Research paper

A new multi-proxy record of environmental change over the last 1000 years on Chiloé Island: Lake Pastahué, south-central Chile (42ºS)

The Holocene
2019, Vol. 29(3) 421–431

DOI: 10.1177/0959683618816492
journals.sagepub.com/home/hol
SAGE

J Max Troncoso Castro,[1,2,3] Carolina Vergara,[1] Denisse Alvarez,[1,4] Gustavo Díaz,[1] Pablo Fierro,[5] Alberto Araneda,[1] Fernando Torrejón,[1] Mauricio Rondanelli,[2] Nathalie Fagel[6] and Roberto Urrutia[1]

Abstract

Knowledge of past environmental and climatic conditions of lake ecosystems on Chiloé Island on a millennial scale is limited. Hence, this study fills a gap in our understanding of this part of southern Chile. The aim of this study was to reconstruct the environmental and climatic history of the last 1000 years of Lake Pastahué through a multi-proxy sediment core analysis. The 1-m-long core was subsampled every centimeter for the organic matter, magnetic susceptibility, grain-size distribution, and biological indicator (pollen, chironomids) analyses. The age model was constructed from ^{210}Pb, ^{137}Cs, and ^{14}C activity. Pollen results revealed a North Patagonian forest composition represented by *Nothofagus, Weinmannia, Drimys, Tepualia*, Myrtaceae, Poaceae, and Pteridophyta. The abundance of *Rumex* and *Pinus* in the most recent part of the pollen assemblage reflects a clear anthropogenic impact. The sedimentological parameters and chironomid assemblage show similar variations, which highlight changes in the trophic state of the lake. The changes observed in all proxies suggest the influence of climate events such as the 'Medieval Climate Anomaly' (MCA) and 'Little Ice Age' (LIA). The variations observed since the beginning of the 20th century could be the result of the combined effect of anthropogenic activities and the increase in temperature recorded in south-central Chile and Patagonia.

Keywords

Chile, chironomids, last millennium, LIA, MCA, multi-proxy, pollen

Received 30 December 2017; revised manuscript accepted 28 September 2018

Introduction

It is important to understand environmental impacts and responses on different time scales to understand past, current, and future trends in climatic and environmental variations (Latorre et al., 2016). Such climatic variability has been described in the Holocene period (~the last 11,500 years), which has been characterized globally as a stage of great variability on millennial, centennial, and decadal time scales (Flantua et al., 2016). During the Holocene, human societies and agriculture developed and were themselves affected or modeled by this natural environmental variability (Moreno et al., 2009). These interactions among humans, the climate, and the environment have been little studied despite their historical importance, and knowledge of these climate changes in terms of their extent, magnitude, and recurrence is very limited (Mayewski et al., 2004). Numerous instrumental and paleoclimatic records have made it possible to effectively detect an increase in global temperature means since the mid-20th century (Ahmed et al., 2013; Jones and Mann, 2004). According to some authors, this warming trend is unprecedented in the context of the last millennium (Mann et al., 2009). Other researchers, however, consider it to be another cycle within the high variability of the Holocene climate (Esper et al., 2002; Soon and Baliunas, 2003). During this time period, the world climate has been unstable and two important climate events have been reported in the Northern Hemisphere: the 'Medieval Climate Anomaly' (MCA) and the 'Little Ice Age' (LIA). The MCA was a period with warmer temperatures between AD 800 and 1300, whereas the LIA was a period with a drop in temperatures between ca. AD 1300 and 1850 (Jones, 2001; Soon et al., 2003; Summerhayes, 2017). In both anomalies, the temperature changes involved increases or decreases of 0.5–1.5ºC compared with the global average (Soon et al., 2003). While the topic has been widely reported in the Northern Hemisphere, there are few publications

[1]School of Environmental Sciences, University of Concepción, Chile
[2]Laboratory of Palynology and Plant Ecology, University of Concepción, Chile
[3]School of Education and Social Sciences, Adventist University of Chile, Chile
[4]School of Science, Universidad Santo Tomás, Chile
[5]Institute of Marine Science and Limnology, Austral University of Chile, Chile
[6]AGEs-Clays, Sedimentary Environments and Geochemistry, Department of Geology, University of Liege, Belgium

Corresponding author:
J Max Troncoso Castro, School of Environmental Sciences, University of Concepción, Casilla 160-C, Concepcion 4451032, Chile.
Email: josemaxtroncoso@gmail.com

on it in South America (Haberzettl et al., 2005; Soon and Baliunas, 2003); hence, the discussion on the occurrence of these events in the Southern Hemisphere is ongoing (Mann, 2001). Some works have addressed the topic of the MCA and the LIA in Chile (Araneda et al., 2009; Bertrand et al., 2005; Carrevedo et al., 2015; Fletcher and Moreno, 2012; Villalba, 1994); however, there are very few that have used a multi-proxy approach to interpret climate behavior.

South America is the only land mass that transects almost the entire southern gradient from the tropics to the sub-Antarctic latitudes, thus making it an important place for the study and discussion of global climate dynamics (Fletcher and Moreno, 2012). Chiloé Island, in southern Chile (41–43ºS), is an important area to examine the interactions among the environment, climate, and anthropogenic impacts (Pesce and Moreno, 2014). Some paleoecological studies have been conducted in this island territory, but few have examined in detail the effects of recent climate change at high temporal resolutions using multiple biological and sedimentological indicators. Although these studies have recorded millennium-scale changes in precipitation and temperature since the Last Glacial (Henríquez et al., 2015; Maximum Abarzúa and Moreno, 2008), there has been no detailed analysis of the last millennium that shows the response of the environment to climate events manifested on this time scale and its relation to anthropogenic impacts.

Significant advances have been made in the study of the last millennium in Chile (Bertrand et al., 2005), as well as in recent multi-decadal and inter-annual reconstructions of temperature variations in the recent past in South America (Neukom et al., 2011). Yet, this information is still insufficient to establish the effect of recent climate change on the ecosystems and their response to anthropogenic disturbances.

Tree ring (Roig et al., 2001) and lake sediment records (Moreno et al., 2014; Urrutia et al., 2010; Von Gunten et al., 2009) have been used in the study of environmental, climatic, and anthropogenic changes during the late Holocene. These records have revealed significant changes over the last millennium, with some showing synchrony with the LIA (AD 1500–1850) and MCA (AD 800–1350) (Chambers, 2016), although the temporality and intensity of the climate signal often reveal disparities (Flantua et al., 2016).

Historical records serve as another proxy to reconstruct the environmental conditions of past centuries (Bradley and Jones, 1993), providing information with a high temporal resolution. Few reports on Chiloé Island include historical data (Abarzúa and Moreno, 2008) to allow an interpretation of human effects on the environment. Chiloé has historical records that date from its time as part of a Spanish colony, which can serve as a foundation for contemporary environmental reconstruction (Otero, 2006). Some environmental historical studies (Torrejón et al., 2004, 2011; Urbina, 2011) have indicated that a large part of the anthropogenic impact on the Island of Chiloé took place in the post-Hispanic period (>AD 1850), since the indigenous population used forests for private consumption and worked with rudimentary tools, and there is a lack of evidence that fire was used to clear vegetation; therefore, it is unlikely that their intervention had any significant effect on the environment (Torrejón et al., 2011). Against this background, we hypothesize that if the MCA and LIA were manifested on Chiloé Island, with magnitudes of change similar to those of the events in the northern hemisphere, it would be possible to track them through our multi-proxy approach that combines records from the watershed (pollen) and the lake itself (chironomids, sedimentological properties), as well as records from historical sources from the most recent periods.

This study presents a multi-proxy analysis of biological indicators (pollen and chironomids) and sedimentological indicators (organic matter (OM), magnetic susceptibility (MS), and granulometry) of a sediment core from Lake Pastahué (42º22′S; 73º49′W, 150 m a.s.l.), as well as historical records, in order to determine the environmental response to climate events and anthropogenic activities over the last 1000 years (MCA and LIA). The following questions are addressed:

- Are the MCA and LIA events evidenced in the sedimentary record on Chiloé Island?
- If so, how are they expressed and for how long?
- Did colonization affect this part of Chiloé and, if so, what was its impact on this lake ecosystem?

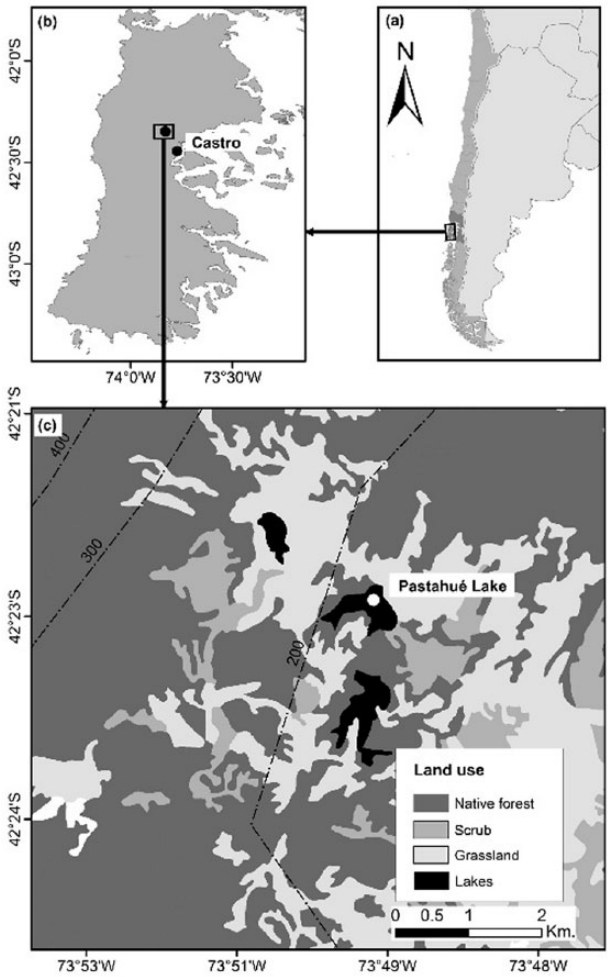

Figure 1. Location of Lake Pastahué: (a) South America, (b) the Island of Chiloé, and (c) current land use types and core location (42°22′S; 73°49′W).

Material and methods

Study area

Lake Pastahué (42°22′S; 73°49′W) is located 10 km NW of Castro at an altitude of 150 m a.s.l. (Figure 1) on the eastern side of Chiloé Island. The climate in the area is temperate rainy, with precipitation throughout the year, but less rain during summer. The precipitation pattern results from the displacement of the westerly wind belt toward the Equator in summer and toward the pole through the annual cycle, respectively. The annual average temperature is 11ºC, with winter temperatures reaching 0ºC and summer temperatures 17ºC. The average annual precipitation is 2500 mm. This ecosystem is located in the driest part of the island, with >4000 mm of annual rainfall on its western slopes and ~2000 mm on its eastern slopes (Dirección General de Aguas (DGA), 1987). It reflects the orographic effect of the coastal mountain range.

Table 1. AMS radiocarbon ages from bulk sediment or shells from Lake Pastahué.

Lab code	Material	Core depth	$\delta^{13}C$ (PBD)	^{14}C yr BP ± 1σ	Calibrate age (AD/BC) Min (mean) max
ETH-58315	Sediment	51.5	–28.3	1390 ± 28	AD 600 (AD 63) AD 670
ETH-58316	Sediment	66.5	–28.9	1580 ± 28	AD 410 (AD 480) AD 550
ETH-58317	Sediment	75.5	–24.2	1980 ± 28	BC 20 (BC 15) BC 10
ETH-58318	Shells (conchiolin)	103.5	–28.1	2390 ± 28	BC 490 (BC 445) BC 400

The Lake Pastahué sub-basin forms part of a small system of lakes associated with glacial morphogenesis (Arenas, 2001). It has a surface area of 0.4 km^2 and a maximum depth of 17 m. Hydrologically, it is a closed basin, in which no continuous surface effluents or tributaries are observed. There are no data regarding the thermal regime of this lake; however, information from Lake Auquilda (Arenas, 2001), which is located 500 m away and has the same origin and a similar shape and size, can be used as a reference. This lake has a monomictic temperate thermal regime, with thermal stratification between January and April, when the thermocline is at an approximate depth of 4.5 m. The maximum surface temperature is 19°C, with an almost 10º difference between the epilimnion and the hypolimnion. Lake Auquilda is characterized by an anoxic hypolimnion during the entire stratification period, a characteristic that it may share with Lake Pastahué. The annual variation in the water level of the lake likely fluctuates around 50 cm, using Lake Auquilda as a reference. A map of current soil use was obtained through the CONAF et al. (1997) native forest land registry and processed with ArcGIS 9.1 software (Figure 1). The study area presents a mixed productive structure of native forest, managed livestock pastures, and cropland. The native vegetation composition can be categorized as 'North Patagonian forest' (Schmithusen, 1956), the distributional center of which is between latitudes 41 and 43ºS. Some elements of the Valdivian forest are also observed throughout the entire study area, represented essentially by *Eucryphia cordifolia, Aextoxicon punctatum, Gevuina avellana, Amomyrtus meli*, and *Caldcluvia paniculata*. The dominant species are common to both the Valdivian forest and the North Patagonian forest, including *Myrceugenia planipes, Amomyrtus luma, Laureliopsis philippiana*, and *Nothofagus dombeyi* (Villagrán, 1985). The study area is therefore at the interface between those two regional formations.

Coring and sedimentological parameters

A 110-cm-long sediment core was obtained in the deepest part of the lake using an Uwitec gravity corer. Then, in the laboratory, the sediment core was divided lengthwise into two halves. One of these was used to determine MS and the other was cut every centimeter for the sedimentological and biological analyses. During the cutting, organic residue (shell) and bulk sediment were separated for the radiocarbon analyses (Table 1).

MS (in 10^{-8} SI) was measured using a Bartington susceptibility meter with an MS2E sensor at a resolution of 1 cm.

The OM content was estimated using the Loss-on-Ignition (LOI) technique. The analysis was performed at each centimeter of the sediment core. About 1 g of dry sediment was heated for 4 h at 550°C (Heiri et al., 2001). LOI550 variations are related to the OM input from the watershed and productivity changes in the lake system.

Grain-size analysis was performed with a Malvern Mastersizer 3000 laser particle size analyzer. About 5 mg of sediment were treated with H_2O_2 (30%) in a thermal bath to eliminate OM. The OM–free samples were then analyzed using water as a dispersant. The percentage by volume of each size fraction was analyzed using the Gradistat program.

Chronology and age model

The chronology was established by determining the radioisotopes ^{210}Pb, ^{137}Cs, and ^{14}C. ^{210}Pb and ^{137}Cs activity was analyzed by high-efficiency gamma spectrometry with a germanium detector, equipped with a cryocycle in the EPOC laboratory (Oceanic and Continental Environments and Paleoenvironments) at the University of Bordeaux, France. The ^{14}C AMS radiocarbon analyses were performed in the ETH laboratory in Zurich, Switzerland. Four samples were analyzed: three were bulk sediment and one the shell of *Diplodon* sp. (conchiolin) (Table 1).

For ^{210}Pb, the ages were obtained using the constant rate supply (CRS) model, which assumes a variable sedimentation rate over time. In order to obtain the radiocarbon ages, the ^{14}C values were calibrated with OxCal 3.10 software (Bronk Ramsey, 2005) using the SHCal13 calibration chart (Hogg et al., 2013). Finally, all the estimated ages were processed with R software using the Clam code (Blaauw, 2010) to construct the chronological model, assigning ages to undated layers using linear interpolation.

Pollen analysis

The samples were processed every 2 cm for palynological analysis using the classic methodology of Faegri and Iversen (1989). HCl (10%) was added to the dry sediment, with two tablets of *Lycopodium* added as a foreign marker to calculate the pollen concentration in grains per gram of dry sediment (Stockmarr, 1971). To perform the microscopic analysis, an aliquot of the pollen concentrate, of known volume, was mounted using the Hydromatrix mounting medium. The pollen grains were identified with the aid of the pollen atlases of Heusser (1971) and Markgraf and D'Antoni (1978), which specialize in the native vegetation of Chile and Argentina, respectively. The pollen count was determined under a Carl Zeiss Axiostar trinocular optical microscope (at magnifications of 10× and 40×). In all, 300 pollen grains per preparation were counted as the minimum, excluding fungal and fern spores. The pollen counts were organized in a data matrix, with the pollen type values expressed in percentages.

Chironomid analysis

For the chironomid analysis and processing, 30 samples taken every 2 cm (until a core depth of 60 cm) from the same core used for pollen were examined. A total of 600 head capsules from the sediment were processed based on the standard methodology for fossil chironomid preparation (Brooks et al., 2007). Next, the head capsules were separated under an Olympus SZ stereoscopic zoom microscope (10–40×), and for the final identification of the capsules, an Olympus CX31 trinocular optical microscope (10, 40, or 100×) was used. For the taxonomic determination of the head capsules, the chironomid identification guides of Brooks et al. (2007), Cranston (1996), Epler (2001), Ruiz-Moreno et al. (2000), and Massaferro et al. (2013) were consulted, which allowed a comparison of the extracted material with the current species, staying consistent with the taxonomy proposed for the Southern Hemisphere. The pollen and chironomid diagrams were constructed in the TILIA program (Grimm, 1987) and using the strat.plot function in the Rioja package (Juggins, 2017).

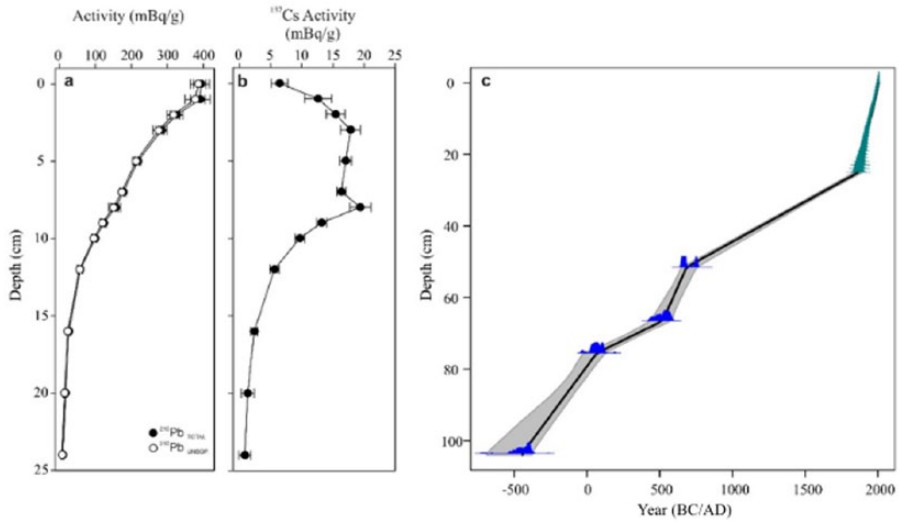

Figure 2. Age model of Lago Pastahué: (a) Isotope activity profile of ^{210}Pb (mBq/g) calculated according to a Constant Rate Supply (CRS) model. (b) Isotope activity profile of ^{137}Cs (mBq/g). Note the marked increase at 8 cm which according to the age model would correspond to AD 1964. (c) Age depth model constructed by linear interpolation with the R software and the Clam code (Blaauw, 2010). The upper part was calculated from Cs and Pb data, the lower part was derived from four radiocarbon ages: three were bulk sediment and one the shell of *Diplodon* sp. (conchiolin) (Table 1).

Data analysis

In order to determine the different associations in the profile, a cluster analysis of both pollen and chironomids was performed with CONISS (Grimm, 1987). The dissimilarity index or Euclidean distance gives the degree of similarity between the layers. This clustering method establishes the variance within the groups (Birks and Gordon, 1985). Once the percentage data on the pollen and chironomids were collected, a detrended correspondence analysis (DCA) was applied to determine the species turnover throughout the profile (Birks, 1998). This was done using the Vegan (Oksanen et al., 2015) and Rioja (Juggins, 2017) packages in R software. Finally, a broken-stick model test was used to determine whether the proposed zonings were statistically significant (Bennett, 1996).

Historical records

The use of historical records to reconstruct the past environments of Chiloé Island required an exhaustive selection and analysis of bibliographical sources from the 18th and 19th centuries. These were first-hand documentary sources, including geographic descriptions made by explorers of the area. Later, all the documentary historical data were analyzed, with a focus on references to the climatic aspects of the area. In addition, specialized dictionaries were used (Corominas, 1976; Novo and Chicarro, 1957; Real Academia Española, 1933) to allow the meaning of key concepts used by the explorers to be understood. Finally, the historical data were compared with data obtained through the analysis of the biological proxies.

Results

Sedimentological parameters

MS is stable from 110 to 8 cm, with only a small increase at 49 cm (4 SI $\times$ 10^{-8}). From 8 cm upward, it undergoes an exponential increase until the surface (20 SI $\times$ 10^{-8}). The mean grain size is relatively stable throughout the core. The abundance of OM presents some minor changes, increasing from 43% in the lowest part of the core (60–40 cm) to 49% in the upper part of the core (16–0 cm) (Figure 5).

Chronological model and sedimentation rates

^{210}Pb activity varied between 394 $\pm$ 22 and 10 $\pm$ 3 mBq, presenting a sharp decay as depth increased (Figure 2a). The application of the CRS model enabled the age of the most recent layers to be determined, which was validated with the ^{137}Cs profile. The profile of this last radioisotope (Figure 2b) showed a marked increase at 8 cm, which, according to the age model, corresponds to AD 1964 $\pm$ 1.1 (Figure 2c), coinciding with the period of greatest ^{137}Cs concentration in the Southern Hemisphere (Ribeiro Guevara and Arribére, 2002).

All the ages estimated from the ^{210}Pb and ^{14}C analysis maintained a stratigraphic order and were used for the chronological model of Lake Pastahué. The applied linear interpolation established that the sediment core spans the last 1400 years.

The sedimentation rates, calculated using the chronological model, varied between 0.02 and 0.10 cm/year in the deepest layers of the profile (100–25 cm), while an increase in the sedimentation rate between 0.20 and 0.26 cm/year occurred toward the surface layers, which correspond to the mid-18th century.

Pollen

The Lake Pastahué pollen record, along with the CONISS cluster analysis and the broken-stick model significance test, made it possible to identify three important areas in the sediment column (Figure 3). These zones, from the base to the surface, are described below.

Zone PI (60–31 cm; from ca. AD 600–1555). In this section, *Nothofagus antarctica*/*dombeyi* (30%), together with *Weinmannia trichosperma* (15%), *Tepualia stipularis* (15%), and *Eucryphia*/*Caldcluvia* (10%), dominates almost the entire spectrum. *Gaultheria* (5%) and *Escallonia* (5%) appear continuously in the scrub. Pasture grass appears consistently throughout this zone (3%), whereas the marshy component, represented only by Juncaceae, reaches 5%. Toward the end of this period, a decrease in thermophilic taxa (*Weinmannia, Tepualia, Eucryphia*/*Caldcluvia*, and *Fuchsia*) and a considerable increase in *Nothofagus antarctica*/*dombeyi* (35%) are observed. In the herbaceous layer, Poaceae is steady at 3%, whereas fungal spores remain at 5% throughout this zone. For the first time

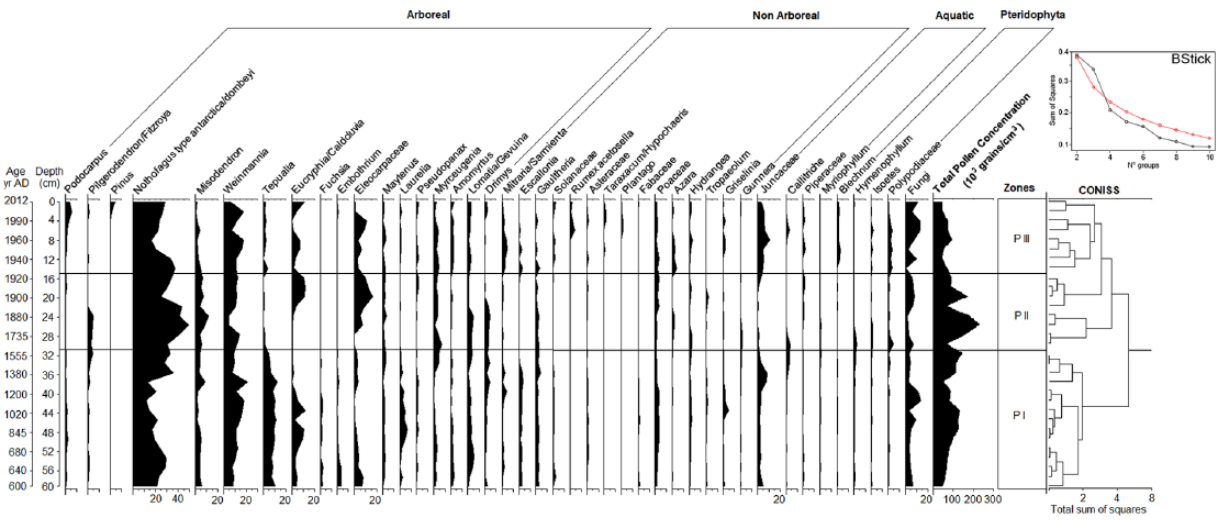

Figure 3. Pollen diagram of Lake Pastahué. The figure presents the percentage abundance of the plant species present in the sediment core >1%, with a minimum count of 300 pollen grains per depth. The observed stratigraphic zones (PI, PII, and PIII) are reported on the right scale. They were confirmed by CONISS statistical treatment. The broken-stick model is presented in the right inset (Bennett, 1996).

in the profile, the presence of *Callitriche* (3%) and ferns from the family Polypodiaceae (<3%) is noted. The pollen content suggests the establishment of a Valdivian forest.

Zone PII (31–15 cm; from ca. AD 1555–1920). From AD 1555 to 1800, new environmental changes are noted, under colder and more humid conditions. Aquatic taxa of the genera *Myriophyllum* (3%) and *Isoetes* (<3%) increase. *Callitriche* increases to 7% and the ferns *Blechnum, Hymenophyllum*, and Polypodiaceae, which altogether total 10%, appear. Regarding scrub, *Gaultheria* (6%) stays constant, whereas *Escallonia* disappears in this section. The arboreal layer is best represented in the profile by *Nothofagus antarctica/dombeyi* (35%) and *Pilgerodendron/Fitzroya* (5%); *Myrceugenia* and *Amomyrtus* have a greater presence than in the previous zone, with approximately 10%. *Drimys winteri* and *Lomatia/Gevuina* reach 10%, reinforcing the assumption of higher moisture in the system.

Later, from ca. AD 1880, *Weinmannia* consistently increases its participation until reaching 20%, with *Tepualia* reaching 15% and *Misodendrum* 10%. *Nothofagus antarctica/dombeyi* records a remarkable increase of 40%, whereas *Podocarpus* remains at 3%. Moreover, arboreal elements like *Drimys, Gevuina/Lomatia*, and *Laurelia* disappear. Meanwhile, the herbaceous component, with Poaceae (5%) and Asteraceae (<5%), stays the same. The minimal presence of aquatic elements in this section of the zone suggests a system with a warm-dry environment.

Zone PIII (15–0 cm; from ca. AD 1920–2012). This wide pollen zone is characterized by the reduction of woodland elements and the appearance of exotic taxa. *Nothofagus antarctica/dombeyi* reaches approximately 25%, while *Podocarpus* (<5%), *Weinmannia* (15%), and *Eucryphia/Caldcluvia* (10%) increase toward the top of the diagram. The presence of *Pinus* pollen is also observed in the arboreal layer, demonstrating the introduction of this fast-growing taxa. In the non-arboreal component, Poaceae remains at 3% and introduced plants – *Rumex* (3%), *Taraxacum/Hypochaeris* (3%), and *Plantago* (3%) – appear, indicating human activity. The marsh environment is represented by Juncaceae (5%), *Callitriche* (3%), and *Blechnum* (3%), while aquatic taxa appear intermittently. The ecosystem in this area of the diagram reveals the development of biological communities under warm conditions with reduced humidity and a clearly altered system.

Chironomids

The chironomid assemblage was composed mainly of 21 taxa, with the most abundant in the entire record being *Polypedilum* (50%), *Tanytarsini* 1A (30%), *Chironomus anthracinus* (5%), and *Labrundinia* (3%).

There were 600 head capsules for the entire record, with a low number in many of the analyzed centimeters. These low abundances meant that the broken-stick model used to test the significance of the CONISS cluster analysis indicated that no group was significant (Figure 4). Nevertheless, according to the main groups formed in the cluster, some tentative groups may still be suggested in CONISS, which could be useful for interpreting the chironomid behavior throughout the core sequence (Figure 4).

Zone CHI-I (60–31 cm; from ca. AD 600–1555). This zone is characterized by a great abundance of *Polypedilum*, which, however, presented low numbers at the beginning of the zone. Other taxa that present greater abundance throughout the record are *Gymnometriocnemus/Bryophaenocladius, Chironomus anthracinus, Apsectrotanypus*, and, to a lesser extent, *Riethia, Cladopelma, Cryptochironomus*, and *Parachironomus*. The tribes Tanytarsini 1B and Tanytarsini 1D show the greatest abundance in this zone.

Zone CHI-II (31–15 cm; from ca. AD 1555–1920). As in the previous area, *Polypedilum* continues its dominance, although it shows a marked decrease. Other taxa that reach their maximum abundance during this area include *Chironomus plumosus*, Tanytarsini 1A, Tanytarsini B, and Tanytarsini 1B. *Lymnophyes, Cricotopus*, and *Riethia. G./Bryophaenocladius* are completely absent from this zone.

Zone CHI-III (15–0 cm; from ca. AD 1920–2012). In this period, almost all the taxa in the assemblage present a decrease. *Polypedilum* exhibits an increase compared with the previous period, reaching one of its greatest abundance levels. *Ablabesmyia* also recovers its abundance in this period and Tanytarsini 1D reaches its maximum abundance. *Lymnophyes* presents a slight increase compared to zone CHI-I, although its abundance was more or less stable throughout the record. In contrast, *Chironomus plumosus* disappears completely at the beginning of this period.

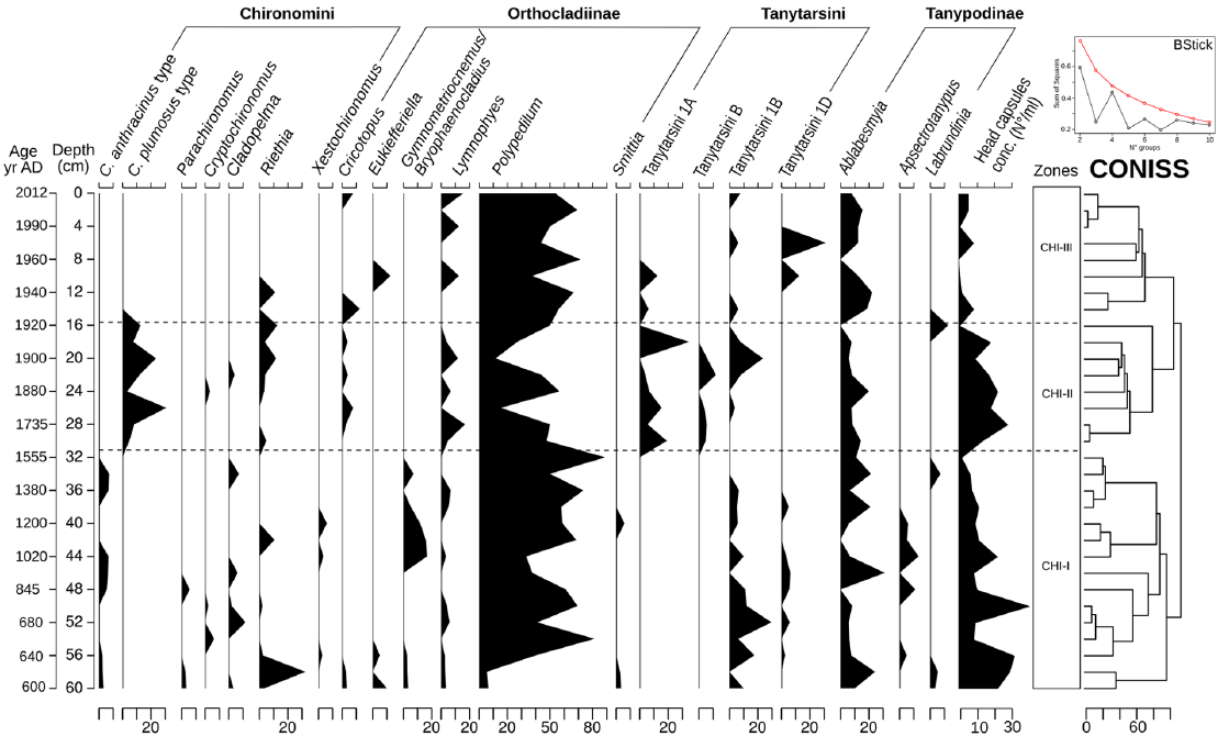

Figure 4. Chironomid diagram of Lake Pastahué. Percentage abundances of the species present in the sediment core >1% are presented. The results are derived from a total counting of 600 cephalic capsules for the entire registry. The stratigraphic zones (CHI-I, CHI-II, and CHI-III) and Coniss results are plotted on the right axis of the figure. The broken-stick model is presented in the right inset (Bennett, 1996).

Discussion

The Lake Pastahué sediment record allows a reconstruction of the climatic and environmental variations of the last 1400 years on Chiloé Island and provides information on the response of the lake system to natural and anthropogenic changes.

Temperature increase and manifestation of the MCA

Regarding pollen assemblages, the highest percentage of abundance of thermophilic taxa was observed in zone PI (Figure 3), between ca. AD 800 and 1300, and was characterized by taxa typical of the temperate Valdivian forest such as *Weinmannia trichosperma, Tepualia stipularis*, and *Eucryphia/Caldcluvia*, suggesting warm conditions in this period. This same trend was reported by Henríquez et al. (2015) in continental Chiloé between BP 7500 and 1000, a period characterized by high temperatures.

The absence of aquatic taxa in this period suggests a moisture shortage in the system, with only traces of marsh taxa that reveal to a certain extent the amphibious nature of the system (Troncoso et al., 2015). The low abundance of taxa characteristic of the Chiloé forest, represented in the diagram by *Myrceugenia* and *Amomyrtus*, and the gradual decrease of Elaeocarpaceae both indicate a decrease in precipitation and an increase in temperature. Warm conditions in this period were also recorded at Laguna San Pedro 38ºS (Fletcher and Moreno, 2012) and Laguna Escondida 45ºS (Elbert et al., 2013). A similar trend of warm conditions in the same time frame was observed in central Chile at Laguna Aculeo (34°S; Von Gunten et al., 2009), although with a delay (AD 1100–1350) in comparison with Pastahué.

The chironomid assemblage (Figure 4), despite having a low concentration of head capsules in the overall profile, presented some changes that may be associated with climatic or trophic variations. The presence of *Polypedilum*, a taxon typical of high-productivity environments, together with the greater abundance of *Gymnometriocnemus*/*Bryophaenocladius*, a taxon common to semi-terrestrial ecosystems, suggests the lake was influenced considerably by the terrestrial ecosystem or had a lower water level similar to that of a marsh. Massaferro et al. (2009) also identify *Polypedilum* as a taxon adapted to warm conditions, which, along with the characteristics of *Gymnometriocnemus*/*Bryophaenocladius*, make it possible to infer the prevalence of warmer, drier conditions in the area during the CHI-I period. This inference is reinforced by the presence of *Chironomus anthracinus* (Brooks, 2000) and *Labrundinia* (Pérez et al., 2013), both considered taxa typical of warm environments with low oxygenation, which are also coincident with increases in OM content in the sediment of up to 50% at some depths (Figure 5).

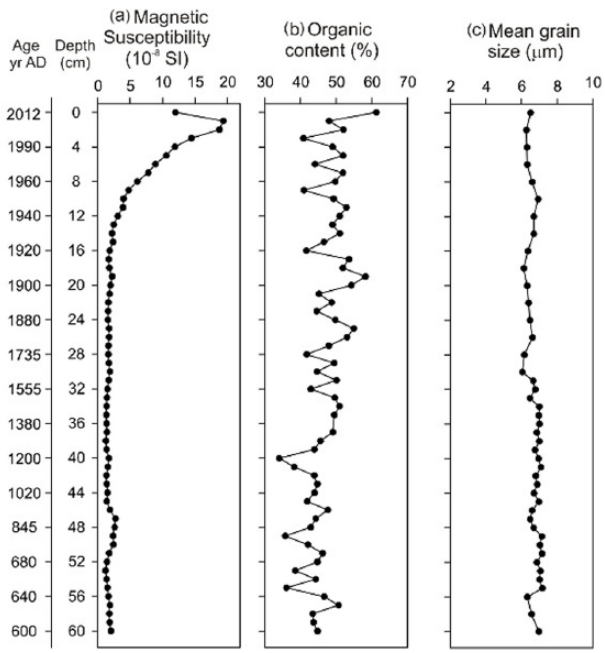

Figure 5. Sedimentological parameters: (a) Magnetic susceptibility in SI units × 10^{-8}, (b) content of organic matter derived from Loss-On-Ignition (LOI) at 550°C, and (c) particle mean size of the sediments.

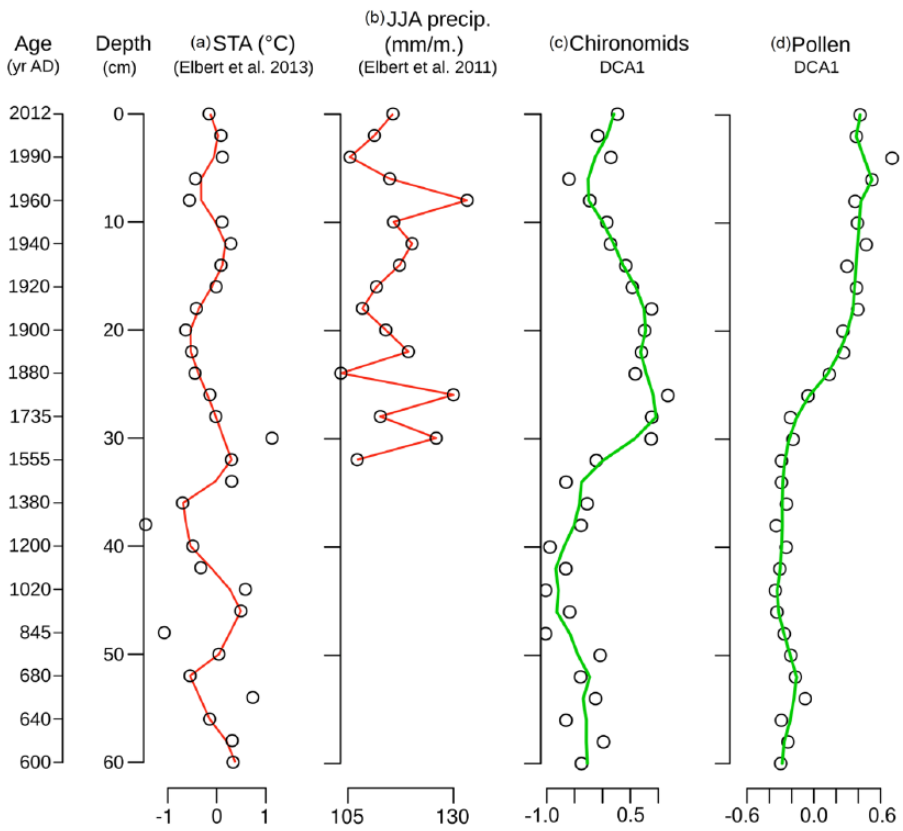

Figure 6. Comparison of DCA analyzes of pollen and chironomids from Lake Pastahué with regional records of precipitation and temperature. (a) Reconstruction of air temperature anomalies (STA°C) for the last 1600 years, Laguna Escondida (45°30′S), Elbert et al., 2013. (b) Reconstruction of winter precipitation, June-July-August (JJA), expressed in millimeters for month (mm/m) for the last 470 years, Lago Plomo (47°S), Elbert et al., 2011. (c) DCA of chironomids and (d) DCA of pollen.

Comparatively, and in a regional context, the DCA scores of the Lake Pastahué pollen and chironomids (Figure 6) present some similarities to those of a quantitative reconstruction of temperature records using biogenic silica (Elbert et al., 2013; Laguna Escondida 45ºS) and precipitation records using sediment laminations (Elbert et al., 2011; Lago Plomo 47ºS), specifically in the period between AD 650 and 1100. The chironomid DCA seems to respond to temperature variation (Figure 6), whereas the pollen DCA exhibits no clear trend. These results suggest warm conditions in this period, and are in agreement with other palynological studies conducted at higher latitudes. For example, a pollen analysis in Lake Cipreses (51ºS) evidenced a dynamic of dry and warm phases between AD 730 and 1350, coincident with the MCA (Moreno et al., 2014). These phases are apparently determined by the displacement of the westerlies because of the intensification of the Southern Annular Mode (SAM). Similarly, a high-temporal-resolution pollen analysis on the South Georgia Islands (54ºS) emphasized warm phases between AD 280 and 1270, which were related to a northward displacement of the westerlies, causing drier conditions that allowed the establishment of grasses (Strother et al., 2015).

Environmental changes and manifestation of the LIA

The major environmental changes since AD 1500 observed in Lake Pastahué have an approximate gap of 150 years relative to some records in central Chile such as those of Laguna Chepical 32ºS (De Jong et al., 2013) and Laguna Maule 36ºS (Carrevedo et al., 2015). These records show that the climate in central Chile was characterized by relatively colder, more humid conditions starting in AD 1350. These climatic signals appear, in these particular cases, prior to the appearance of colder temperatures in the Northern Hemisphere during the LIA (Matthews and Briffa, 2005).

Our pollen results from Lake Pastahué match records from the Northern Hemisphere, where a cold event similar to the LIA is noted by an increase in the abundances of *Nothofagus antarctica/dombeyi* and *Misodendrum*, revealing the recovery of the arboreal layer, with *Podocarpus* and *Pilgerodendron/Fitzroya* pollen, both elements characteristic of the North Patagonian forest, reflecting the prevalence of cold-humid conditions (Villagrán et al., 2004). Moreover, the appearance of taxa characteristic of the Chiloé rainforest is noted in the arboreal layer, mainly *Lomatia, Drimys winteri*, and taxa of the Myrtaceae family, characteristic of a hygrophilous forest (Quintanilla, 2004).

Gaultheria and *Escallonia* appear consistently in the low scrub in this period; this association has been interpreted by some authors as typical of cold environments and Magellanic tundras (Ponce et al., 2011). In addition, the presence of traces of aquatic elements such as *Myriophyllum* and *Isoetes* for the first time in the profile clearly indicates an expansion of the lake basin (Villagrán, 2001). The vegetation structure effectively evidences a more humid environment than in Zone PI.

This vegetation behavior is seen in the study of Villagrán (1985), who, using a sediment core taken from the bank of our study site (Lake Pastahué), performed a palynological analysis to determine the points at which the postglacial recolonization of the plant taxa occurred. Even though the time scale is much greater than that addressed in our study, it is possible to compare the two pollen profiles. In particular, the similarity with respect to plant composition and their abundances in the uppermost centimeters of the profile reinforces our general interpretation: the Lake Pastahué ecosystem contains taxa characteristic of the Chiloé forest, with a predominance of North Patagonian taxa and the presence of elements characteristic of the Valdivian forest. Unfortunately, even though the plant composition is similar, the Villagrán (1985) study lacks geochronological dating for the last thousand years and it is

not possible to express the observed pollen sequence in calendar years.

In other records from south-central Chile, the LIA is recognized through an increase in humidity and cold temperatures, as recorded at 37ºS at Lake Laja (Urrutia et al., 2010). In this lake, a change in pollen, chironomid, and diatom assemblages between AD 1350 and 1700 was interpreted as a cold, dry period determined mainly by the geographic and local characteristics of the study site. At Laguna San Pedro (39ºS), Fletcher and Moreno (2012) found a period with cold, humid phases that they related to ENSO (El Niño–Southern Oscillation) events between AD 1225 and 1829. Our results partly agree with the temporality described by these authors; however, we interpret this humidity at Pastahué as an intensification of the westerlies and a later displacement toward the poles, as described by Bertrand et al. (2014) at 46ºS. This shift caused greater humidity in the environment and, to a certain extent, modified the ecological conditions for the reorganization of the vegetation.

The inferences regarding both the temperature decrease and the humidity increase at Lake Pastahué are supported by the chironomid assemblage. The persistence of *Riethia*, a taxon typical of cold conditions, and the low presence of *Lymnophyes*, associated with a lower water level, suggest an increase in precipitation in the same period.

This view is strengthened by historical events. The discovery of America took place during this period, as did the colonization of Chile by the Spaniards, who established various settlements throughout Chile, including Castro on Chiloé Island. Thus, because of the eagerness of the Europeans to dominate the sea in the south of Chile, there are some written sources of information that describe the climate in this region of Chile (Prieto et al., 2012). It was on this quest to dominate, describe, and explore these remote areas that the English ship HMS Wager of Lord Anson's squadron was shipwrecked on the coast of the Guayaneco Archipelago, 500 km from Chiloé Island. The survivors included John Byron (1768), who, in his book, *The Narrative of the Honourable John Byron*, describes regional climate features. Chiloé in particular in 1741 is cited in some passages of the book: 'it often happened to me on rigorous nights, when the snow and hail lashed the deserted shore where we reposed' and 'we disembarked on the island of Chiloé, in a region that was not uninhabited. There we spent all the following day, with a great snowstorm, to try to recover from the fatigues of the journey; but the cold was so excessive that, as we had neither stockings nor shoes, it seemed to us that we were going to lose our feet'. The author certainly indicates the existence of snow on the beach of the island, shedding light on an anomalous situation on the Chilean coast.

Another historical record that adds to the description of the climate is the chronicle by the priest José García (1871), of the Society of Jesus, who, on his journey from Chiloé to San Rafael Glacier in 1766, describes ice floating along the entire coast until reaching the Glacier. 'At four in the afternoon a piece of ice floated by our side eight yards long, and at least two yards above the surface of the water; a little later another just as big passed by'. In a later period (1871–1873), Captain Enrique Simpson (1875), in his explorations of the Guaitecas, Chonos, and Taitao Archipelagoes, makes reference to the dimensions of San Rafael Glacier:

> The lake is almost circular, eight to nine miles in diameter and, as I have said before, within it the San Rafael Glacier is projected, which comes away from a great sheet of ice in the mountains, which at a height of more than a thousand meters extends many miles from North to South behind the coastal mountains, and descending by a ravine more than a mile wide between jagged mountain peaks, it juts four and half miles into the lake.

In an expedition made in 1898, Hans Steffen (1910) finds a situation similar to that described by Captain Simpson and says,

> Studying the location and the current dimensions of this huge glacier, we found almost no difference with description given by Captain Simpson on his voyages, so that it may be presumed that the glacier has been almost stationary in the last 30 years.

Using historical records of San Rafael Glacier 46ºS (Araneda et al., 2007), a cold, humid period with a peak between AD 1857 and 1871 is found, reinforcing the biological assemblage observation in our study regarding the extreme cold in this region of southern South America, which is consistent with the LIA.

Another argument that reinforces our assumption of a cold-humid period during the LIA is found in Figure 6, which shows a comparison of previous precipitation and temperature reconstructions versus the pollen and chironomid DCAs. It is observed that both proxies had an almost asynchronous response starting in ~AD 1555, when some changes in temperature and precipitation can be recognized. However, while chironomids seem to return to their prior conditions around ~AD 1960, pollen maintains the same trend until the end of the record, which could be related to the sensitivity of each proxy. Therefore, the LIA stands out as a significant period of complex hydrological, environmental, and climatic changes at the southern edge of south-central Chile.

Another important feature of this period is seen in the chironomid assemblage (Figure 4): *C. anthracinus* is replaced by *C. plumosus*. According to Brooks et al. (2007), *C. plumosus* is characteristic of strongly eutrophic lakes, whereas *C. anthracinus* is common in more moderate eutrophic environments, a rare environmental condition considering the low human population at this point in history. The colonization of Chiloé Island for the construction of urban settlements and the extraction of cypress and larch occurred in other areas of the island and continental Chiloé (Torrejón et al., 2011), leaving the Lake Pastahué ecosystem pristine until the mid-20th century (Villagrán, 1985). The absence of charcoal particles is also consistent with the absence of human interventions in the ecosystem.

The sedimentological parameters (Figure 5) present some variations in OM and particle size and a slight increase in MS at the same depth at which a slight decrease in the abundance of *Polypedilum* occurs. This is concomitant with the greater abundance of *C. plumosus* and an increase in the number of head capsules. Such behavior could be explained by the natural eutrophication of the system. The input of sediment to the lake would generate some type of anoxia on the lake shores, making the proliferation of this diptera possible. Other changes in the taxa in this period are not as clear as the defining climatic conditions. Finally, the sediment input would also seem to be forced naturally by seismic activity in the Chiloé area, of which there is evidence in 1575, 1737, and 1837 (Cisternas et al., 2005; Kempf et al., 2017).

Temperature increase and human impact since AD 1900

For the last ca. 100 years, Lake Pastahué has seen a growing reduction in most of the arboreal taxa present in the pollen diagram, except for *Weinmannia* and *Eucryphia/Caldcluvia*, which are favored by the temperature pulses captured since the beginning of the 20th century (Moreno, 2004). Similarly, most of the taxa of the chironomid assemblage are diminished, and the increase in *Polypedilum* compared with the previous zone reveals an improvement in climatic conditions. The absence of

C. anthracinus and *C. plumosus* taxa in this zone, which is related to a high trophic level, suggests that the nutrient contributions to the lake in this period were probably low. These conditions, evidently warmer and drier, are also corroborated by dendrochronological records taken throughout the western Andean slope between 32 and 38°S, which show that the last 100 years are among the driest in recent centuries (Christie et al., 2011; Le Quesne et al., 2009). The delayed intervention in the river basin is appreciable through the appearance of *Pinus*, a fast-growing forestry conifer widely used in Chile (Haig, 1946), only in the last centimeter of the profile. Moreover, the degradation of the system is clear because of the presence of pollen taxa (*Rumex, Plantago*, and *Taraxacum/Hypochaeris* pollen), all classified as invasive species (Herrera et al., 2016). The evolution of the pollen and chironomid assemblages suggests a decrease in precipitation and an increase in temperature in the 20th century.

Conclusion

The history of Lake Pastahué over the last 1400 years was reconstructed from biological, sedimentological, and historical records.

The variation in pollen and chironomid assemblages is partly consistent with climatic events of the past millennium such as the MCA, during which there were warm and dry conditions from ca. AD 800 to 1300, and the LIA, during which the temperature decreased and precipitation increased from ca. AD 1500 to 1900.

The environmental changes recorded starting in ca. AD 1500 are directly related to the fluctuation in the sedimentological proxies, which produced changes in the trophic state of the lake and subsequently affected the biological communities.

The observed increases in all the proxies in the uppermost centimeter of the profile could be the result of the combined effect of increased agricultural and livestock activities carried out by the people of Chiloé since the beginning of the 20th century and the temperature increase recorded in this same period in south-central Chile and Patagonia.

Acknowledgements

The main author is grateful for the constructive suggestions and comments of the anonymous reviewers of this manuscript, Conicyt National Doctoral Scholarship Nº 21140765, the Erasmus Mundus Scholarship, and CRHIAM/Conicyt/Fondap Project 15130015.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

Abarzúa AM and Moreno PI (2008) Changing fire regimes in the temperate rainforest region of southern Chile over the last 16,000 yr. *Quaternary Research* 69(1): 62–71.

Ahmed M, Anchukaitis KJ, Asrat A et al. (2013) Continental-scale temperature variability during the past two millennia. *Nature Geoscience* 6: 339–346.

Araneda A, Torrejon F, Aguayo M et al. (2007) Historical records of San Rafael glacier advances (North Patagonian Icefield): Another clue to 'Little Ice Age' timing in southern Chile? *The Holocene* 17(7): 987–998.

Araneda A, Torrejón F, Aguayo M et al. (2009) Historical records of Cipreses glacier (34°S): Combining documentary-inferred 'Little Ice Age' evidence from Southern and Central Chile. *The Holocene* 19(8): 1173–1183.

Arenas J (2001) Informe final: Determinación de la capacidad de carga de los lagos Auquilda, Yaldad y Tres Marías en Chiloé Insular. Fondo de Investigación Pesquera (FIP), Subsecretaría de Pesca, Ministerio de Economía, Fomento y Reconstrucción y Universidad Austral de Chile, Valdivia, November.

Bennett KD (1996) Determination of the number of zones in a biostratigraphical sequence. *New Phytologist* 132: 155–170.

Bertrand S, Boës X, Castiaux J et al. (2005) Temporal evolution of sediment supply in Lago Puyehue (Southern Chile) during the last 600 yr and its climatic significance. *Quaternary Research* 64(2): 163–175.

Bertrand S, Hughen K, Sepúlveda J et al. (2014) Late Holocene covariability of the southern westerlies and sea surface temperature in northern Chilean Patagonia. *Quaternary Science Reviews* 105: 195–208.

Birks HJB (1998) Deevey review 1: Numerical tools in palaeolimnology – Progress, potentialities, and problems. *Journal of Paleolimnology* 20(4): 307–332.

Birks HJB and Gordon AD (1985) *Numerical Methods in Quaternary Pollen Analysis*. London: Academic Press.

Blaauw M (2010) Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5(5): 512–518.

Bradley RS and Jones PD (1993) 'Little Ice Age' summer temperature variations: Their nature and relevance to recent global warming trends. *The Holocene* 3(4): 367–376.

Bronk Ramsey C (2005) *OxCal Program v3.10*. Oxford: University of Oxford Radiocarbon Acceleration Unit.

Brooks SJ (2000) Late-glacial fossil midge stratigraphies (Insecta: Diptera: Chironomidae) from the Swiss Alps. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159(3–4): 261–279.

Brooks SJ, Langdon PG and Heiri O (2007) *The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology*. London: QRA Technical, Quaternary Research Association.

Byron J (1768) *The Narrative of the Honourable John Byron: Containing an Account of the Great Distresses Suffered by Himself and His Companions on the Coast of Patagonia, From the Year 1740, till their Arrival in England, 1746*. 2nd Edition. London: S. Baker, G. Leigh and T. Davies.

Carrevedo ML, Frugone M, Latorre C et al. (2015) A 700-year record of climate and environmental change from a high Andean lake: Laguna del Maule, central Chile (36°S). *The Holocene* 25(6): 956–972.

Chambers FM (2016) The 'Little Ice Age': The first virtual issue of The Holocene. *The Holocene* 26(3): 335–337.

Christie DA, Boninsegna JA, Cleaveland MK et al. (2011) Aridity changes in the Temperate-Mediterranean transition of the Andes since AD 1346 reconstructed from tree-rings. *Climate Dynamics* 36(7): 1505–1521.

Cisternas M, Atwater BF, Torrejón F et al. (2005) Predecessors of the giant 1960 Chile earthquake. *Nature* 437(7057): 404–407.

Corporación Nacional Forestal (CONAF), Comisión Nacional del Medio Ambiente (CONAMA) and Banco Internacional de Reconstrucción y Fomento (BIRF) (1999) *Catastro y evaluación de los recursos vegetacionales nativos de Chile*. Santiago: CONAF, Informe Nacional con Variables Ambientales. Available at: http://bosques.ciren.cl/bitstream/handle/123456789/10656/CONAF_BD_21.pdf?sequence=1&isAllowed=y

Corominas J (1976) *Diccionario crítico etimológico de la Lengua Castellana*, vol. IV. Barcelona: Editorial Gredos.

Cranston P (1996) *Identification Guide to the Chironomidae of New South Wales*. Sydney: Australian Water Technologies Pty Limited.

De Jong R, Von Gunten L, Maldonado A et al. (2013) Late-Holocene summer temperatures in the central Andes reconstructed from the sediments of high-elevation Laguna Chepical, Chile (32 S). *Climate of the Past* 9(4): 1921–1932.

Dirección General de Aguas (DGA) (1987) *Balance hídrico de Chile*. Santiago: Ministerio de Obras Públicas.

Elbert E, Wartenburger R, von Gunten L et al. (2013) Late-Holocene air temperature reconstructed from sediments of Laguna Escondida, Patagonia, Chile (45°S 30'W). *Palaeogeography, Palaeoclimatology, Palaeoecology* 369: 482–492.

Elbert J, Grosjean M, von Gunten L et al. (2011) Quantitative high-resolution winter (JJA) precipitation reconstruction from varved sediments of Lago Plomo 47°S, Patagonian Andes, AD 1530–2001. *The Holocene* 22: 465–474.

Epler JH (2001) *Identification Manual for the Larval Chironomidae (Diptera) of North and South Carolina* (Special Publication). Raleigh, NC: North Carolina Department of Environment and Natural Resources.

Esper J, Cook ER and Schweingruber F (2002) Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 2002; 295(5563): 2250–2253.

Faegri K and Iversen J (1989) *Textbook of Pollen Analysis*. Chichester: John Wiley.

Flantua SGA, Hooghiemstra H, Vuille M et al. (2016) Climate variability and human impact in South America during the last 2000 years: Synthesis and perspectives from pollen records. *Climate of the Past* 12(2): 483–523.

Fletcher MS and Moreno PI (2012) Vegetation, climate and fire regime changes in the Andean region of southern Chile (38°S) covaried with centennial-scale climate anomalies in the tropical Pacific over the last 1500 years. *Quaternary Science Reviews* 46: 46–56.

García J (1871) Diario del viaje i navegacion hechos por el padre José García, de la compañía de Jesus, desde su mision de Caylin, en Chiloé hácia el sur, en los años 1766 i 1767. *Anales de la Universidad de Chile (20 semestre, Santiago de Chile)* XXXIX: 351–379, 358–359.

Grimm EC (1987) Constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13(1): 13–35.

Haberzettl T, Fey M, Lücke A et al. (2005) Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). *Journal of Paleolimnology* 33(3): 283–302.

Haig T (1946) *Forest Resources of Chile as a Basis for Industrial Expansion*. Santiago: Corfo.

Heiri O, Lotter AF and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25(1): 101–110.

Henríquez WI, Moreno PI, Alloway B et al. (2015) Vegetation and climate change, fire-regime shifts and volcanic disturbance in Chiloé Continental (43°S) during the last 10,000 years. *Quaternary Science Reviews* 123: 158–167.

Herrera I, Goncalves E, Pauchard A et al. (eds) (2016) *Manual de plantas invasoras de sudamérica*. 1st edn. Santiago: Instituto de Ecología y Biodiversidad, 116 pp.

Heusser CJ (1971) *Pollen and Spores of Chile: Modern Types of the* Pteridophyta, *Gymnospermae, Angiospermae*. Tucson, AZ: University of Arizona Press.

Hogg AG, Hua Q, Blackwell PG et al. (2013) SHCal13 southern hemisphere calibration, 0–50,000 years cal BP. *Radiocarbon* 55(4): 1889–1903.

Jones PD (2001) The evolution of climate over the last millennium. *Science* 292(5517): 662–667.

Jones PD and Mann ME (2004) Climate over past mellinia. *Reviews of Geophysics* 42(2): 1–42.

Juggins S (2017) Analysis of Quaternary Science data, Package 'rioja'. Available at: http://www.staff.ncl.ac.uk/stephen.juggins/.

Kempf P, Moernaut J, Van Daele M et al. (2017) Coastal lake sediments reveal 5500 years of tsunami history in south central Chile. *Quaternary Science Reviews* 161: 99–116.

Latorre C, Wilmshurst J and Von Gunten L (2016) Climate change and cultural diversity. *Past Global Changes* 24(2): 131–140.

Le Quesne C, Acuña C, Boninsegna JA et al. (2009) Long-term glacier variations in the Central Andes of Argentina and Chile, inferred from historical records and tree-ring reconstructed precipitation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281(3–4): 334–344.

Mann ME (2001) Climate during the past millennium. *Weather* 56: 91–102.

Mann ME, Zhang Z, Rutherford S et al. (2009) Global signatures and dynamical origins of the little ice age and medieval climate anomaly. *Science* 326(5957): 1256–1260.

Markgraf V and D'Antoni HL (1978) *Pollen Flora of Argentina*. Tucson, AZ: University of Arizona Press.

Massaferro J, Ortega C, Fuentes R et al. (2013) Guia Para la Identificacion de Tanytarsini Subfosiles (Diptera: Chironomidae: Chironominae) de la Patagonia. *Ameghiniana* 50(3): 319–334.

Massaferro JI, Moreno PI, Denton GH et al. (2009) Chironomid and pollen evidence for climate fluctuations during the Last Glacial Termination in NW Patagonia. *Quaternary Science Reviews* 28(5–6): 517–525.

Matthews JA and Briffa KA (2005) The 'Little Ice Age': Re-evaluation of an evolving concept. *Geografiska Annaler Series A Physical Geography* 87(1): 17–36.

Mayewski PA, Rohling EE, Stager JC et al. (2004) Holocene climate variability. *Quaternary Research* 62(3): 243–255.

Moreno PI (2004) Millennial-scale climate variability in northwest Patagonia over the last 25,000 yr. *Journal of Quaternary Science* 19: 35–47.

Moreno PI, François JP, Villa-Martínez RP et al. (2009) Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia. *Quaternary Science Reviews* 28(1–2): 25–38.

Moreno PI, Vilanova I, Villa-Martínez R et al. (2014) Southern Annular Mode-like changes in southwestern Patagonia at centennial timescales over the last three millennia. *Nature Communications* 5: 4375.

Neukom R, Luterbacher J, Villalba R et al. (2011) Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. *Climate Dynamics* 37(1): 35–51.

Novo P and Chicarro F (1957) *Diccionario de Geología y ciencias afines*. Madrid: Editorial La Bor S.A.

Oksanen J, Blanchet FG, Friendly M et al. (2015) Vegan: Community Ecology Package, R Packag, version 2.*3-2*. Available at: https://github.com/vegandevs/vegan.

Otero L (2006) *La huella del fuego. Historia de los bosques nativos. Poblamiento y cambios en el paisaje del sur de Chile*. Santiago: Pehuén Editores, 171 pp.

Pérez L, Lorenschat J, Massaferro J et al. (2013) Bioindicators of climate and thophic state lowland and highland aquatic ecosystems of the northern Neotropics. *Revista de Biología Tropical* 61(2): 603–644.

Pesce OH and Moreno PI (2014) Vegetation, fire and climate change in central-east Isla Grande de Chiloé (43oS) since the Last Glacial Maximum, northwestern Patagonia. *Quaternary Science Reviews* 90: 143–157.

Ponce J, Borromei AM, Rabassa J et al. (2011) Late Quaternary palaeoenvironmental change in western Staaten Island (54.5° S, 64° W), Fuegian Archipelago. *Quaternary International* 233(2): 89–100.

Prieto M, Solari ME, Crouchet J et al. (2012) Fuentes documentales para el estudio del clima en la región sur-austral de Chile

(40o - 51o S) durante los últimos siglos. *Bosque (Valdivia)* 33(2): 5–6.

Quintanilla V (2004) Degradación del bosque pluvial en una cuenca hidrográfica del norte de la Isla Grande de Chiloé 1. *Revista de Geografia Norte Grande* 31: 73–84.

Real Academia Española (1933) *Diccionario histórico de la lengua española*. Madrid: Imprenta de Librería y Casa Editorial Hernandon. Available at: http://web.frl.es/DH1936.html

Ribeiro Guevara S and Arribére M (2002) 37Cs dating of lake cores from the Nahuel Huapi National Park, Patagonia, Argentina: Historical records and profile measurements. *Journal of Radioanalytical and Nuclear Chemistry* 252(1): 37–45.

Roig F, Le-Quesne C and Boninsegna J (2001) Climate variability 50,000 years ago in mid-latitude Chile as reconstructed from tree rings. *Nature* 410(6828): 567–570.

Ruiz-Moreno J, Ospina-Torres R and Gómez-Sierra H (2000) Guía para la identificación genérica de larvas de quironómidos (Diptera: Chironomidae) de la sabana de Bogotá. III. Subfamilias Tanypodinae, Podonominae y Diamesinae. *Caldasia* 22: 34–60.

Schmithüsen J (1956) Die räumliche Ordnung der chilenischen Vegetation. In: Schmithüsen J, Klapp E and Schwabe GH (eds) *Forschungen in Chile. Bonner Geographische Abhandlungen, vol. 17*. Bonn: Geographisches Institut, Universität Bonn, pp. 1–86. Available at: https://issuu.com/jpintoz/docs/1956_schmith_sen_ra_mordnchilveg_bo

Simpson E (1875) *Esploraciones hechas por la corbeta Chacabuco, al mando del Capitán de Fragata D. Enrique M. Simpson, en los archipiélagos de Guaitecas, Chonos i Taitao'*. Anuario Hidrográfico de la Marina de Chile, No 1, Santiago de Chile, pp. 3–147, 30–33.

Soon W and Baliunas S (2003) Proxy climatic and environmental changes of the past 1000 years. *Climate Research* 23: 89–110.

Soon W, Baliunas S, Idso C et al. (2003) Reconstructing climatic and environmental changes of the past 1000 years: A reappraisal. *Energy Environ* 14(2/3): 233–296.

Steffen H (1910) *Viajes de exploracion i estudio en la Patagonia Occidental 1892–1902*, vol. II. Santiago de Chile: Imprenta Cervantes, pp. 549–303.

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. *Pollen Et Spores* 13(4): 615–621.

Strother SL, Salzmann U, Roberts S et al. (2015) Changes in Holocene climate and the intensity of Southern Hemisphere Westerly Winds based on a high-resolution palynological record from sub-Antarctic South Georgia. *The Holocene* 25: 263–279.

Summerhayes C (2017) Comment on 'The Medieval Quiet Period' – Implications arising from models of solar irradiance. *The Holocene* 27(2): 315–316.

Torrejón F, Cisternas M and Araneda A (2004) Efectos ambientales de la colonización Española desde el río Maullín al archipiélago de Chiloé, sur de Chile. *Revista Chilena de Historia Natural* 77(4): 661–677.

Torrejón F, Cisternas M, Alvial I et al. (2011) Consecuencias de la tala maderera colonial en los bosques de Alerce de Chiloé, sur de Chile (Siglos XVI-XIX). *Magallania (Punta Arenas)* 39(2): 75–95.

Troncoso Castro JM, Saldaña A and Rondanelli-Reyes MJ (2015) Historia vegetal y regímenes de fuego recientes de la turbera costera de Chepu, Isla Grande de Chiloé, Chile. *Gayana Botánica* 72(2): 340–349.

Urbina M (2011) Análisis Histórico-Cultural del Alerce en la Patagonia Septentrional Occidental, Chiloé, Siglos XVI al XIX. *Magallania (Punta Arenas)* 39(2): 57–73.

Urrutia R, Araneda A, Torres L et al. (2010) Late-Holocene environmental changes inferred from diatom, chironomid, and pollen assemblages in an Andean lake in Central Chile, Lake Laja (36°S). *Hydrobiologia* 648(1): 207–225.

Villagrán C (1985) Análisis palinológico de los cambios vegetacionales durante el Tardiglacial y Postglacial. *Revista Chilena de Historia Natural* 58: 57–69.

Villagrán C (2001) Un Modelo de la historia de la vegetación de la Cordillera de La Costa de Chile central-sur: la hipótesis glacial de Darwin. *Revista Chilena de Historia Natural* 74: 793–803.

Villagrán C, León A and Roig FA (2004) Paleodistribución del alerce y ciprés de las Guaitecas durante períodos interestadiales de la Glaciación Llanquihue: provincias de Llanquihue y Chiloé, Región de Los Lagos, Chile. *Revista Geológica de Chile* 31(1): 133–151.

Villalba R (1994) Tree-ring and glacial evidence for the medieval warm epoch and the little ice age in southern South America. *Climatic Change* 26: 183–197.

Von Gunten L, Grosjean M, Rein B et al. (2009) A quantitative high-resolution summer temperature reconstruction based on sedimentary pigments from Laguna Aculeo, central Chile, back to AD 850. *The Holocene* 19(6): 873–881.