & Mancini, 2021; Marcos *et al.*, 2022a). The arid conditions before the beginning of the Holocene were inferred by an expansion of more arid steppes toward the west. These conditions could have been the result of a southward shift of the westerlies. During the early Holocene, forest expansion was registered in the Andean zone, whereas in the extra-Andean areas, grass, and shrub/grass steppes developed. Intensification of the westerlies for the mid Holocene favored forest development in the Andean areas. Moisture conditions variations were reflected in the vegetation heterogeneity at smaller scale, mainly by the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) events that characterized the late Holocene (Echeverría *et al.*, 2022). Different areas for Patagonia presented evidence for anthropic impact since the 19th century (Flantua *et al.*, 2016).

Mancini *et al.* (2018) presented a preliminary isotopic analysis from two sedimentary sequences located NW of Santa Cruz at 47°S. This information, together with pollen analysis, allowed obtaining a more robust scenario of paleoenvironmental variations. The C_3 photosynthesis is practically exclusive in Patagonia (Paruelo *et al.*, 1998) and the $\delta^{13}C$ values for C_3 plants range between -38 ‰ and -22 ‰ with an average of -25 ‰ (Fritz & Fontes, 1980; Sanchez *et al.*, 1986; Panarello & Sánchez, 1985). Thus, the relationship between pollen and isotopic information (lower $\delta^{13}C$ values) suggests the presence of C_3 plants associated with forest taxa (Mancini *et al.*, 2018). They inferred vegetation changes from a forest-shrub steppe transition in the mid Holocene to a shrub steppe development during the late Holocene. Other studies about pollen/$\delta^{13}C$ relationship at lower latitudes in the Andean piedmont were carried out (Rojo *et al.*, 2018). In northwest Patagonia, a $\delta^{13}C$ analysis as part of a multi-isotope study for the late Pleistocene and Holocene was made (Panarello *et al.*, 2018). In southern Patagonia, lowest $\delta^{13}C$ values were obtained as part of paleoecological aspects. Higher $\delta^{13}C$ values in the Deseado Massif, where precipitation decreases concerning to the west, are directly related with climatic variables as moisture availability, temperature, and arid conditions (Tessone & Belardi, 2010; Tessone *et al.*, 2020a, 2020b; Tessone, 2022).

In this paper, we reconstruct the paleoenvironmental changes since 10,200 cal. years BP from a sedimentary sequence from the Patagonian steppe and close to the *Nothofagus* forest. Also, we integrate those inferences in a paleoenvironmental scenario at regional scale. The analysis of modern pollen and vegetation relationship is taken into account to interpret the paleoenvironmental information obtained.

Study area

The San Martín Lake basin located in the southwest-central zone of the Santa Cruz Province (49° S; 72° W; Fig. 1) is a proglacial lake that is in contact with the Southern Patagonian Ice Field by its western area (Horta *et al.*, 2019). Its northeastern shore is within limits of a system of subdued moraine ridges that encloses the eastern arms of San Martín Lake with an age of 22.4 ± 2.3 ka years BP according to Glasser *et al.* (2011). A chronology of lacustrine and glaciolacustrine levels of the San Martín Lake basin was presented by Horta *et al.* (2019), who showed that the water levels would have reached the maximum expansion around 12 ka years BP and the initial contraction started around 11 ka years BP, generating the current configuration of the coastlines. Bahía La Lancha (Fig. 1.2), located at 345 m.a.s.l. in the northeastern of the basin, is an outcrop of lacustrine sediments that presents a basal age of 10,361±30 ka years BP (12,111 cal. years BP) when the levels of the Tar and San Martín lakes stabilized and the current landscape was shaped (Horta *et al.*, 2019). A wetland sedimentary deposit (*mallín*) from the northeastern shore was selected for fossil sequence extraction (Mallín Ñire, MÑ) for the paleoenvironmental reconstruction.

This area is characterized by a temperate-cold climate with an annual mean temperature below 5 °C (Borrelli & Oliva, 2001). The topographic conditions generate a rain-shadow effect from 800 mm in the west of the San Martín Lake basin to 200 mm in the east (Paruelo *et al.*, 1998; Borrelli & Oliva, 2001), which is reflected in the vegetation patterns.

The San Martín Lake area belongs to the Patagonian Phytogeographic Province (Fig. 2.1; Movia *et al.*, 1987; Oyarzabal *et al.*, 2018). *Nothofagus* forest covers the west of the basin (Movia *et al.*, 1987) and limits a wide ecotone with the *Festuca pallescens* grass steppe accompanied by *Rytidosperma pictum*, *Lathyrus magellanicus*, and low shrubs such as *Senecio sericeonitens* and *Mulinum spinosum*. This unit covers the southern and eastern areas of the basin (Fig. 2.1). To the northeast of the basin, the *Nardophyllum bryoides* shrub steppe is dominated by low shrubs and grasses (mainly *Festuca pallescens*) and in contact with this unit to the east, the dwarf-shrub steppe develops (Fig. 2.1; Oyarzabal

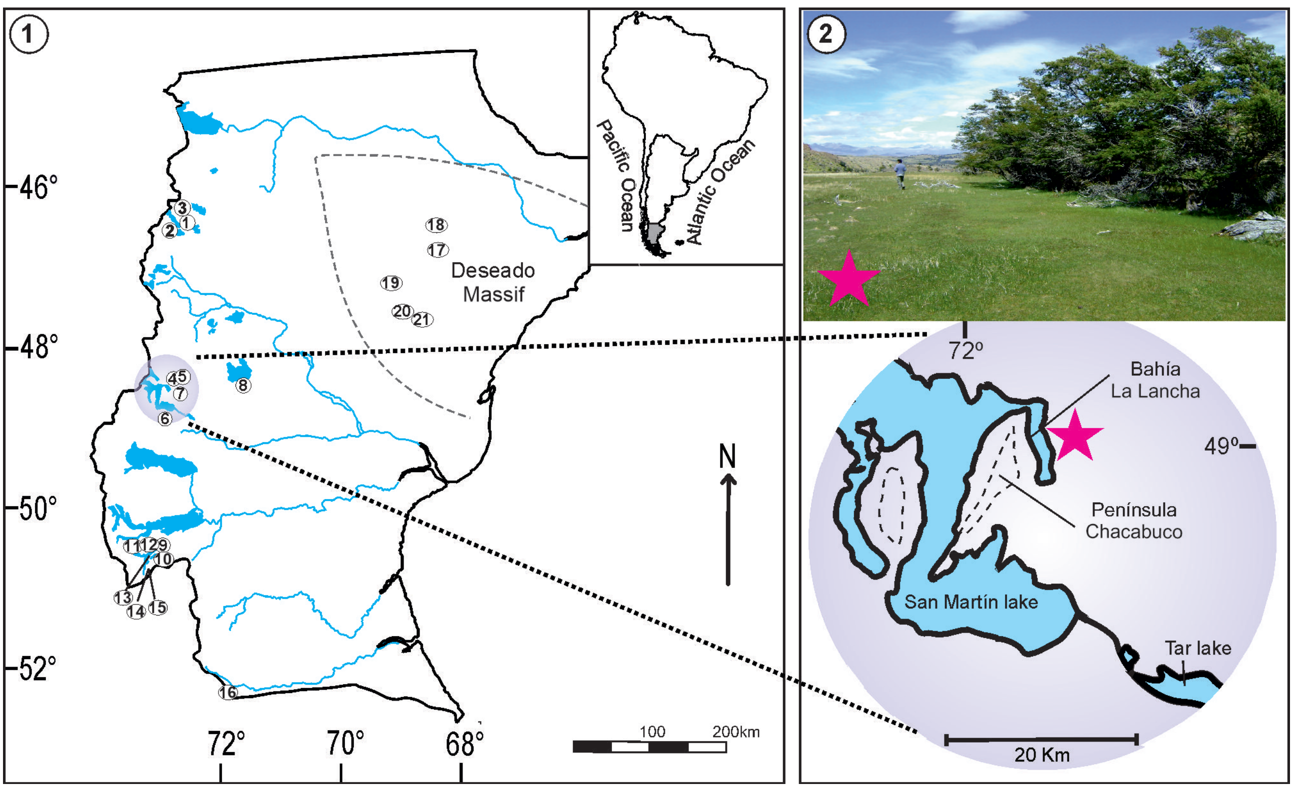

Figure 1. 1, Map of southern South America and Santa Cruz Province showing the sites considered in the text: 47–48° S, 1-Los Flamencos (Marcos *et al.*, 2022a); 2-Zorro Bayo (Marcos *et al.*, 2022b); 3-Cueva Milodon Norte 1 (Horta *et al.*, 2016; Marcos *et al.*, 2020); 49° S, 4-Mallín Paisano desconocido (Bamonte *et al.*, 2015); 5-Cueva Paisano Desconocido (Bamonte *et al.*, 2013; Bamonte & Marcos, 2019); 6-La Tercera (Bamonte & Mancini, 2011); 7-Mallín Ñire (this paper); 8-Lago Cardiel (Stine & Stine, 1990; Markgraf *et al.*, 2003); 50° S, 9-Cerro Frías (Mancini, 2009); 10-Chorrillo Malo 2 (Mancini, 2002); 11-Península Avellaneda Alto (Echeverría *et al.*, 2018; Sottile *et al.*, 2020); 12-Península Avellaneda Bajo (Echeverría *et al.*, 2018); 13-Brazo Sur (Wille & Schäbitz, 2009); 14-Vega Ñandú (Villa-Martínez & Moreno, 2007); 15-Lago Guanaco (Moreno *et al.*, 2009); 16-Río Rubens (Huber & Markgraf, 2003; Huber *et al.*, 2004); Deseado Massif, 17-Mallín La Primavera (Mosquera & Mancini, 2021); 18-Los Toldos (Paez *et al.*, 1999); 19-La Martita (Mancini, 1998); 20-La Gruta (Mancini *et al.*, 2013; Brook *et al.*, 2015); 21-Mallín La Esmeralda (Franco *et al.*, 2020). **2,** San Martín Lake basin zoom (the star represents the Mallín Ñire location) and corresponding photography of the site.

et al., 2018). The MÑ is dominated by *Cyperaceae matrix* and trunks and specimens of *Nothofagus antarctica* (*ñire*), as shown in Figure 1.2. *Nothofagus antarctica* is a native forest species with remarkable plasticity to adapt to a great variety of environmental conditions, growing in sites with excessive humidity, such as wetlands, bogs, and marshes (Peri & Ormaechea, 2013).

Paleoenvironmental background for the area. La Tercera sequence (Fig. 1.1; Bamonte & Mancini, 2011) was analyzed for the paleoenvironmental reconstruction of the southern shore of the San Martín Lake basin. This fossil sequence with a basal age of 11,300 cal. years BP allowed us to understand the paleoenvironmental variation for this area. To the north of the lake, the Mallín Paisano Desconocido sequence (Fig. 1.1; Bamonte *et al*., 2015), which corresponds to the last *ca*. 6,600 cal. years BP, was analyzed, and next to this, the Cueva Paisano Desconocido (CPD) archaeological site (Fig. 1.1; Bamonte *et al*., 2013), which corresponds to a temporary window at *ca*. 7,700 cal. years BP. For this reason, the comparative analysis between archaeological sites with continuous sedimentary sequences strengthened paleoecological studies. However, although the interpretations from archaeological sites provided information of interest, it was necessary to consider taphonomic problems that may have occurred at the site so that the interpretations were reliable (Marcos *et al*., 2019, 2020). Despite the lack of paleoenvironmental information for the early Holocene and part of the middle Holocene for the northeast of the basin (see fig. 7 in Echeverría *et al*., 2022), the available information was of great value to interpret the variations in the vegetation communities associated with climatic changes conditions at a regional scale. In this sense, MÑ provided information that complemented the previously available one, and helped generate a framework of paleoenvironmental variations since the beginning of the Holocene for the basin area. In general terms, arid conditions were inferred between 11,300 and 9,500 cal. years BP for the southern shore of the lake. So, the limits of the vegetation communities were displaced toward the west (Bamonte & Mancini, 2011). The early Holocene was characterized by an increase in moisture availability, as reflected by the development of a grass steppe, while toward the middle Holocene up to 4,200 cal. years BP, conditions must have become less humid as observed from the increase in shrubby elements (Bamonte & Mancini, 2011; Bamonte *et al*., 2013, 2015). For the last 4,000 cal. years BP, the development of a grass steppe associated with higher humidity levels was inferred. Finally, the last century was characterized by an increase in shrub vegetation and indicators of anthropic impact (Bamonte & Mancini, 2011; Bamonte *et al*., 2015; Echeverría *et al*., 2022).

Modern pollen and vegetation relationship in the area. The vegetation patterns proposed by Oyarzabal *et al.* (2018) and

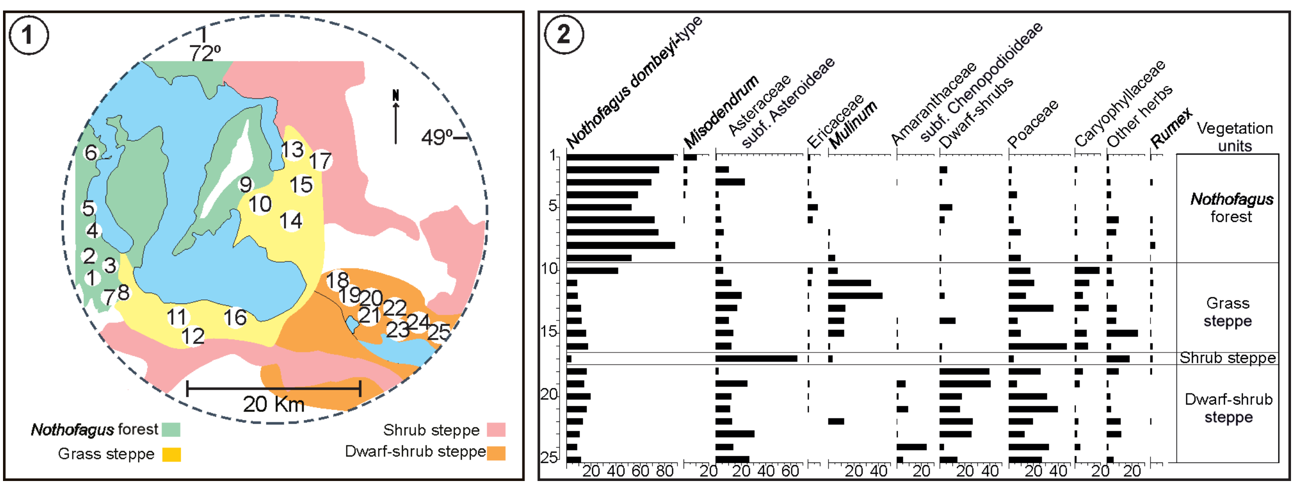

Figure 2. 1, Modern vegetation units from San Martín Lake basin modified from Movia *et al.* (1987) and 25 surface pollen samples for the area; **2,** Pollen diagram in percentage (%) modified from Bamonte & Mancini (2011) and Echeverría *et al.* (2022). "Other herbs" category groups Rubiaceae, Convolvulaceae, Ranunculaceae, Polemoniaceae, Malvaceae, Valerianaceae, Lamiaceae, *Osmorhiza*, and Orchidaceae, and "Dwarf-shrubs" includes *Ephedra*, *Nassauvia*, and *Azorella*.

the relationship with pollen assemblages from four areas between 46° and 51° S from Santa Cruz Province reviewed by Echeverría *et al.* (2022) were the first step for the paleoenvironmental research (Fig. 2). The authors described four pollen units for the San Martín Lake basin (Fig. 2.2): 1-Forest*:* this unit is characterized by high percentages of *Nothofagus* (40–95%) together with the mistletoe *Misodendrum* (<10%). The herbaceous layer is represented by Poaceae and the shrubs by Asteraceae subf. Asteroideae. 2-Grass steppe: Poaceae dominate (75%), accompanied by other herbs and shrubs with relatively low values (up to 15%). However, samples with *Mulinum* (15–45%) are characteristic of the western grass steppe in contact with the forest in a wide ecotone. 3-Shrub steppe: this unit is represented by high values of Asteraceae subf. Asteroideae (25–70%) together with shrubs and matrix of herbs. 4-Dwarf-shrub steppe: it is characterized by Asteraceae subf. Asteroideae (up to 30%), dwarf-shrubs (*Nassauvia* and *Ephedra*), and Amaranthaceae subf. Chenopodioideae (up to 45%), while Poaceae present values between 5 and 50% and lower values of other herbs. The modern-pollen vegetation relationship for the area allowed us to interpret the vegetation communities' changes in the fossil record, contributing with highly precise reconstructions.

MATERIAL AND METHODS

Material

The core MÑ (4.37 m; 49° 00′ 23.5″ S; 72° 13′ 34.5″ W; Fig. 1) was obtained from a Cyperaceae wetland located in the northeastern shore of San Martín Lake using a Livingstone piston corer. The core was sampled every 1 cm for further proxy studios. The modern pollen-vegetation relationship model, published by Bamonte & Mancini (2011) and Echeverría *et al.* (2022), was used to interpret the fossil changes.

Methods

Chronology. The chronology of the sediment sequence was based on six radiocarbon dates. These radiocarbon dates were obtained at the Direct AMS-Radiocarbon Dating Service-Bothell, USA, and NSF-Arizona AMS Laboratory-Tucson, USA. Radiocarbon dating was calibrated using the CALIB 8.2 program (Stuiver & Reimer, 1993; Stuiver *et al.*, 2021) and the Southern Hemisphere curve (SHCal 20) (Hogg *et al.*, 2020). In Table 1 we present the calibrated ages obtained from this run. The proposed age model was made using the Southern Hemisphere curve (SHCal 20; Hogg *et al.*, 2020) and a Bayesian-type age-depth model built using the Bacon package-R program (Blaauw & Christen, 2011).

Lithostratigraphic characterization. A lithological description was made and an analysis of organic matter and carbonated content was realized by loss-on-ignition (LOI). The samples were dried at 105 °C for 24 hours, ignited at 550 °C for 4 hours and at 950 °C for 2 hours in a muffle furnace (Bengtsson & Enell, 1986; Heiri *et al.*, 2001). Each of these steps allowed the loss of water, organic matter, and carbonates, respectively.

Carbon isotopes. The isotopic analysis was made at the Instituto de Geocronología y Geología Isotópica, Universidad de Buenos Aires, Consejo Nacional de Investigaciones Científicas y Técnicas (INGEIS-UBA-CONICET). Carbon isotopes

TABLE 1. Radiocarbon and calibrated age from MÑ fossil sequence

Depth (cm)	Laboratory N°	^{14}C BP	Median probability (cal BP)	2 range	Material
45–47	D-AMS 024163	1193 ± 25	1021	961 – 1080	organic sediment
91–92	D-AMS 036891	1756 ± 31	1628	1561 – 1701	wood
150–151	AA102756	3058 ± 41	3217	3073 – 3353	organic sediment
221–223	D-AMS 024162	3681 ± 29	3964	3868 – 4086	organic sediment
311–312	AA102755	6679 ± 39	7520	7430 – 7579	organic sediment
430–431	AA89408	9033 ± 50	10,172	10,113 – 10,245	organic sediment

were determined ($\delta^{13}C$). For this study, 29 samples were analyzed, every 16 cm. The samples were dried at 60 °C and roots and plant remains were discarded by manual harvesting and/or removal by flotation in 0.01 M HCl. Then, the samples were sieved and the soil fraction less than 0.2 mm was used for the analysis (Hoefs & Schidlowski, 1967; Panarello, 1987 and modifications). Results are expressed considering Samec *et al.* (2019) in the notation $\delta^{13}C$ per mil (‰) relative to the standard V-PDB (carbon) Vienna Pee Dee Belemnite and normalized to the NBS19-LSVEC scale (calcium carbonate-lithium carbonate isotopic reference materials) as follows:

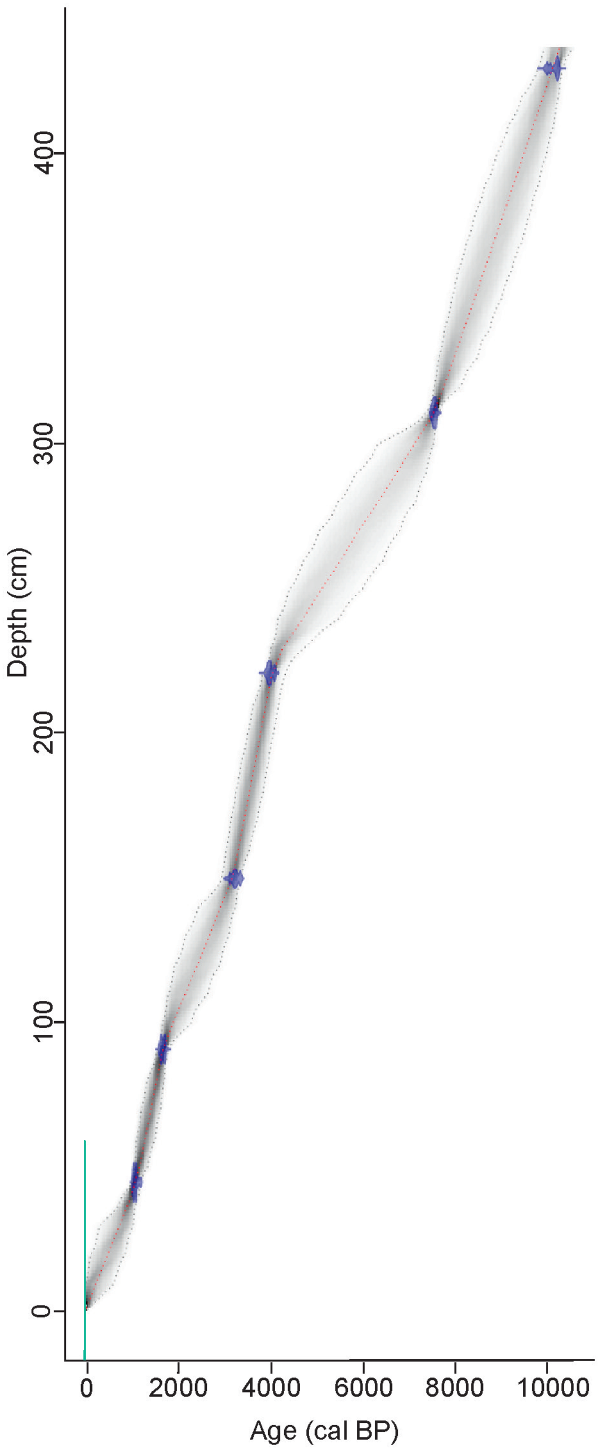

Figure 3. Age-depth model from the MÑ.

$$\delta^{13}C= [(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{VPDB} / (^{13}C/^{12}C)_{VPDB}] \times 10^3$$

Pollen analysis. The pollen analysis was carried out at the Laboratorio de Paleoecología y Palinología, Instituto de Investigaciones Marinas y Costeras, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional de Mar del Plata (IIMyC-CONICET-UNMdP). The fossil samples were dried at 60 °C before pollen analysis. In each sample (weighing between 0.3 and 4.3 g) *Lycopodium clavatum* spores were added and sieved through 120 μm mesh screens. Wood remains (<1 cm) were collected in this step for later identification and results are presented as "wood remains presence". The samples were treated following Faegri & Iversen (1989) standard procedures for pollen extraction: KOH 10% to remove clay and humic acids, HCl 10% to remove carbonates, $ZnCl_2$ (δ= 2 g/ml) to separate the mineral fraction by flotation (this step was omitted in some samples in which the sedimentology showed a high content of organic matter), HF to remove silicates, and finally acetolysis. Each taxon was expressed as a percentage of the total pollen sum. Cyperaceae was excluded because it represents local vegetation; similarly, *Myriophyllum*, Zygnemataceae, and *Botryococcus* algae were also excluded from the analysis for representing wetland components. *Rumex* was excluded because it is related to anthropic impact and *Podocarpus* because it represents an extra-regional taxon. *Nassauvia*, *Ephedra*, and *Azorella* were grouped as "dwarf-shrub" vegetation. Fabaceae, Malvaceae, Asteraceae subf. Cichorioideae, *Lathyrsus*, Ranunculaceae, Asteraceae subf. Mutisiaeae, Euphorbiaceae, *Gunnera*, and Urticaceae were included in the "other herbs" category. The samples were grouped by cluster analysis using the TILIA program (Grimm, 2004), applying square root transformation with

Edwards's dissimilarity coefficient and Cavalli-Sforza's chord distance to distinguish pollen zones, considering taxa that reach at least 2% of the sum of terrestrial pollen.

RESULTS

Chronology

The age-depth model is based on six radiocarbon dates (Tab. 1). The basal age of the MÑ sequence is 10,200 cal. years BP. This model allows interpreting paleoenvironmental variations in this temporal range (Fig. 3).

Stratigraphy – Loss on ignition (LOI)

The sequence is composed mainly by organic sediment and clay layers (Fig. 4). From the base of the sequence at 437 cm to 366 cm, the sediment is composed of a mix of organic sediment with clay layers. Following, there is a package of clay until 266 cm. The next 30 cm present a mix between organic matter and clays. From 237 cm until the top is composed by organic sediments. The results generated by LOI analysis show that the highest percentages of organic matter are present in these 237 cm, reaching 80%, whereas in the base of the sequence, the organic matter reaches 40% in some samples. On the other hand, the carbonates appear around 400–375 cm with values up to 55%, and from 325 cm to 275 cm they reach 35%, where the sediment is mainly composed by clays. In the rest of the sequence, the carbonates present values lower than 5% (Fig. 4).

Carbon isotopes

The $\delta^{13}C$ values show variations between -25.7 ‰ at 8,400 cal. years BP and -30.4 ‰ at the top of the sequence. Specifically, between 7,000 and 5,000 cal. years BP, isotopic

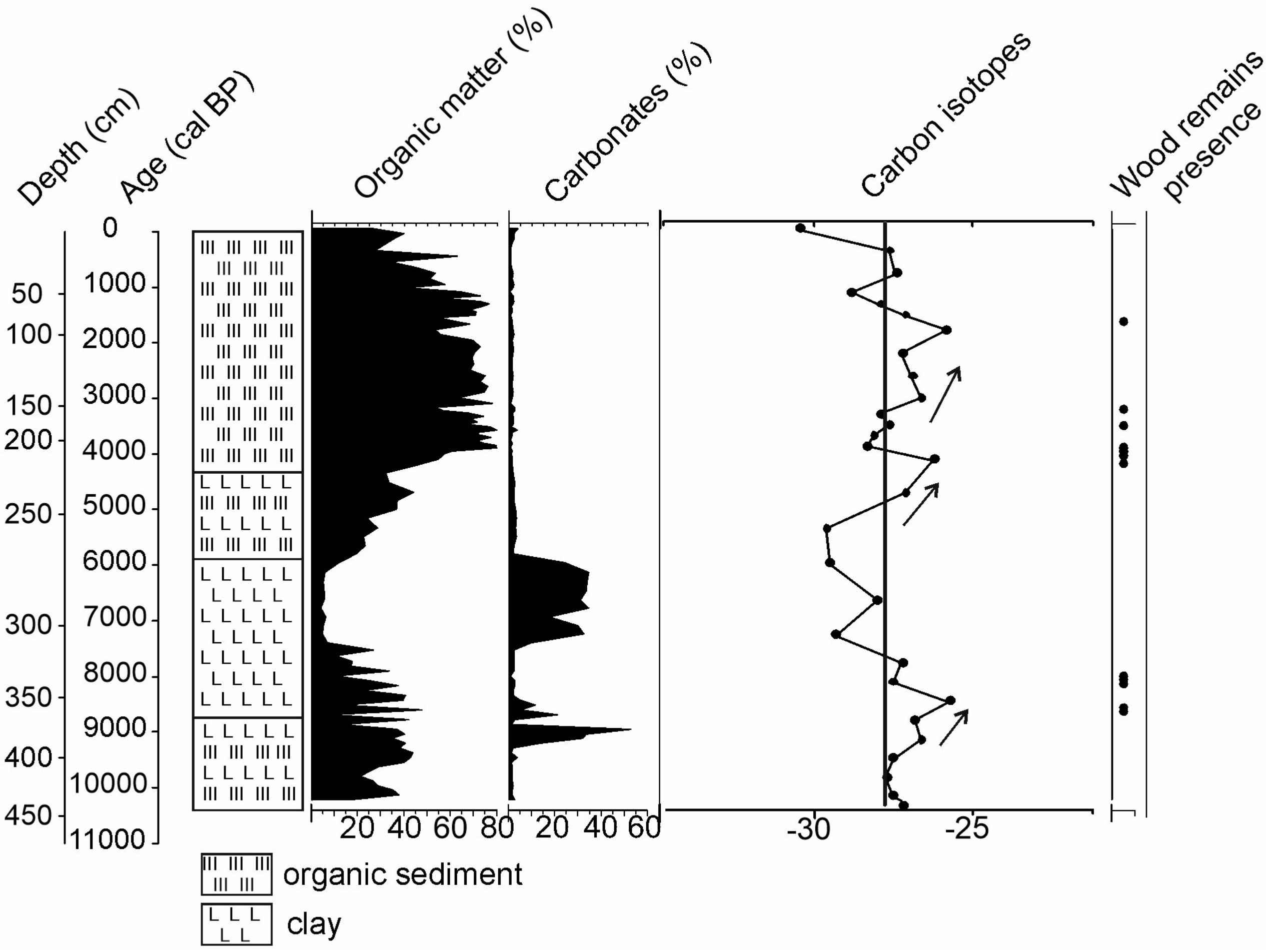

Figure 4. Stratigraphy, loss-on-ignition carbon isotopes (arrows indicate a positive correlation between Cyperaceae and $\delta^{13}C$ values), and *Nothofagus* wood remains from the MÑ.

values are the lowest, between -29.6 ‰ and -28 ‰. Between 10,200 and 8,000 cal. years BP and between 5,000 and 1,400 cal. years BP, the isotopic values register variations between -28.3 ‰ and -25.7 ‰ (Fig. 4). The organic matter source is environment-dependent with different $\delta^{13}C$ compositions, so the C_3 terrestrial plants (herbs, shrubs, and trees) show $\delta^{13}C$ values between -38 ‰ and -22 ‰ (Fritz & Fontes, 1980; Panarello & Sánchez, 1985; Sanchez *et al.*, 1986), which are likely dominant throughout the record. Slightly enriched values occur in the sequence, which may reflect compositional changes to the plant com-munity on the wetland. A positive correlation is observed between Cyperaceae development and $\delta^{13}C$ values (Fig. 4).

Wood macro-fossil remains

The presence of woods (>1cm long) is registered between 8,600–8,000 cal. years BP, between 4,100–3,100 cal. years BP, and at 1,600 cal. years BP (Fig. 4). The wood macro-fossil remains correspond to *Nothofagus* sp.

Fossil pollen record

The pollen sequence is divided into four zones according to cluster analysis (Fig. 5).

Zone 1 (437–288 cm; 10,200–6,600 cal. years BP). This zone was divided into three subzones.

Subzone 1a (437–370 cm; 10,200–9,000 cal. years BP). This subzone is characterized by Poaceae (32–58%) and Asteraceae subf. Asteroideae (5–30%). The "other herbs" category (Asteraceae subf. Cichorioideae and Asteraceae subf. Mutisiaeae) and Caryophyllaceae, Monocotyledoneae, Valerianaceae, Rubiaceae, *Acaena*, and *Gentianella* present values <10%. Amaranthaceae subf. Chenopodioideae, the "dwarf-shrubs" (*Ephedra* and *Azorella*), and the shrubs *Mulinum* and Ericaceae present values <5%. *Nothofagus* reaches 25% and Cyperaceae 65%. Zygnemataceae algae reach 40%.

Subzones 1b and 1c (370–288 cm; 9,000–6,600 cal. years BP). These subzones are characterized by Poaceae (17–60%), Asteraceae subf. Asteroideae (up to 20%) accompanied by Monocotyledoneae (15%), Caryophyllaceae and *Acaena* (<10%), and herbs such as Valerianaceae, Brassicaceae, *Acaena*, Rubiaceae, and *Gentianella* (<5%). Among the shrubs, Ericaceae reaches 10% and Solanaceae, 5%. *Nothofagus* reaches up to 47% and Cyperaceae ranges between 31–86%.

Zone 2 (288–224 cm; 6,600–4,000 cal. years BP). This zone is characterized by Asteraceae subf. Asteroideae (22%) and

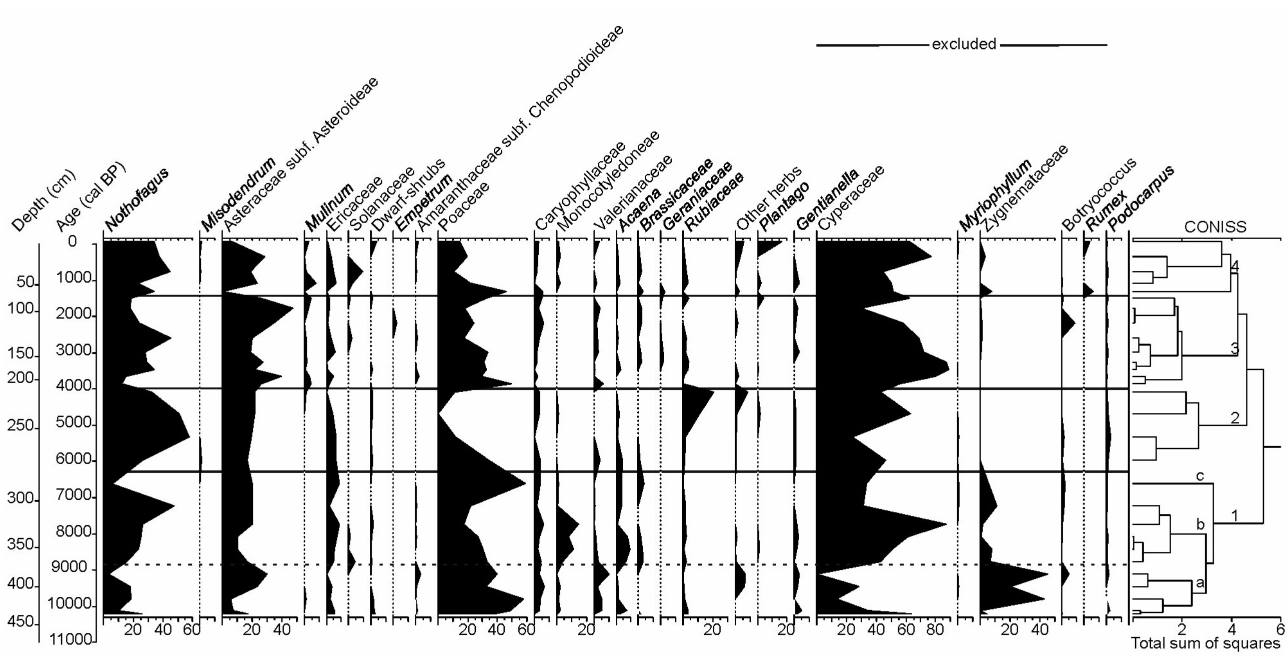

Figure 5. Pollen fossil diagram from the MÑ (in percentages). **CONISS** (constrained incremental sum of squares cluster analysis).

a marked decrease of Poaceae (up to 34%). Among the shrubs Ericaceae presents values up to 10% and among the herbs, Rubiaceae presents values up to 21%, whereas the rest of the herbs present values lower than 5%. *Nothofagus* reaches 60% and *Misodendrum* is represented by very low values (<2%). Cyperaceae ranges between 23–63%.

Zone 3 (224–73 cm; 4,000–1,400 cal. years BP). The zone is characterized by Asteraceae subf. Asteroideae (47%) and Poaceae (50%). Ericaceae presents values <10%, *Mulinum* reaches 5% and the rest of the shrubs <5%. Among the herbs are Caryophyllaceae and Valerianaceae (<10%) and the rest of the herbs with values lower than 5% are present. *Nothofagus* reaches up to 45%. Cyperaceae presents values up to 88%.

Zone 4 (73–0 cm; 1,400–present cal. years BP). In the last zone, Asteraceae subf. Asteroideae reaches 30% and Poaceae 45%. Among the shrubs are represented Ericaceae (<10%), *Mulinum* (5%), "dwarf-shrubs" (*Nassauvia*, *Azorella)* (5%), and Amaranthaceae subf. Chenopodioideae (<2%). Among the herbs, we find *Plantago* (16%), Geraniaceae, and Caryophyllaceae (<10%) and "other herbs" (<5%). *Nothofagus* reaches 45% and *Misodendrum* is present in low values (<2%). Cyperaceae is represented by 62%. *Rumex* appears with 6%.

DISCUSSION

Modern pollen data

Pollen and vegetation relationship studies at different scales along the west-east precipitation gradient were applied in the interpretation of fossil samples from southern Patagonia at a regional scale (*e.g.*, Mancini *et al.*, 2012; Marcos & Mancini, 2012; Bamonte *et al.*, 2015; Echeverría *et al.*, 2022). The modern pollen data suggests a close relationship between pollen-vegetation representation and precipitation gradient in the San Martín Lake basin area (Fig. 2; Bamonte & Mancini, 2011; Echeverría *et al.*, 2022). This analysis shows that the forest vegetation unit is represented by *Nothofagus* pollen and the mistletoe *Misodendrum*. The dominance of Poaceae associated with "other herbs", Caryophyllaceae, and *Mulinum*, represent the grass steppe unit. The shrub steppe is characterized by Asteraceae subf. Asteroideae (Bamonte & Mancini, 2011) and the eastern arid steppes by "dwarf-shrubs" (*Ephedra*, *Nassauvia*, *Azorella*) and Poaceae (Fig. 2). As indicated by another fossil sequence located in the northeastern zone of the basin (Bamonte *et al.*, 2015), the fossil pollen record is influenced by local and extra-local pollen input. The forest pollen signal may be related to the intensification and weakening of the west wind. These conditions allow for the development of a forest in the Península Chacabuco slope (Fig. 1.2), whereas the herbs and shrubs pollen types are related to local conditions.

Wetland dynamic

The relatively low values of Cyperaceae, accompanied by *Gentianella*, a herb that grows in wetlands and lagoon shores (Guerrido & Fernandez, 2007), and the algae Zygnemataceae, could be indicating that from the base of the sequence at 10,200 until 9,000 cal. years BP, the wetland had wetter conditions. These conditions also were registered by the laminated sediment with intermediate values of organic matter and the highest carbonates values at the end of this period. Between 9,000 and 7,500 cal. years BP, the increase of Cyperaceae accompanied by *Gentianella* contributed to the input of organic matter content. Together with the Zygnemataceae decrease, it may be indicating less free water availability in the wetland, giving place to *Nothofagus* growth. The presence of *Nothofagus* wood remains between 8,600 and 8,000 cal. years BP also contributed to the organic matter input on the wetland surface. Toward 6,000 cal. years BP, Zygnemataceae algae and Cyperaceae decrease together with the organic matter input and the sediment is composed mainly of clays. Between 6,500 and 4,500 cal. years BP, the organic matter increases together with the Cyperaceae values, although with minor fluctuations in their values. Cyperaceae presents the highest values between 4,000 and 1,400 cal. years BP, adding organic matter to the deposit, which registers the high percentages values; *Gentianella* also contributes to the organic matter input suggesting it grew on the wetland. Between 4,100 and 3,100 cal. years BP, there are some remains of *Nothofagus* woods. These remains are a good contribution of organic matter to the deposit and appear after the moment of the highest pollen recording of *Nothofagus*. However, the values of this continue to be relatively high. From 1,400 cal. years BP to present, Cyperaceae continues with high values, contributing to organic matter. In wet seasons, Zygnemataceae and *Botryococcus* developed (Figs. 4, 5).

The positive correlation between Cyperaceae development and δ^{13}C values is probably due to this family including plants with a C_4 photosynthesis pathway (Fig. 4). Therefore, when there was an increase in Cyperaceae pollen percentages, the isotopic values shifted toward less negative values. Extant Cyperaceae grows on the wetland surface; for this reason, it is considered as a local element and its variations are mainly used to analyze the wetland dynamics. For this reason, the Cyperaceae variations throughout the sequence could have generated higher values of δ^{13}C.

Vegetation reconstruction around MÑ from 10,200 cal. years BP

Between 10,200 and 9,000 cal. years BP, the pollen assemblages reflect a grass-shrub steppe dominance represented by Poaceae accompanied by Asteraceae subf. Asteroideae with some herbs, Amaranthaceae subf. Chenopodioideae and "dwarf-shrubs" (*Ephedra* and *Azorella*) (Fig. 5). The dwarf-shrub pollen presents lower values in relation to the present dwarf-shrub steppes (Fig. 2), suggesting the conditions were drier than the modern ones. This information is consistent with the δ^{13}C average values for this period (-27.2 ‰).

Since 9,000 and until 6,500 cal. years BP, the pollen assemblages show a dominance of Poaceae accompanied by other herbs (Fig. 5). These conditions could reflect an increase in the precipitation. *Nothofagus* values also increase, suggesting the development of a forest. Ericaceae and *Nothofagus* indicate the presence of forest in the Andean zone, Península Chacabuco, and in the wetland area (Fig. 1.2) mainly between 8,000 and 7,000 cal. years BP, a period for which low δ^{13}C values (mean: -28.08 ‰) were registered. The presence of *Nothofagus* wood in this period (Fig. 4) indicates that it not only expanded in the Andean zone but also grew in the wetland area.

Between 6,500 and 4,000 cal. years BP, a retraction in the grass steppe and an increase in the shrub steppe and forest elements were registered. However, within this period, we can recognize vegetation changes succession. Between 6,500 and 5,000 cal. years BP, the pollen record shows an increase in *Nothofagus* together with *Misodendrum* and Ericaceae, suggesting a forest development. Between 5,000 and 4,000 cal. years BP, the pollen record shows a shrub steppe characterized by a smooth increase of Asteraceae subf. Asteroideae associated with some herbs that may have grown between the shrub matrix. *Nothofagus* pollen values together with Ericaceae decrease gradually toward 4,000 cal. years BP (Fig. 5). The increase in forest pollen types (*Nothofagus* and *Misodendrum*) is consistent with low δ^{13}C values (mean: -29.5 ‰) between 6,500 and 5,000 cal. years BP. Later, between 5,000 and 4,000 cal. years BP, the decrease of *Nothofagus* and the moderate increase of shrubs corresponds to more enriched δ^{13}C values (mean: -26.6 ‰) (Fig. 4). However, the forest signal can also come from the nearby slope.

Between 4,000 and 1,400 cal. years BP, the presence of shrubs and grasses increase, showing a more heterogeneous environment. Until 2,500 cal. years BP, the pollen record suggests a grass-shrub steppe dominated by Poaceae and Asteraceae subf. Asteroideae, accompanied by other subordinate herbs (Fig. 5). *Nothofagus* appears together with *Mulinum*, suggesting an ecotonal environment similar to the current conditions. The presence of *Nothofagus* wood remains support this idea. Ericaceae continues with relatively constant values throughout the sequence; however, forest elements seem to decrease compared to the previous period. Between 2,500 and 1,400 cal. years BP, *Nothofagus* and Ericaceae decrease smoothly and Asteraceae subf Asteroideae with other shrubs (*Mulinum* and *Empetrum*) increase, suggesting a shrub steppe development. δ^{13}C values until 2,500 cal. years BP average -27.7 ‰. Later, these values decrease when the forest decreases its pollen representation.

During the last 1,400 cal. years BP a shrub-grass steppe developed, dominated by Asteraceae subf. Asteroideae and Poaceae, accompanied by a diversity of herbs. The presence of Ericaceae together with *Mulinum* suggest a transitional environment between the steppe and the forest (Figs. 2, 5). During the last centuries, the "dwarf-shrubs" (*Nassauvia*, *Azorella*) and Amaranthaceae subf. Chenopodioideae took over. Signals of human impact are represented by *Rumex* and *Plantago*. Although *Plantago* could be associated with impact conditions for the last century, there are native species such as *P. correae* and *P. patagonica* (Correa, 1999).

The lowest $\delta^{13}C$ values at the top of the sequence (-30.5 ‰) could be related to forest elements increasing on the wetland. The foliar and soil $\delta^{13}C$ from *N. antarctica* were determined by Peri *et al.* (2012) as -30.4 ‰ and -26.8 ‰, respectively. The vegetation contributes to soil carbon through the deposition of leaves and dead roots (Peri *et al.*, 2012). However, these foliar and soil values, as well as the low $\delta^{13}C$ recorded at the top of the sequence, could be the consequence of changes in atmospheric $\delta^{13}C$ by the Suess Effect; this implies algebraically adding +1.5 ‰ to be compared with fossil samples (Keeling, 1976; Keeling *et al.*, 2017).

Regional interpretation

For the regional interpretation, we consider different sequences from lakes/lagoon, peat/wetlands, and archaeological sites located at 47–48° S (Pueyrredón Lake basin); at 49° S (San Martín Lake basin); at 50° S (Argentino Lake basin); and the Deseado Massif, as shown in Figure 1.

10,200–9,000 cal. years BP. Aridity conditions were inferred from a grass-shrub steppe with some dwarf-shrubs developed for MÑ between 10,200 and 9,000 cal. years BP. On the southern shore of the San Martín Lake, Bamonte & Mancini (2011) analyzed a pollen record from La Tercera (Fig. 1.1), which includes the Pleistocene–Holocene transition. La Tercera pollen record reflects assemblages that are similar to those that are dominant in the dwarf-shrub steppe nowadays under arid conditions until 9,500 cal. years BP. The grass steppe expansion and the high fire frequency for continuity in the fuel suggest an increment in the precipitations toward 9,000 cal. years BP (Bamonte & Mancini, 2011; Sottile *et al.*, 2012).

Records from the Deseado Massif (Fig. 1.1) showed high values of *Ephedra*, suggesting a dwarf-shrub steppe under very arid conditions (Paez *et al.*, 1999). However, other sites in the south of Deseado Massif presented evidence of a grass steppe with dwarf-shrubs and wetter conditions than the present (Mancini *et al.*, 2013; Brook *et al.*, 2013, 2015; Franco *et al.*, 2020).

To the south, in the Argentino Lake area from Cerro Frías and Chorrillo Malo 2 pollen sequences (Fig. 1.1), a grass steppe was recorded up to 9,500 cal. years BP when the forest signal increased, suggesting a change from dryer to wetter conditions (Mancini, 2002, 2009). The Península Avellaneda Alto (Fig. 1.1) sequence shows a grass steppe in a dry environment with a high diversity of shrubs and herbs previous to 9,000 cal. years BP,when the *Nothofagus* signal increases (Echeverría *et al.*, 2018; Sottile *et al.*, 2020). Similar conditions were registered for the Brazo Sur sequence (Wille & Schäbitz, 2009) and other southern sites as Vega Ñandú (Villa Martínez & Moreno, 2007) and Río Rubens (Huber *et al.*, 2004), among others (Fig. 1.1).

The vegetation reconstruction for the early Holocene from CMN1 archaeological site, located on the Pueyrredón Lake basin (Fig. 1.1), indicated a dwarf-shrub-grass steppe characterized by Poaceae and *Empetrum*, pointing to dry conditions at the area (Horta *et al.*, 2016).

The reconstructions from fossil sites located at both Andean and extra-Andean areas, as well as the Patagonian plateau, suggest a weakening of the westerly winds at the beginning of this period. Dry conditions are inferred for the extra-Andean areas of the basins at the Argentino, San Martín, and Pueyrredón lakes by the development of arid and semi-arid steppes, in contrast to those recorded for the Deseado Massif. By the end of this period, the slight increase in the forest signal in the southwest sites and in MÑ could be related to a strengthening of the westerly winds with increased humidity and temperature for these areas, and a marked precipitation gradient. However, according to Tonello *et al.* (2009), the precipitations in the extra-Andean areas were lower than the present. Until 9,500 cal. years BP, a sharp drop occurred in the San Martín Lake levels by the opening of the Ice Field associated with the drainage of the bodies of water into the Pacific Ocean. These variations in lake levels may be related to the balance of the ice masses that produced local advances and retreats of glaciers (Horta *et al.*, 2019) and changes in the atmospheric circulation and temperature increase.

9,000–6,500 cal. years BP. A grass steppe development was inferred from MÑ between 9,000 and 6,500 cal. years BP. This condition could be associated with an increase in moisture availability. From La Tercera (Fig. 1.1), wetter conditions were registered from a grass steppe developed at least until 8,000 cal. years BP, when an increase of shrubs and decrease of grasses were recorded. Moreover, an increase in *Nothofagus* around 8,000–7,500 cal. years BP suggests a forest expansion in the Andean zone (Bamonte & Mancini, 2011). In MÑ, *Nothofagus*, together with Ericaceae, could have expanded both in the Península Chacabuco and in the wetland, resulting in a wide ecotone between the forest and the grass steppe. Wood remains from *Nothofagus,* between 9,000 and 8,000 cal. years BP, would support this idea. Also, low δ^{13}C values from MÑ between 8,000 and 6,500 cal. years BP could be related to forest fluctuations, as indicated by Mancini *et al.* (2018) for the SW of Santa Cruz. The archaeological site CPD (Fig. 1.1), in the north-eastern part of the basin, also suggests moisture availability until 7,700 cal. years BP (Bamonte *et al.*, 2013; Bamonte & Marcos, 2019).

Lake level data from Lago Cardiel suggest wet conditions until 7,500 cal. years BP (Stine & Stine, 1990; Markgraf *et al.*, 2003). Similar conditions were inferred from Mallín La Primavera until 7,700 cal. years BP (Fig. 1.1; Mosquera & Mancini, 2021). At the Deseado Massif, a shrub-grass steppe dominated by Asteraceae subf. Asteroideae would be related with dwarf-shrubs (*Nassauvia* and *Ephedra*) before 8,000 cal. years BP. After that, a change in the shrub steppe composition suggests a gradual increase in the temperature and a decrease in the water availability (Brook *et al.*, 2015).

From the Cerro Frías (Fig. 1.1) pollen record, we infer the development of an open *Nothofagus* forest and the contraction of the grass steppe between 8,000 and 7,000 cal. years BP. Then, the forest signal decreases between 7,000 and 6,000 cal. years BP (Mancini, 2009). The Brazo Sur (Fig. 1.1) pollen record also recorded high *Nothofagus* pollen values at 7,500–7,000 cal. years BP (Wille & Schäbitz, 2009). In addition, in the Península Avellaneda Alto, an increase of the same taxa is shown at 8,000 and 7,000 cal. years BP, together with a high abundance of *Nothofagus* remains due to the rise in SWW precipitation (Echeverría *et al.*, 2018; Sottile *et al.*, 2020). In other sites, as Río Rubens, Lago Guanaco, and Vega Ñandú (Fig. 1.1), a *Nothofagus* dominance is registered around 7,700 cal. years BP (Huber and Markgraf, 2003; Villa-Martínez & Moreno, 2007; Moreno *et al.,* 2009). Finally, at 7,000 cal. years BP, the forest-steppe ecotone was established in the Chorrillo Malo 2 (Mancini, 2002).

In the area of the Pueyrredón Lake basin, a sequence from the Los Flamencos Lagoon (Fig. 1.1) was studied by Marcos *et al.* (2022a). They inferred that between 7,500 and 6,600 cal. years BP, the vegetation reconstruction was represented by patches of shrub accompanied by grasses in an ecotonal environment between forest and steppe, associated to wetter conditions or a shift eastward to the forest-steppe ecotone. The CMN1 archaeological site (Fig. 1.1) suggests the development of a grass steppe under moisture conditions (Horta *et al.*, 2016; Bamonte & Marcos, 2019; Marcos *et al.*, 2020). The first paleoenvironmental inference for the Pueyrredón Lake basin shows a grass-dwarf shrub steppe for 8,500 cal. years BP (Horta *et al.*, 2016, 2019).

The environmental heterogeneity for this period in the different areas is reflected in some communities' reconstructions, as a consequence to their different water requirements (Fig. 2). A more significant forest development can be inferred due to greater availability of humidity and a strengthening of the westerly winds. These conditions would have influenced the development of more arid steppes in the eastern areas.

6,500–4,000 cal. years BP. A shrub steppe increase was inferred from 6,500 until 4,000 cal. years BP, suggesting a decrease in moisture availability from MÑ. In this sense, an increase of *Nothofagus* was registered at the beginning of this period, meaning a high forest development in the Andean zone, and the low isotopic values could relate to the development of *Nothofagus* on the wetland. These conditions of moisture availability decrease were also registered in the Mallín Paisano Desconocido (Fig. 1.1; Bamonte *et al.*, 2015) and in La Tercera, together with low fire activity by fuel discontinuity (Fig. 1.1; Bamonte & Mancini, 2011; Sottile *et al.*, 2012) by an increase of shrubby communities, suggesting low moisture availability in the extra-Andean zone. According to this, Mallín Paisano Desconocido presents a forest development in the Andean area with relatively high Ericaceae values between *ca.* 6,000–5,000 cal. years BP (Bamonte *et al.*, 2015), probably related to increased moisture availability in Andean communities. The CPD archaeological site (Fig. 1), shows a change to more arid conditions since 7,700 cal. years BP (Bamonte *et al.*, 2013; Bamonte & Marcos, 2019).

In sites located in the north of the Deseado Massif (Fig.

1.1), the shrub steppe with *Ephedra* and low Cyperaceae values suggest dry conditions (Franco *et al.*, 2020; Mosquera & Mancini, 2021).

The Cerro Frías and Península Avellaneda Bajo records (Fig. 1.1) suggest a closed *Nothofagus* forest between 6,000 and 4,000 cal. years BP (Mancini, 2009; Sottile *et al.*, 2012; Echeverría *et al.*, 2014, 2018), probably due to an increase in SWW precipitation. In Península Avellaneda Alto (Fig. 1.1), a high abundance of *Nothofagus* macro-fossils indicate local forest expansion at the beginning of this period (Echeverría *et al.*, 2018). The Lago Guanaco site analysis suggests *Nothofagus* forest dominance at *ca.* 4,400 cal. years BP (Fig. 1.1; Moreno *et al.*, 2009).

The Los Flamencos Lagoon sequence (Fig. 1.1) shows a change to drier conditions under a heterogeneous environment by a shrub steppe of *Mulinum* and Asteraceae subf. Asteroideae, and other shrubs and dwarf-shrubs increase at *ca.* 5,000 cal. years BP (Marcos *et al.*, 2022a). Similar conditions were recorded at the CMN1 archaeological site (Fig. 1.1; Horta *et al.*, 2016; Bamonte & Marcos, 2019; Marcos *et al.*, 2020).

The environmental heterogeneity continues to be evident with forest developments in the Andean zone, especially at the beginning of this period which later decrease, and shrubby steppes in the extra-Andean areas. By the end of this period, the winds began to weaken.

4,000–1,400 cal. years BP. The pollen record from MÑ suggests a development from a shrub-grass steppe to a shrub steppe with herbs. These changes could be indicating a slight increase in moisture. The association between *Nothofagus*, Ericaceae, and *Mulinum*, mainly recorded until *ca.* 2,500 cal. years BP, indicates transitional environments such as the modern conditions (Fig. 2).

A gradual increase in the moisture availability was evidenced by a change from shrub-grass to grass steppe and a *Nothofagus* signal decrease from the Mallín Paisano Desconocido and La Tercera (Fig. 1.1; Bamonte & Mancini, 2011; Bamonte *et al.*, 2015). However, the conditions remained dry. The fuel continuity inferred from the La Tercera at *ca.* 2,500–1,500 cal. years BP favored a high fire frequency (Sottile *et al.*, 2012).

In the Deseado Massif, the records show a dominance of dwarf-shrub steppe taxa represented similar conditions to the modern and small-scale changes, resulting in heterogeneity regional vegetation patterns (Mancini, 1998; Brook *et al.,* 2015).

To the south, the Cerro Frías and Península Avellaneda Bajo pollen records indicate the development of grass-shrub steppe from 4,000 to 2,000 cal. years BP, suggesting a decrease in water availability (Fig. 1.1; Mancini, 2009; Echeverría *et al.*, 2018). High correlations between high fire frequencies and charcoal accumulation rates (CHAR) from the Cerro Frías record suggest an open forest landscape and intermediate modeled Pann values (~400 mm; Tonello *et al.*, 2009; Sottile *et al.*, 2012). From other southern sites, an open forest between 3,500–2,500 cal. years BP were also registered (Fig. 1.1; Villa Martínez & Moreno, 2007; Moreno *et al.*, 2009; Wille & Schäbitz, 2009). The moisture availability decrease was probably linked to westerly winds weakening. After that, an increase in forest development was registered.

From the Los Flamencos Lagoon (Fig. 1.1), between 3,500–3,000 cal. years BP, the pollen record shows a decrease of dwarf-shrubs and the development of a shrub steppe mainly composed of Asteraceae subf. Asteorideae, *Mulinum*, *Berberi*s, and an increase of herbs, suggesting higher moisture availability compared to the previous periods but similar to the current arid conditions for this area. Accordingly, the CMN1 archaeological site shows an ecotonal environment with moisture availability (Fig. 1.1; Horta *et al.*, 2016; Bamonte & Marcos, 2019; Marcos *et al.*, 2022a). Zorro Bayo sequence shows a shrub-grass steppe and the increase of forest elements, suggesting wetter conditions between 2,800 and 1,000 cal. years BP (Fig. 1.1; Marcos *et al.*, 2022b).

The extra-Andean records from the San Martín Lake basin suggest an increase in moisture availability evidenced by the abundance of grasses and ecotonal environments, which could be related to westerly winds weakening. In addition, the information obtained from *Nothofagus* values suggests a precipitation decrease in the Andean zone that would indicate an amelioration of westerly winds, allowing humid air masses to reach eastward into the steppe next to the Andes (Moy *et al.*, 2009; Sottile *et al.*, 2012). The Deseado Massif area presents vegetation patterns heterogeneity, representing oscillations in humidity-dryness.

1,400–present cal. years BP. The high paleoenvironmental variability during the last millennium was related to aridity events such as the Medieval Climate Anomaly (MCA, 950–750 cal. years BP) and the Little Ice Age (LIA, 380–50 cal. years BP) (Moy *et al.*, 2009).

For the last 1,400 cal. years BP, a shrub-grass steppe continues to develop in the area. *Mulinum* increases, suggesting a transitional environment between the forest and the steppe from MÑ.

The pollen record from the Mallín Paisano Desconocido (Fig. 1.1) shows a dominance of a grass steppe in the extra-Andean communities for the San Martín Lake basin during the MCA. There is a significant change at the beginning of MCA (*ca*. 400 cal. years BP) from grass to shrubby communities, similar to those that develop in the modern forest-steppe ecotone. The *Nothofagus* increase may be related to a slight forest re-establishment in the Andean zone. During the last centuries in MÑ, dwarf-shrubs could indicate drier and colder conditions potentially associated with the LIA. Changes in temperature and moisture availability may have driven important vegetation changes, favoring dominance of cushion plants such as *Mulinum*, *Azorella*, and Amaranthaceae subf. Chenopodioideae (Bamonte *et al.*, 2015). After 100 cal. years BP, a steppe with shrubs is inferred, indicating a trend toward lower moisture availability conditions. The La Tercera (Fig. 1.1) pollen spectra shows wetter conditions than today's, interpreted from an increase in herbs and a pronounced decrease in shrubs. This increment in fuel accumulation was reflected by the high levels of CHAR (Sottile *et al.*, 2012). However, decreased moisture availability was registered by an increase in Amaranthaceae subf. Chenopodioideae (Bamonte & Mancini, 2011).

In the Deseado Massif, heterogeneity environments similar to the modern were inferred for the last millennium (Fig. 1.1; Brook *et al.*, 2015)

Southern sequences, *i.e.*, the Cerro Frías, Península Avellaneda Alto, and Bajo and Brazo Sur (Fig. 1.1), have suggested an increase in moisture availability after 2,000 cal. years BP, due to the expansion of the forest, in turn related to the increase in global temperature during the MCA (950–750 cal. years BP) and in the precipitations due to SWW strengthening (Mancini, 2009; Wille & Schäbitz, 2009; Echeverría *et al.*, 2018). However, toward the end of this period (*ca*. 400 cal. years BP), lower moisture availability also was registered at the Cerro Frías. A trend from wet to dry conditions was recorded by an open forest signal (Mancini, 2009; Echeverría *et al.*, 2014). This trend could be related to the LIA (380–50 cal. years BP). The Chorrillo Malo 2 and records from other archaeological sites from the Argentino Lake basin show an increase in the grass steppe under cold and wet conditions for the last 1,000 cal. years BP (Mancini, 2002).

The paleoenvironmental conditions from archaeological sites at the Pueyrredón Lake area (Fig. 1.1) did not show significant changes since the previous period. For the last 1,000 cal. years BP, a change toward a decrease of moisture availability is evidenced by shrubs and dwarf-shrubs elements from Zorro Bayo by Marcos *et al.* (2022b).

CONCLUSIONS

The integration of pollen analysis and carbon isotopic data together with other complementary analyses such as the litho-stratigraphic description and the presence of wood macro-fossil remains allow us to reconstruct the vegetation communities changes associated with climatic variations and wetland dynamics of the northeastern shore of the San Martín Lake basin. The deposit evolution indicated changes from a wetland with laminated clayey sediment, characteristic of an environment with water availability that favors the development of algae, toward a deposit with less water availability and dominance of Cyperaceae from *ca*. 9,000 cal. years BP with signs of development of *Nothofagus* forests.

MÑ is a fossil pollen record that allowed us to reconstruct the paleoenvironmental conditions from the northeastern area of the basin, where no previous information between *ca*. 11,000 and 6,600 cal. years BP was available, complementing the paleoenvironmental reconstructions available for southern Patagonia. Synchronous changes in arid conditions can be observed between MÑ and La Tercera for this period. However, the drier conditions reflected by dwarf-shrub steppe elements are not so clearly evident in the northeastern shore of the basin (MÑ) as it is in the southern area until 9,000 cal. years BP. These arid conditions could have been the result from a southward shift of the westerly winds. At the beginning of the

Holocene, grass steppes developed, whereas in the Andean areas *Nothofagus* forests began to grow, indicating an increase in temperature and precipitation (Stine & Stine, 1990; Markgraf *et al.*, 2003). During the middle Holocene, a decrease in moisture conditions is inferred by the more xeric steppes in the extra-Andean area and the *Nothofagus* forest development in Andean areas. These lower humidity conditions in the MÑ area could be related to an intensification of the westerly winds, which caused a steep precipitation gradient. From 4,000 cal. years BP, an environment related to the transition between forest and steppe was inferred in MÑ. However, more significant environmental heterogeneity was observed from the different fossil sequences of southern Patagonia. This heterogeneity was related to climatic variability events recorded for the last millennium and impact indicators for the last century in response to the European settlement.

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