The Holocene 14,3 (2004) pp. 363–369

Pollen evidence for late-Holocene climatic variability at Laguna de Aculeo, Central Chile (lat. 34°S)

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Abstract: A pollen record is presented from Laguna de Aculeo (33°50′S, 70°55′W, 360 m a.s.l.) that documents important vegetation changes over the last 2500 cal. yr in Central Chile. Grasses, composites, trees, paludal and aquatic taxa dominated the Aculeo watershed between 2500 and 100 cal. yr BP under a humid climate. Large amplitude fluctuations of pollen and microalgal accumulation rates and numerous turbidite layers during this interval, however, suggest high precipitation variability probably linked to El Niño-Southern Oscillation (ENSO) events. Although the expansion of warm sclerophyllous forest taxa over the last 100 years could be interpreted as an onset of a drier and warmer climate, this trend was more likely linked to human activities in the watershed. High accumulation rates of microscopic charcoal particles, exotic pollen taxa, and a shift from oligo-mesotrophic to hypereutrophic indicators would seem to back the latter hypothesis.

Key words: Late Holocene, Central Chile, pollen, vegetation history, climatic variability, ENSO-like, Laguna Aculeo.

Introduction

The precipitation regime in Central Chile (lat. 30–38°S) is primarily controlled by changes in the subtropical high-pressure cell, also referred to as the South Pacific Anticyclone (SPA), which drives the frequency, intensity and geographic extent of frontal activity associated with the westerly circulation. The seasonality of precipitation changes around 34°S. South of this latitude, winter precipitation is regular, while north of 34°S precipitation occurs episodically (van Husen, 1967). The region is characterized by large seasonal and interannual variations in winter precipitation, in part caused by the El Niño-Southern Oscillation (ENSO) phenomenon. This is related to pressure anomalies associated with the negative ENSO phases, which allow a northward shift of westerly storms, causing higher-than-average annual precipitation in Central Chile. Conversely, positive ENSO phases reinforce the SPA, resulting in cold and dry conditions in this region (Aceituno, 1988; 1990; Aceituno *et al.*, 1993; Rutlland and Fuenzalida, 1991). This high climate sensitivity means that the Mediterranean region of Chile is a key area to monitor past variations of the westerly wind belt at subtropical latitudes.

Few studies in the Mediterranean region of Central Chile have examined in detail the vegetation, climate and disturbance history over the last two millennia. Tree-ring chronologies from the Andes of Central Chile (Boninsegna, 1988; Villalba, 1990) have reconstructed extreme drought events and latitudinal movements of the SPA over the last 750 and 500 years, respectively. Using historical documents, Ortlieb (1994) inferred precipitation variability linked to ENSO events in Central Chile over the last 500 years. Within the same interval, historical records indicate that Central Chile has experienced profound landscape transformations resulting from logging, agriculture and livestock overgrazing since the mid-sixteenth century (Elizalde, 1970). Deep-sea records off the central Chilean coast evidence humid conditions and ENSO-like variability over the last 3000 cal. yr (Lamy *et al.*, 1999; Marchant *et al.*, 1999).

Palaeoclimate records suggest that Central Chile during the late Holocene has experienced (i) high-frequency climatic variability, probably linked to ENSO, (ii) climate changes at decadal and centennial timescales, and (iii) strong landscape degradation over the last few centuries. The few palynological studies of this area (Heusser, 1983; 1990; Villa-Martínez and Villagrán, 1997) suggest humid conditions over the last two millennia, but low sedimentation rates and poor temporal resolution of these records prevented detection of any climatic

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 10.1191/0959683604hl712rp

variability linked either to ENSO or to the beginning of human impact on the landscape.

Continuous, high-resolution sedimentary records from closed-basin lakes in Central Chile provide the opportunity to monitor past changes in local vegetation, hydrologic balance and human disturbance. Detailed sedimentological and geochemical analyses from sediment cores from Laguna de Aculeo (33°50′S, 70°54′W), one of the few inland lakes in Central Chile suitable for the study of past variations at the northern edge of the westerly winds show past precipitation variations throughout the late Holocene (Jenny *et al.*, 2002). Here we report results of pollen analyses performed on the same sediment core and focus on exploring the climate impacts on the local vegetation.

The study area

Laguna de Aculeo (33°50′S; 70°54′W, 360 m a.s.l.) is located 50 km SE of Santiago (Figure 1), in the inland foothills of the Cordillera de la Costa, and constitutes one of the largest natural lakes in the region. The modern lake covers 12 km^2 and has a present maximum depth of 6 m (Cabrera and Montecino, 1982).

Laguna Aculeo is surrounded by the Cordillera de la Costa, the summits of which surpass 2000 m in altitude (Figure 1), with steep slopes containing numerous small gullies and canyons that transport water and sediment into the lake. The lake has a small outflow on the eastern side, the Estero Aculeo, which is rarely filled with water in winter, and at times during rainy winters functions as an inflow (Mülhlhauser and Vila, 1987). The discharge through the Estero Aculeo, however, is minimal and the lake is considered a closed basin (I. Vila, personal communication), chiefly fed by local precipitation and runoff.

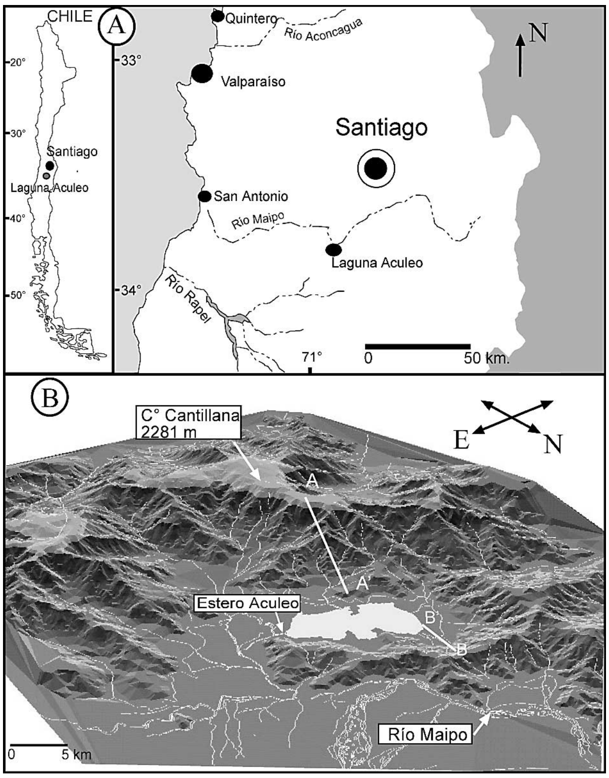

Figure 1 (A) Map showing the location of Laguna Aculeo in Central Chile, just within the northern border of the regular westerly influence. (B) Oblique view of the study site, showing the *rinconada* (amphitheater) formed by the encircling eastern slopes of the Cordillera de la Costa. Vegetation surveys were conducted along transects between points A–A' and B–B'.

A semiarid-Mediterranean climate is dominant today at Laguna Aculeo (di Castri and Hajek, 1976), with dry summer and wet winters. Mean annual precipitation is ~550 mm and mean annual temperature is 14°C (Almeyda and Saez, 1958). Precipitation variability in this area is strongly related with ENSO (Aceituno, 1988; Montecinos *et al.*, 2000; Rutlland and Fuenzalida, 1991).

Sclerophyllous forests dominate the vegetation that today surrounds Laguna de Aculeo (Rundel, 1981; Schmithüsen, 1956). A survey around the lake revealed the following vegetation zones (R. Villa-Martínez, unpublished data):

(1) Sclerophyllous forest (400–1250 m a.s.l.) with *Quillaja saponaria*, *Lithrea caustica*, *Cryptocarya alba* and *Peumus boldus* as dominant trees. Moist ravines and canyons are dominated by*Persea lingue*, *Crinodendron patagua*, *Beilschmiedia miersii* and *Maytenus boaria*. Shrublands of *Talguenea trinervis* commonly occupy drier areas that have been cleared by human disturbance.

2) Sclerophyllous mountain matorral (1250–1900 m a.s.l.) succeeds the sclerophyllous forest in altitude. This community includes the trees *Lithrea caustica*, *Schinus montanus*, *Escallonia pulverulenta*, *Baccharis linearis*, *B. concava*, *Azara* sp. and *Kageneckia angustifolia*. Herbs are dominant on dry slopes and important among these are the Andean tussock grasses *Stipa* and *Poa*, along with *Acaena alpina*, *Mulinum spinosum*, *Chuquiraga oppositifolia*, *Mutisia* spp. *Tetraglochin alatum* and *Chaetanthera*, sp.

(3) Monospecific stands of *Nothofagus obliqua* occur between 1900 and 2000 m a.s.l., interspersed and succeeded by a high-elevation scrubland, which contains species also found in the high Andean vegetation, such as *Chuquiraga oppositifolia*, *Verbena spathulata*, *Tetraglochin alatum*, *Laretia acaulis* and *Viola cotyledon*.

Materials and methods

We obtained a 180 cm core from the deepest part of the lake using an anchored raft and a Livingstone piston corer. Absolute chronology for the core was based on seven radiocarbon and 25 ^{210}Pb dates (Tables 1 and 2). Radiocarbon samples were calibrated to calendar years using Calib 4.2 (Stuiver and Reimer, 1993). Based on these results we developed a calendar-age model to assign interpolated calendar ages to the pollen levels. The model consists of a second-order polynomial ($r^2 = 0.99$; $p < 0.001$) based on both ^{210}Pb and ^{14}C dates (Figure 2).

The lake sediments consist of organic mud (gyttja), and numerous (>20) silty-clay laminae considered turbidites (Figure 3). Eight of these layers, thinner and less well-developed than those found between 180 and 50 cm, occur in the upper 50 cm (AD 1948–98). These recent turbidites correlate mainly with El Niño years (Jenny *et al.*, 2002). For calculation of the calibrated age scale, the thickness of the relatively 'instantaneous' turbidites layers was subtracted.

We processed a constant volume of sediment samples (3 cm^3) at regular 5 cm intervals along the core for pollen analysis. The samples were processed following standard techniques (KOH, HF, acetolysis) (Faegri and Iversen, 1989), and by adding *Lycopodium* spore tablets (Stockmarr, 1971) to calculate concentration and accumulation rates (influx) of pollen, spores, green microalgae and charcoal particles. The basic

Table 1 Radiocarbon dates for Laguna de Aculeo record. (Ua) Armstrong Laboratory, Uppsala (AMS); (OS) Radiocarbon Laboratory, Boulder (AMS); (Hv) Radiocarbon Laboratory, Hannover (conventional)

Lab. code	Depth (cm)	δ^{13}C‰PDB range	^{14}C age	Cal. yr
Hv 23487	5	–17.6	AD1963	–
Ua-16877	89.5	–24.8	755 ± 70	731 (673) 561
Ua 15089	110	–29.60	920 ± 65	954 (877) 690
Hv 22728	116	–24.60	1065 ± 165	1295 (964) 668
NSRL-10855	145.5	–28.50	1630 ± 55	1691 (1529) 1393
NSRL-10856	162	–15.60	1800 ± 40	1856 (1712) 1632
Hv 22729	169.5	–22.10	2195 ± 95	2355 (2226) 1948

pollen sum for each level includes at least 300 terrestrial pollen grains (excluding aquatic and fern taxa), which were analysed at × 400 and × 1000 magnification. The results are expressed in percentage, concentration and influx diagrams, using the results of the calendar age model. Pollen assemblage zones were defined with the aid of a constrained incremental sum of squares (CONISS) cluster analysis (Grimm, 1987), applied to the terrestrial pollen taxa with abundances ≥2%, after recalculating pollen sums and percentages.

Results

Pollen stratigraphy

We defined three pollen zones for the Laguna de Aculeo record (Figures 3, 4 and 5), based on conspicuous changes in the pollen stratigraphy and a CONISS ordination.

Zone LA-1 (2500–700 cal. yr BP)

Herbs (Gramineae, Chenopodiaceae, Compositae, Euphorbiaceae, Umbelliferae) are dominant, along with wetland and aquatic taxa (Cyperaceae, *Typha*, *Myriophyllum*), and trace amounts (< 5%) of mesic trees and vines (*Maytenus boaria*, *Azara*, *Hydrangea serratifolia*; Figure 2). With the sole exception of Gramineae, all the other taxa have low accumulation rates throughout this zone (Figure 5). Both pollen concentration and accumulation rate diagrams display the same pattern, i.e., synchronous fluctuating values (Figures 5 and 6).

Table 2 ^{210}Pb chronology for Laguna de Aculeo Record. For more details about ^{210}Pb dating, see Jenny *et al.* (2002)

Depth (cm)	^{210}Pb age	Age (AD)
0	0 ± 0	1998
1	0 ± 1	1998
3	1 ± 1	1997
5	2 ± 2	1996
7	3 ± 2	1995
9	4 ± 2	1994
11	5 ± 2	1993
13	6 ± 2	1992
15	7 ± 2	1991
17	8 ± 2	1990
19	10 ± 3	1988
21	11 ± 3	1987
23	14 ± 4	1984
25	18 ± 4	1980
27	23 ± 4	1975
29	28 ± 4	1970
31	31 ± 4	1967
33	33 ± 4	1965
35	34 ± 4	1964
37	36 ± 4	1962
39	38 ± 5	1960
41	40 ± 5	1958
43	41 ± 6	1957
45	43 ± 6	1955
47	45 ± 7	1953
49	47 ± 8	1951

Zone LA-2 (700–100 cal. yr BP)

Most wetland and herbaceous taxa decline (Gramineae, Umbelliferae, Euphorbiaceae, *Typha*, *Myriophyllum*, Cyperaceae), and arboreal pollen percentages increase (*Maytenus boaria*, *Azara*). Accumulation rates decline substantially for most taxa, except for *Maytenus boaria* and *Azara*, which exhibit only a modest decline. The arboreal taxa *Quillaja saponaria*, *Talguenea trinervis* and *Hydrangea serratifolia* disappear from the record.

Zone LA-3 (100–0 cal. yr BP)

Chenopodiaceae pollen percentages reach a maximum of 30%, whereas Gramineae retain the same abundance of the previous zone (~ 20%). Percentage values of other herbs (Compositae, Euphorbiaceae) increase slightly. The presence of *Pinus* and *Plantago* attest to human disturbance. *Maytenus boaria* virtually disappears from the record, and increases occur in the more drought-resistant *Quillaja saponaria* and *Talguenea trinervis*. An abrupt increase in the pollen accumulation rates of all taxa (Figure 5) is associated with a prominent change in sedimentation rate. In contrast, the accumulation rates of *Maytenus boaria* decline to minimal values.

Microalgae and charcoal stratigraphy

The accumulation rates of microalgae are consistently low throughout the record, except for the last 100 years (Figure 6 A). *Pediastrum boryanum* and *P. duplex*, both oligo-mesotrophic indicators, fluctuate at relatively high levels near the base of

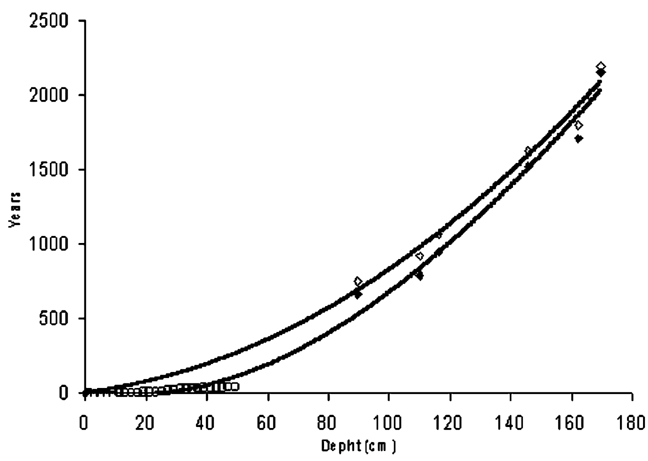

Figure 2 Age-depth model for Laguna Aculeo record. Open diamonds represent ^{14}C dates, open circles ^{210}Pb dates and filled diamond calibrated dates.

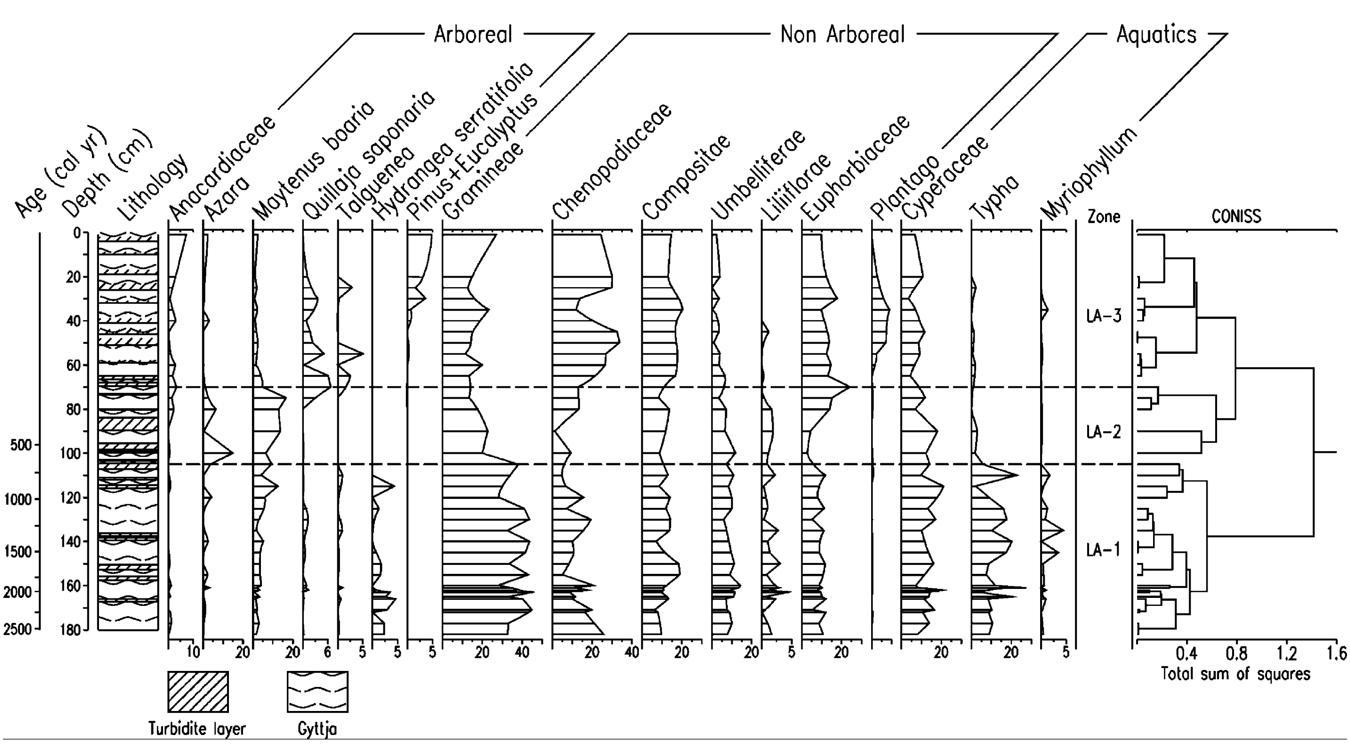

Figure 3 Percentage diagram of selected taxa and stratigraphic column of the Laguna Aculeo record. Percentage scales among species vary for visual depiction only.

the core but decrease upwards. Microalgal remains virtually disappear in zone LA-2. This situation reverts during the last 100 years, when microalgae reach maximum values (Figure 6b). The record indicates that between 100 and 30 cal. yr BP the oligo-mesotrophic *Pediastrum boryanum* and *P. duplex* are dominant, whereas the hypereutrophic *P. simplex* and *Scenedesmus* become dominant over the last 30 years.

The accumulation rates of microscopic charcoal particles remain are consistently low throughout the record (Figure 6), except for a sharp increase observed at 2400 cal. yr and the last 90 years.

Discussion

The Laguna Aculeo pollen record shows important changes in the local vegetation over the last 2500 years. These changes are evident in the percentage, concentration and accumulation rate data of all plant taxa, microalgae and microscopic charcoal particles.

The results show that Gramineae, Compositae, Umbelliferae and Euphorbiaceae, along with wetland (*Typha*, *Myriophyllum*, Cyperaceae) and arboreal taxa, dominate the record between 2500 and 700 cal. yr BP (zone LA-1), and indicate humid conditions. The presence of *Maytenus boaria* and *Hydrangea serratifolia* suggest humid conditions and dense forests considering that (i) *M. boaria* commonly thrives on moist soils (S. Tellier and C. LeQuesne, personal communication) and that (ii) *H. serratifolia* is a woody climber of large trees characteristic of humid coastal forest in this region and is absent from the modern flora and pollen rain in the Laguna Aculeo watershed. Low and variable amounts of microalgal remains during the same interval suggest oligotrophic conditions (Figure 6). The multiple, large-amplitude fluctuations observed in *Maytenus boaria* and *Hydrangea serratifolia*, Gramineae, Chenopodiaceae, Euphorbiaceae, Cyperaceae and *Typha* within this interval suggest high precipitation variability

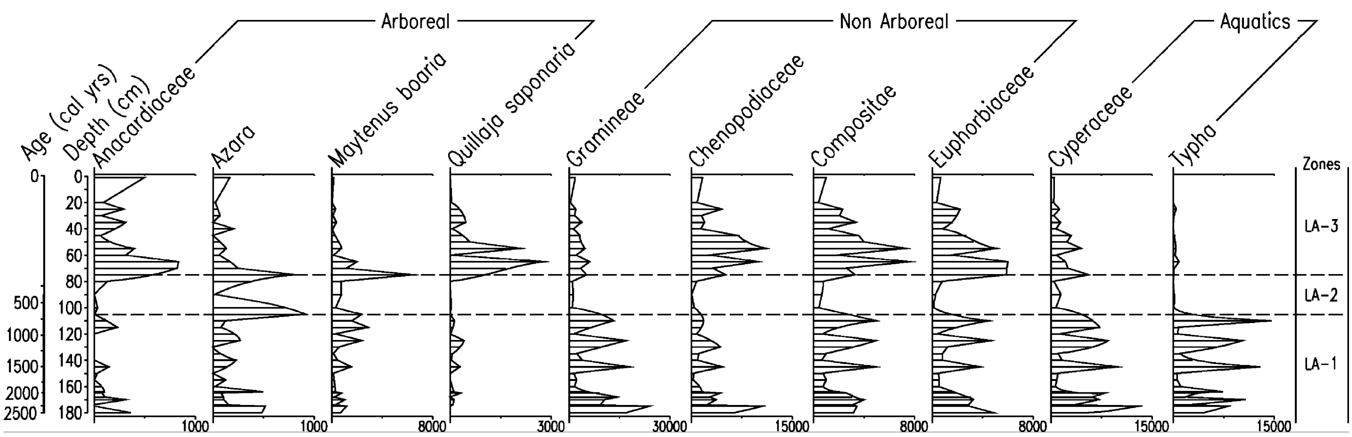

Figure 4 Pollen concentration of selected taxa from Laguna Aculeo record. Note that concentration scales vary among taxa.

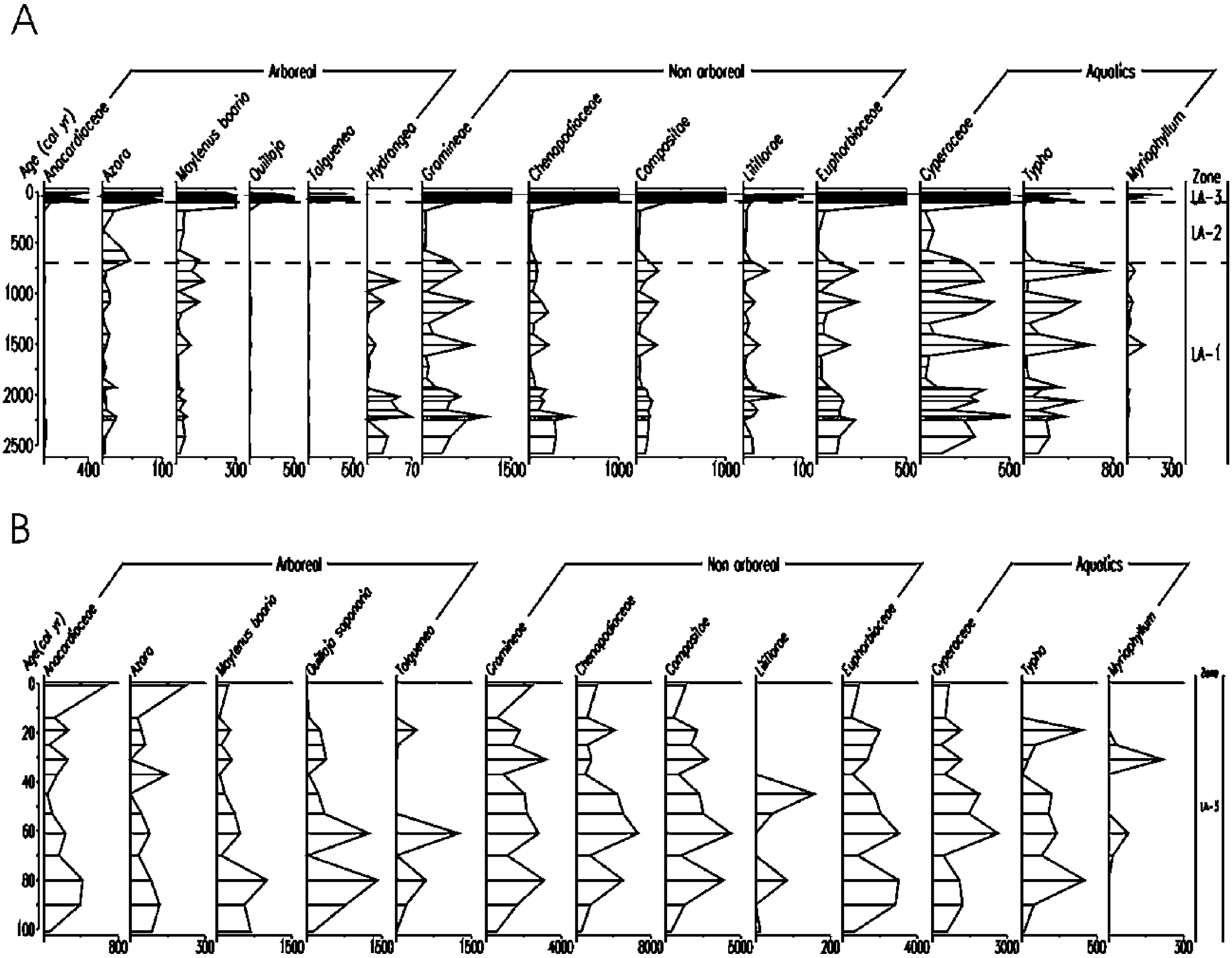

Figure 5 Pollen accumulation rates of selected taxa from the Laguna Aculeo record. (A) Accumulation rates for pollen zones LA-1 and LA-2. The LA-3 accumulation values have been truncated. (B) Accumulation rates for pollen zone LA-3. Note that accumulation rate scales vary between both graphs and among taxa. Units are in number of grains per cm^2 per yr.

(Figures 4 and 5). The occurrence of numerous turbidite layers, interpreted as local flooding resulting from above-average rainy winters over the watershed, suggests high precipitation variability. Recurring periods of high precipitation might account for the abrupt fluctuations observed in the pollen concentration and influx and, to a lesser degree, the microalgae and charcoal records.

Between 700 and 100 cal. yr BP (zone LA-2, Figure 3) percentages of arboreal taxa (*Maytenus boaria*, *Azara*) increase, while Gramineae, Chenopodiaceae, Euphorbiaceae, *Typha* and *Myriophyllum* decline. The increase of *Maytenus boaria* and *Azara* suggest humid climatic conditions during this interval. The accumulation rates and concentration, however, show that all taxa either decline (*Maytenus boaria*, *Azara*, Cyperaceae) or disappear (*Quillaja*, *Talguenea*, herbs, *Typha*, *Myriophyllum*). This pattern is also observed in the microalgal record (Figure 6). Sediment analyses indicate during this interval the occurrence of various turbidite layers indicating periods of sustained precipitation. High sediment input into the lake would explain the extreme low pollen concentration and accumulation rate values over this lapse.

The decline and disappearance of *Maytenus boaria* in the last 100 years (zone LA-3) of the record would imply drier and slightly warmer conditions. Concomitant increases in Chenopodiaceae and warm sclerophyllous arboreal taxa pollen (*Quillaja saponaria*, *Talguenea trinervis*, Anacardiaceae) are also consistent with this interpretation. The microalgae record, however, suggests that these recent vegetation changes observed in the Aculeo watershed may in fact be anthropogenically induced. The transition from oligo-mesotrophic to hypereutrophic conditions, as implied by the decline in *Pediastrum boryanum* and *P. duplex*, and the expansion of *P. simplex* and *Scenedesmus*, is synchronous with increasing phosphate concentrations and the maximum abundance of the diatoms *Aulacoseira granulata*, *Melosira pseudogranulata* and *Cyclotella operculata* from Laguna de Aculeo (Jenny *et al.*, 2002). Habitat degradation of anthropogenic origin is also suggested by prominent peaks in the stratigraphy of microscopic charcoal particles over the last 100 years. There is ample historical evidence of fire use in agricultural practices and land clearance in Central Chile over the last 400 years (Elizalde, 1970).

Overall, our results suggest humid conditions in Central Chile during the last 2500 years and generally agree with previous palaeoclimate studies in the region such as: (i) the establishment of swamp forest vegetation in the Quintero (32°47′S), and Ñague (31°50′S) sites around 2000 ^{14}C yr BP (1970 cal. yr) in the coastal region of central Chile (Maldonado and Villagrán, 2002; Villagrán and Varela, 1990; Villa-Martínez and Villagrán, 1997); and (ii) an increase in Gramineae and *Nothofagus dombeyi*-type pollen at Laguna Tagua Tagua (34°30′S) starting at about 2600 ^{14}C yr BP (2750 cal. yr;

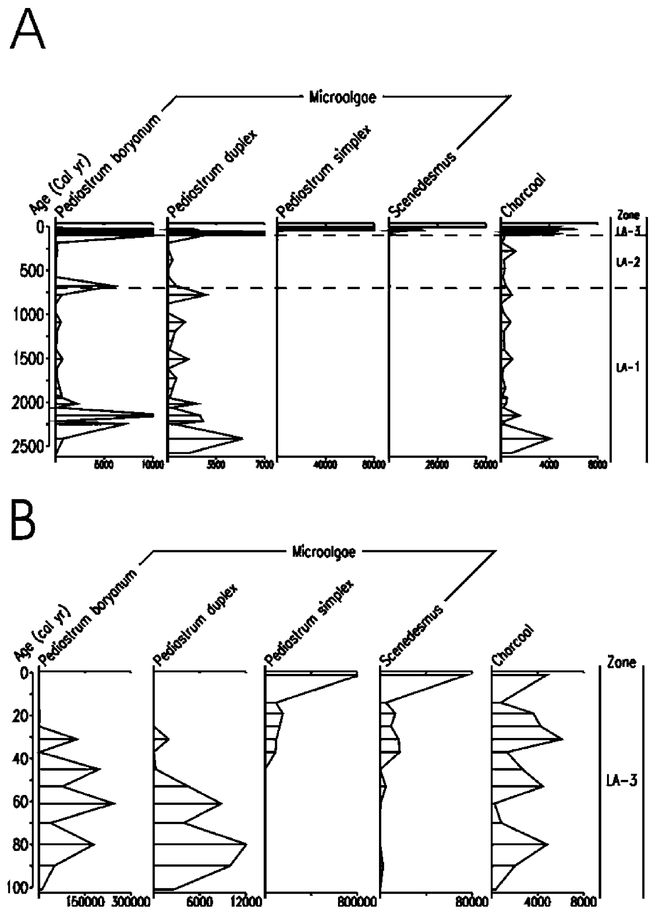

Figure 6 Accumulation rates for microscopic charcoal particles and microalgae from the Laguna de Aculeo record. (A) Accumulation rates for pollen zones LA-1 and LA-2. The accumulation values for LA-3 have been truncated. (B) Accumulation rates for pollen zone LA-3. Note that accumulation rate scales vary between both graphs and among species of microalgae and charcoal. Units are in microalgae/charcoal microparticles per cm^2 per yr.

Heusser, 1983; 1990). Veit (1996), based on palaeosoils evidence between 27 and 33° lat. S, hypothesized that wet periods occurred in 2000–1600 and 600–200 ^{14}C yr BP (1970–1500; 630–285 cal. yrs BP) and dry periods in 1600–600 ^{14}C yr BP and since 200 ^{14}C yr BP. The alternation between wet and dry periods could be explained by northward and southward shifts of the westerly rainfall belt. A similar wet phase between 2200 and 1800 ^{14}C yr BP (2180–1720 cal. yr BP) was attributed to enhanced westerly activity at Laguna del Negro Francisco (27°28′S, 4125 m a.s.l.; Grosjean *et al.*, 1997).

Based on the pollen, microalgal and charcoal record from Laguna Aculeo we conclude that precipitation variability over the last 2500 years in Central Chile was probably the result of changes in the frequency and/or intensity of westerly storms on interdecadal and subcentennial timescales. As mentioned earlier, interannual precipitation variability in Central Chile is highly correlated with ENSO (Aceituno, 1988). The data from Laguna de Aculeo indicate periods of large-amplitude rainfall variability at subcentennial timescales, possibly linked to strong ENSO-like events. This interpretation is consistent with recent historical studies about El Niño that show interdecadal and multidecadal ENSO-like variability (Garreaud and Battisti, 1999; Jones and Allan, 1999; Urban *et al.*, 2000; Zhang *et al.*, 1997) and with strong ENSO events occurring at subcentennial timescales (Trenberth and Stepaniak, 2001).

On the other hand, several authors have proposed that ENSO-like events have *intensified over the last* 3000 *years (Mc Glone et al.*, 1992; Mörner, 1993; Ortlieb *et al.*, 1993; Veit, 1996). Based on fossil mollusc assemblages from beach ridges in northern Peru, Ortlieb *et al.* (1993) documented exceptionally strong El Niño events for the middle and late Holocene. More recently, Tudhope *et al.* (2001) suggested that the amplitude of ENSO events has been significantly larger over the last 3000 years compared to 6500 yr BP. Moreover, deep-sea records off the coast of central Chile present elevated variability in planktic foraminifera assemblages, which are thought to correspond to precipitation increases, coupled with strong, ENSO-like, climatic variability over the last 3000 years (Marchant *et al.*, 1999).

In conclusion, our pollen, microalgae and charcoal data document that the humid climate present in Central Chile was highly variable in terms of precipitation and was clearly caused by changes in the frequency and/or intensity of westerly storms, probably related to high frequency and/or intensity ENSO-like variability. Changes in plant composition and water nutrient content over the last century were most likely caused by increase human activity and have produced an advanced degree of modern landscape transformation around the lake. Denudation of the watershed has also increased sediment input and thus higher sedimentation rates over the last 100 years. This interpretation is consistent with historical accounts by Graham (Graham, 1824), who described dense forests surrounding a lake of crystalline waters, a picture very different from the hypereutrophic lake and the *Acacia caven* thornscrub that occupies the watershed today. The nineteenth-century Chilean painter Onofre Jarpa, in his painting entitled 'Laguna de Aculeo', captured lush green scenery surrounding the lake, with dense forests of what can only be *Maytenus boaria*.

Acknowledgements

Research was funded by FONDECYT grant No 2990012 to R.V.M. AMS ^{14}C dating was funded by NSF (ATM-9809285) to the University of Colorado-INSTAAR's Laboratory of AMS Radiocarbon Preparation and Research. Core sampling at Laguna de Aculeo was funded by Swiss NSF 20.56908.99 to Heinz Veit. We thank Peter Appleby for ^{210}Pb dates and Mebus Geyh for ^{14}C dates. We also thank Willi Tanner and Martin Grosjean for help in core sampling and I. Vila and V. Montecino for their help with the microalgae record. We thank P.I. Moreno and C. Latorre for constructive reviews and editorial assistance. V. Markgraf and an anonymous reviewer are thanked for constructive comments.

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