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Late Holocene vegetation dynamics and lake geochemistry at Laguna Miranda, XI Region, Chile

Dinámica vegetaciónal y geoquímica lacustre del Holoceno tardío en Laguna Miranda, XI Región, Chile

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ABSTRACT

Palynological and geochemical analysis of late Holocene lake sediments and dendrochronological analysis of *Pilgerodendron* in a volcanically active region of southern Chile reveal the long-term impact of a series of tephra fall events and tectonic activity on lake sedimentation and local vegetation. An upper 0,75 m core overlaps with a 4,35 m long Livingstone piston core to give a 4,60 m long sediment record, extending back to 4800 yr BP. Geochemical data shows the shift from allogenic dominance to authigenic and biogenic dominance as waterlogged soils developed within the catchment. This is presumed to have occurred under the influence of continued addition of nutrients to the catchment from tephra deposition and the associated high sedimentation rates. The palynological record from this site is dominated by *Nothofagus dombeyi*-type and Filicales. The most prominent changes in the pollen record, however, are the gradual decline in *Podocarpus nubigena* pollen throughout the last 4800 yr; the appearance and increase of Gramineae pollen during the past 2100 yr; and the rapid increase in the pollen of *Pilgerodendron uviferum* within the past 300-400 yr. *Pilgerodendron* tree-ring analysis and the pollen results over the last 400 years show that the most recent expansion of *Pilgerodendron* at the northern and eastern margins of this site is a response to either, periodic tectonic induced watertable changes, or is part of a long-term trend in gymnosperm growth around a shallowing lake margin. The decline of shade-intolerant trees such as *Weinmannia* and *Podocarpus* within a *Nothofagus*-rich forest community towards an increased presence of *Pilgerodendron* and Gramineae (likely *Chusquea* bamboo), that began over 2100 yr BP, may have been due as much to autogenic processes such as a change in the disturbance regime resulting in the development of waterlogged soils, rather than to an episode of climate change. It is important to recognise the potential effects of autogenic processes that may result from disturbance such as volcanic/ tectonic activity in reconstructing past vegetation dynamics from pollen records.

Key words: Hudson Volcano, tephra, pollen, geochemistry, dendrochronology.

RESUMEN

Análisis palinológicos y geoquímicos de sedimentos lacustres del holoceno tardío y análisis dendrocronológicos de *Pilgerodendron uviferum* en una zona volcánica activa del sur de Chile revelan el impacto a largo plazo de diversas caidas de tefra y actividad tectónica en la sedimentación lacustre y la vegetación de la zona. Una sección sedimentaria superior de 0,75 m traslapa una columna de pistón Livingstone de 4,35 m de largo para dar un registro de sedimentación de 4,60 m de longitud extendiéndose 4800 años AP. Datos geoquímicos muestran el cambio de dominancia alogénica a dominancia autígena y biogénica según se formaban los terrenos anegadizos dentro de la cuenca. Se presume que esto pudo producirse bajo la influencia de la llegada constante de nutrientes a la cuenca del lago procedentes del depósito de materias volcánicas conjuntamente con una alta sedimentación. El registro palinológico de este lugar está dominado por el tipo *Nothofagus dombeyi* y Filicales. Los cambios más notables que registra el polen son, no obstante, la declinación gradual del polen *Podocarpus nubigena* durante los últimos 4800 años; la aparición y aumento del polen Geamineae durante los pasados 2100 años; y el rápido aumento del polen *Pilgerodendron uviferum* en los últimos 300 a 400 años. El análisis de los anillos de leño de *Pilgerodendron* y los resultados que da el polen en los últimos 400 años muestran que la expansión más reciente de *Pilgerodendron* en las márgenes norte y este del lugar es una respuesta, bien a cambios periódicos de la capa freática por interacción tectónica, o es parte de un lento proceso de desarrollo de gimnospermas en las márgenes poco profundas del lago. La disminución de *Weinmannia* y *Podocarpus*, hace alrededor de 2100 años AP, se podría deber a procesos autogénicos resultando en el desarrollo de terrenos anegadizos, o a cambios en el régimen de perturbación, más bien que a un episodio de enfriamiento climático. En la reconstrucción de la dinámica de vegetaciones pasadas y partiendo de los registros del polen, es importante reconocer los efectos potenciales de los procesos autogénicos que pueden derivarse de perturbaciones tales como actividad volcánico/tectónica.

Palabras clave: volcán Hudson, tefra, polen, geoquímica, dendrocronológico.

INTRODUCTION

The eruption of Hudson Volcano in the austral winter (August) of 1991 was the second most violent volcanic event in Chile this century. It produced large plumes of tephra, accompanied by SO_2 gas emissions, that had a major environmental impact over an area of 150 000 km^2 in Chile and Argentina (Naranjo et al. 1993). The impact of the tephra fall and associated tectonic disturbance on vegetation was widespread and led to mortality and severe damage to many species in the regional forest communities (Vogel 1996). While there have been a number of studies in Chile on the impact of volcanic eruptions on vegetation over time scales of years to decades (Kitzberger et al. 1995, Veblen et al. 1977, Vogel 1996), the consequences of volcanic and tectonic disturbance on vegetation dynamics over longer time scales (century to millennium) are not well understood.

The importance of large and small scale disturbance in the vegetation dynamics of southern Chilean forest communities is now well established (Veblen et al. 1996). Disturbance may vary from processes associated with large scale mass movement triggered by tectonic activity, volcanic eruptions, glacial processes, wind blowdown, and fire (natural or anthropogenic) to the finer-scale treefall gap processes. Climatic fluctuations also have an impact on vegetation, either directly through changes in parameters such as temperature and precipitation, or indirectly through the influence of these changes on the disturbance regime. That short-term fluctuations in climate are also important determinants of the disturbance regime has been demonstrated by recent ecological based studies that show population level dynamics being affected by annual to decadal scale climate change (Kitzberger et al. 1997, Szeicz 1997, Villalba & Veblen 1997). For example, forest dieback due to drought stress and fire, or the patchy destruction of canopy trees after blowdown events, create gaps and speed up regeneration dynamics. However, the relatively short time span involved in these ecological studies limits their insight into the actual long-term environmental variance that may affect many generations of trees.

Tephra layers preserved in lake or bog deposits provide clear evidence for past volcanic eruptions. This evidence can be used for stratigraphic correlation and chronological markers when reliably dated, and also provide the opportunity to investigate the effect of past eruptions on the environment and the pattern of ecosystem recovery. Surveys of lakes have shown many lake basins where tephras are preserved and that are suitable for palaeoenvironmental investigations (Haberle et al. in press). A multiproxy approach, using high-resolution palynology, dendrochronology and palaeolimnology records, has been employed to investigate the natural and human induced processes driving late Holocene vegetation change in southern South America at decadal to century time scales over the last millennium (Szeicz et al. 1998). Here, we extend this analysis of vegetation change to over the last 5 millennia, by focussing on the impact of successive volcanic eruptions on vegetation and lake sedimentation at a small lake basin in the vicinity of Hudson Volcano, as evidenced by pollen, geochemistry, and tephra analysis.

Study Area

Laguna Miranda (46°08'40"S, 73°26'40"W) is a small (0.5 ha), more or less ombrotrophic lake, lying at an altitude of 120 m above sea level in a remote forested region some 50 km southwest of Hudson Volcano and 65 km north of the San Rafael Glacier (Fig. 1). The site is about 0.5 km from the shoreline of a complex channel system,

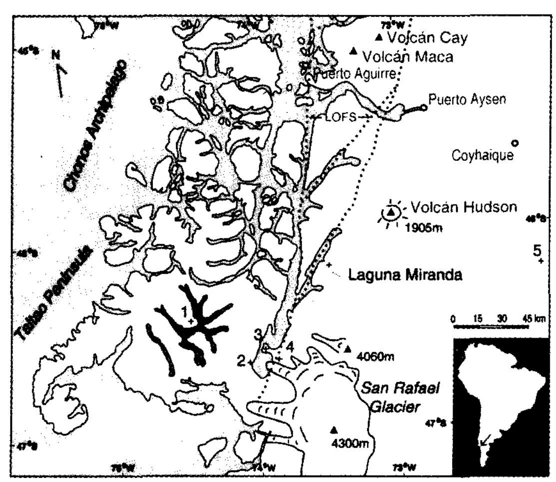

Fig. 1. Location map of the Taitao-Coyhaique area, XI Region, Chile. Key to numbers representing sites referred to in the text: 1, Laguna Stibnite (Lumley & Switsur 1993); 2, Istmo de Ofqui I and II (Heusser 1964); 3, Río Témpanos (Heusser 1964); 4, Interfluctuational section (Heusser 1964); 5, Juncal Alto (Naranjo & Stern 1998). The Liquiñe-Ofqui fault system (LOFS) is shown as a dotted line.

Mapa del área de Taitao-Coyhaique, XI Región, Chile. La clave numérica de los lugares mencionados en el texto: 1, Laguna Stibnite (Lumley & Switsur 1993); 2, Istmo de Ofqui I y II (Heusser 1964); 3, Río Témpanos (Heusser 1964); 4, sección interfluctuante (Heusser 1964); 5, Juncal Alto (Naranjo & Stern 1998). El sistema de falla Liquiñe-Ofqui (LOFS) está representado con una línea de puntos.

carved by extensive ice erosion from the Patagonian icefield that covered this region during the last glaciation (Clapperton & Sugden 1988). The bedrock of the region consists of granite of Cretaceous age (Niemeyer et al. 1984). Tectonic activity is centred around the Liquiñe-Ofqui fault system, with the main north-south aligned fault only 5 km to the west of Laguna Miranda. The site lies within a zone of high precipitation, produced by the coupled ocean-atmospheric influence of the Southern Polar Front, that migrates seasonally between 50°S (summer) and 40-45°S (winter). In general the climate is strongly oceanic, with annual precipitation in the region of 3000 mm and mean annual temperatures around 8-10°C. In the nearby Andes, rising to 4300 m altitude, precipitation is much higher with estimates for annual rainfall as much as 10,000 mm (Fujiyoshi et al. 1987).

The vegetation of the lake catchment is North Patagonian rain forest dominated by evergreen broadleaf and conifer taxa (Gajardo 1995, Veblen et al. 1983). The lowlands of this region support a dense forest of *Nothofagus nitida*, *N. betuloides*, *Podocarpus nubigena*, *Weinmannia trichosperma*, *Drimys winteri*, *Caldcluvia paniculata*, and *Pseudopanax laetevirens* (botanical nomenclature follows Marticorena & Quezada 1985). The understorey of these forests, particularly where light can easily penetrate, are frequently occupied by bamboo (*Chusquea* spp.). Poorly drained sites, including the waterlogged margins of Laguna Miranda, are dominated by *Pilgerodendron uviferum* and *Tepualia stipularis*. The branches of *Nothofagus* spp. are occasionally observed to be infested with the semiparasitic plant *Misodendron* spp. *Potamogeton* spp. was common around the margins of the lake.

METHODS

Fieldwork was conducted in the southern hemisphere summer of 1995, with the logistic support of Raleigh International and CONAF. Parallel cores were taken from the centre of Laguna Miranda with a modified Livingstone corer. An undisturbed core of the uppermost sediment was obtained from the centre of the lake using a clear plastic piston corer. Each core was described in detail and scanned by a magnetic susceptibility core scanning loop at 10-20 mm intervals. This identifies changes in the abundance of ferrimagnetic minerals, which is used as an indication of changing erosional input to the lake, and to assist in the location of basaltic tephras. Three major tephra layers were located in this way and the glass shards extracted (H_2O_2 digestion) and mounted for electron microprobe analysis (EMPA, Department of Earth Sciences, University of Cambridge), following the guidelines set down by Froggatt (1992) and Hunt & Hill (1993). The amount of organic matter was determined by loss-on-ignition at 550°C. Chronological control is provided by using a combination of AMS/bulk radiometric ^{14}C dating (Table 1) and the dates are reported throughout this paper as calibrated years before present (present is 1950 AD, Stuiver & Reimer 1993).

TABLE 1

Radiocarbon analysis of Laguna Miranda samples (TO-series are AMS dates and Q-series are bulk sample ^{14}C dates). Calibrated ages are calculated by the intercept with curve method and 2 sigma values (95% confidence interval) using the Stuiver & Reimer (1993) computer program CALIB 3.0.3c

Análisis por radiocarbono de las muestras de Laguna Miranda (Las series TO son fechas AMS y las series Q son fechas ^{14}C de muestras a granel). Las edades calibradas se calculan por intercepción con el método de curva y 2 valores sigma (95% intervalo de confianza), usando el programa de computadora CALIB 3.0.3c de Stuiver & Reimer (1993)

Lab Code	Sample depth (m)	Radiocarbon Age (^{14}C yr BP)	Calibrated Age Range max (cal yr BP) min
TO-5682[1]	4.30-4.32	400 ± 50	521 (477) 309
TO-5683[2]	4.52-4.53	430 ± 50	536 (501) 319
Q-2977[3]	5.05-5.15	1160 ± 30	1162 (1062) 975
Q-2976[3]	6.89-6.99	2710 ± 35	2862 (2781) 2753
Q-2975[3]	8.36-8.46	4250 ±35	4863 (4833) 4651

[1] *Nothofagus* and *Podocarpus* leaf; [2] *Nothofagus* leaf; [3] Bulk gyttja samples.

Geochemical analysis of lake sediments follows a fractional method introduced by Engstrom & Wright (1984) and modified by Lumley (1993), providing information on the chemical environment in the lake in relation to erosional inputs and redox conditions within the surrounding landscape (identifying the elements Mn, Fe, Al, Mg, Na, K, Ca, Ti, and Si). The wet-chemical extraction technique separates acid-soluble "authigenic fraction" and biogenic (diatom) silica from the clastic mineral "allogenic fraction". Element analysis of the separate fractions was carried out on an ICPES (Inductively Coupled Plasma Emission Spectrometer, University of London, Royal Holloway, UK).

Pollen analysis follows the standard acetolysis method described by Faegri & Iversen (1989). Pollen identification and nomenclature follows that set out in authored reference material (Heusser 1971, Villagran 1980, Zhou & Heusser 1996) and regional reference collections held at the Department of Plant Sciences, University of Cambridge (Appendix 1). Pollen counts are expressed as percentages of the total pollen sum (excluding pollen of aquatic vascular plants and all spores) which reaches a minimum of 300 in all samples. Charcoal particle concentrations were calculated following the point counting method outlined by Clark (1982). Charcoal analysis provides basic data on the abundance of charcoal in the sediment, from which the extent and intensity of fires around the site can be inferred. Numerical zonation and principal components analysis (PCA) were performed with only major taxa whose pollen or spore values exceeded 5% at least once. Numerical zonation employed optimal splitting by sum-of-squares analysis to partition the Laguna Miranda data into 3 significantly different pollen zones (Bennett 1996). PCA is used to reduce the pollen and spore data to a two-dimensional plot and the resulting data set is displayed as a biplot for samples and taxa (Birks and Gordon 1985). All numerical analyses, including zonation and principal component analysis (PCA), have been implemented within PSIMPOLL, a c program for plotting pollen data, developed by Bennett (1994).

RESULTS

Sediment, tephra analysis and chronology

The sediment stratigraphies for two cores from Laguna Miranda are shown in Fig. 2. The sedi-

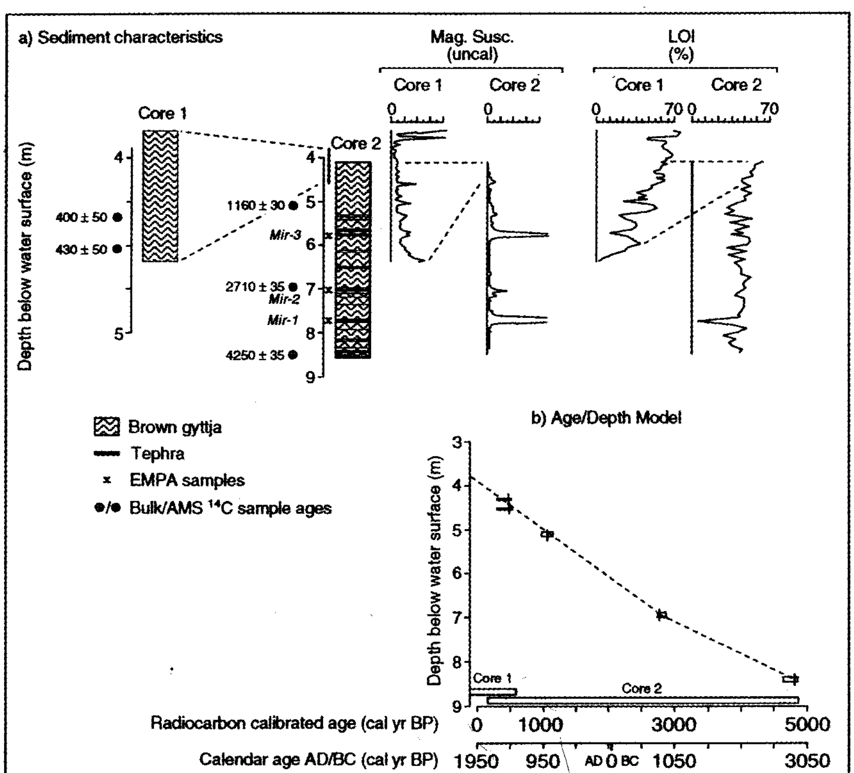

Fig. 2. a) Sediment characteristics, stratigraphic correlations between cores, and b) sediment chronology from Laguna Miranda.

Características sedimentarias, correlaciones estratigráficas entre columnas, y b) cronología sedimentaria de Laguna Miranda.

ment is brown gyttja with thin green to grey inorganic inclusions. The upper 0.75 m core overlaps with the 4,35 m long Livingstone piston core to give a 4.60 m long sediment record at the site. Penetration of the core to greater depth was not possible due to increased sand (tephra) content at the base.

A total of 22 distinct inorganic layers, all containing volcanic glass shards, were identified as tephra deposited directly from atmospheric fallout, or from remobilised deposits within the lake catchment. Three tephra deposits, Mir-3 (olive silty sand, 15 mm), Mir-2 (olive silty sand, 8 mm) and Mir-1 (Olive grey silty sand, 80 mm) that gave strong magnetic susceptibility signals and were clearly visible in the core, were selected for tephra analysis. Geochemical compositions of these different tephra layers are shown in Appendix 2. The analysis show that the three tephras contain a suite of glass shards derived from both dacitic-andesite type eruptions (SiO_2 content of 60-65%, and a high K_2O content), and basaltic-andesite type eruptions (SiO_2 of around 50-55 % and a high TiO_2 content). Comparison with geochemical data from the nearest volcanic sources (Austral Volcanic Zone, 49°-55°S, and the Southern Southern Volcanic Zone, 41.5°-46°S, see Futa & Stern 1988, López-Escobar et al. 1993, Haberle & Lumley 1998, Stern 1990, 1991, Naranjo et al. 1993, Naranjo & Stern 1998) show that the distinct geochemical signature from Volcán Hudson eruptions (Fig 3a) is consistent with those obtained from tephras deposited in Laguna Miranda (Fig. 3b).

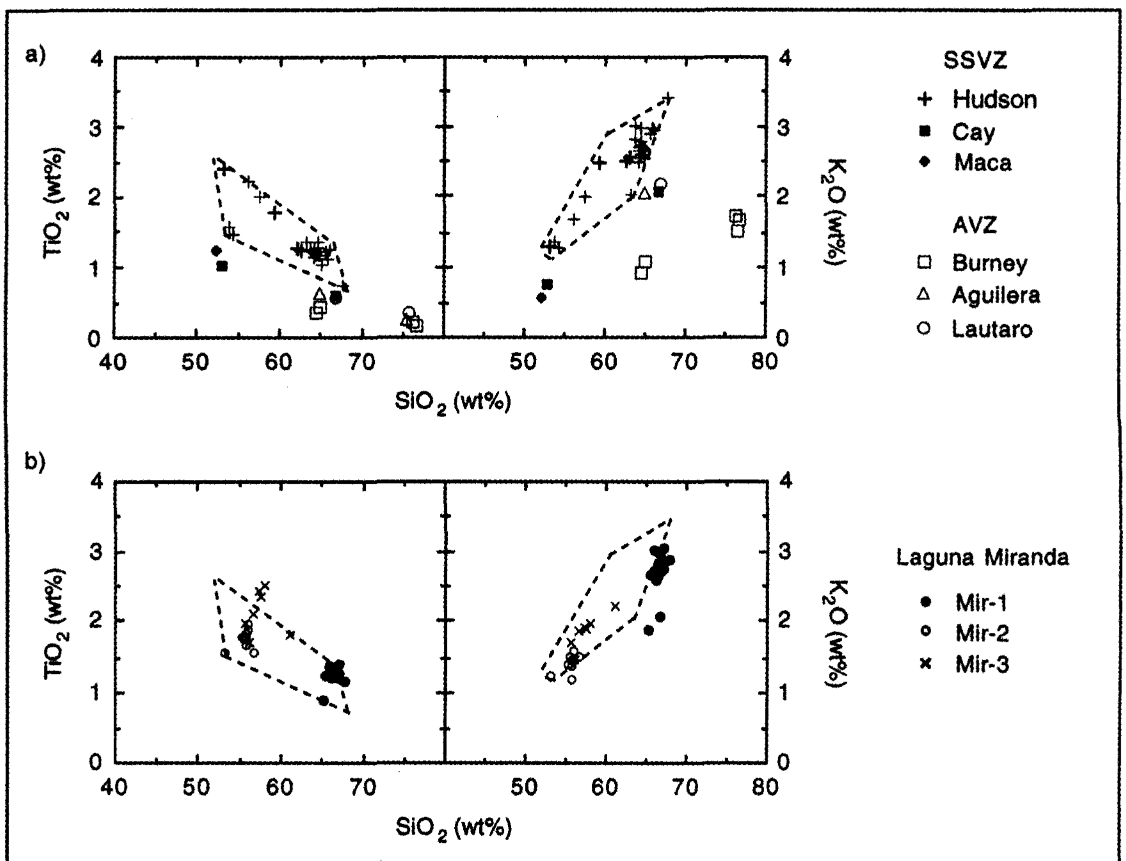

Fig. 3. a) SiO_2 versus TiO_2 and K_2O for selected volcanic sources in Southern South America. Data for the Hudson, Maca, Cay volcanoes in the South Southern Volcanic Zone (SSVZ) and the Lautaro, Burney and Aguilera volcanoes in the Austral Volcanic Zone (AVZ) is from Futa & Stern (1988), Haberle & Lumley (1998), López-Escobar et al. (1993), Stern (1990, 1991) and Naranjo et al. (1993). b) SiO_2 versus TiO_2 and K_2O for analysis on the three Laguna Miranda tephras compared to the tephra analysis envelope for Hudson Volcano (data given in Appendix 2).

a) SiO_2 versus TiO_2 y K_2O por fuentes volcánicas seleccionadas de la parte meridional de Sudamérica. Los datos sobre los volcanes Hudson, Maca y Cay en el Zona Volcánica Sur Sur (ZVSS), y los volcanes Lautaro, Burney y Aguilera en la Zona Volcánica Austral (ZVA) son de Futa & Stern (1988), Haberle y Lumley (1998), López-Escobar et al. (1993), Stern (1990, 1991) y Naranjo et al. (1993). (b) SiO_2 versus TiO_2 y K_2O por análisis de las tres tefras de Laguna Miranda comparadas con el análisis de tefra del Volcán Hudson (datos en el apéndice 2).

Radiocarbon dating indicates that average rates of sedimentation at Laguna Miranda were close to linear throughout the last 4800 years (Fig. 2). The temporal resolution of the cores varies from 9 to 14 year $10mm^{-1}$ depending on the depth. Table 2 lists the inferred age of inorganic (tephra) layers, showing that major phases with high frequency deposition events occur between 2800 - 3100 cal yr BP and 4400 - 4830 cal yr BP. The tephras identified at this site have not been dated directly, but there is a strong correspondence between the ages determined for two Hudson Volcano tephras recorded 70 km to the southwest in Laguna Stibnite (1690-1530 cal yr BP and 2790-2490 cal yr BP, Haberle and Lumley 1998), one recorded 80 km to the east of Hudson Volcano at Junco Alto (3885 cal yr BP, Naranjo & Stern 1998), and those recorded at Laguna Miranda (1695 cal yr BP, 2800 cal yr BP and 3820 cal yr BP). These results may provide additional chronological control when compared to regional tephrochronology being developed from lake sediment records (e.g., Haberle & Lumley 1998, Naranjo & Stern 1998).

TABLE 2

Depths, inferred ages and thickness of inorganic layers (tephra and reworked tephra/ clays) recorded in Laguna Miranda

Profundidades, edades y espesores colegidos de capas inorgánicas (tefra y tefra reprocesadas/arcillas) registradas en Laguna Miranda

Depth (m)	Inferred Age (cal yr BP)	Thickness (mm)	Comments
5.28	1230	1	
5.29	1240	3	
5.31	1265	5	
5.68	1605	2	
5.70	1620	2	
5.78	1695	15	Mir-3
6.13	2025	1	
6.14	2035	3	
6.50	2400	8	
6.97	2750	3	
7.01	2800	8	Mir-2
7.06	2900	1	high-frequency
7.15	3065	2	deposition phase
7.32	3295	6	
7.75	3820	80	Mir-1
7.97	4170	2	
8.13	4385	5	
8.18	4480	3	
8.34	4680	13	
8.37	4710	10	high-frequency
8.40	4750	1	deposition phase
8.44	4805	2	
8.46	4830	7	

Sediment chemistry (Fig. 4)

Authigenic fraction: Fe, Al, Ca and Si dominate the authigenic chemistry of the Laguna Miranda sediments (Fig. 4a). Ca and Mn concentrations are high between ca. 4800 and 4000 cal yr BP, though subsequently decreasing towards the top of the core. The Fe:Mn ratio shows a steady increase upwards through the core. i, Fe, Al and Si reach maximum concentrations between 4000 cal yr BP and 1200 cal yr BP, when there is a striking decrease in the concentrations of all these elements.This coincides with a decrease in the total authigenic content and an increase in sediment organic content, Mg and the Fe:Mn ratio.

Biogenic fraction: Biogenic Si shows a general trend of increasing concentrations towards the top of the core (Fig. 4b). Two periods in which biogenic Si increases markedly are ca. 2000 cal yr BP and after ca. 1200 cal yr BP.

Allogenic fraction:The allogenic fraction is dominated by Si, Al, Fe and Ca (Fig. 4b), which is similar to the elemental composition of the three tephra deposits. Total allogenic content is highest in the basal sediments, between ca. 4800 - 4000 cal yr BP, and higher in the core 1800 - 1200 cal yr BP. All elements follow a similar pattern of change as shown in the total allogenic curve.

Pollen, spores and microscopic charcoal (Fig. 5)

Zone 1 (ca 4800 - 2100 cal yr BP): Pollen spectra are dominated by *Nothofagus dombeyi* type (50-70%), *Podocarpus nubigena* (15-25%), and Filicales (30-40%). *Podocarpus nubigena* and *Weinmannia trichosperma* have relatively high percentages between ca. 4800 - 4000 cal yr BP, followed by a gradual decline towards the upper part of the core. Other tree taxa remain in consistently low abundances. The first appearance of Gramineae pollen occurs after ca. 2400 cal yr BP. The ratio between *Misodendron* and *Nothofagus* pollen shows only minor fluctuations. Microscopic charcoal is also low in abundance with only a slight rise between ca. 4000 - 3300 cal yr BP.

Zone 2 (ca 2100 - 200 cal yr BP): This zone is characterised by a rise in the percentage abundance of Gramineae. Cyperaceae and the aquatic, *Potamogeton*, increase after 1200 cal yr BP. Other taxa are relatively unchanged. The are slight increases in *Pilgerodendron uviferum* and *Tepualia stipularis*, and a decrease in *Nothofagus dombeyi*

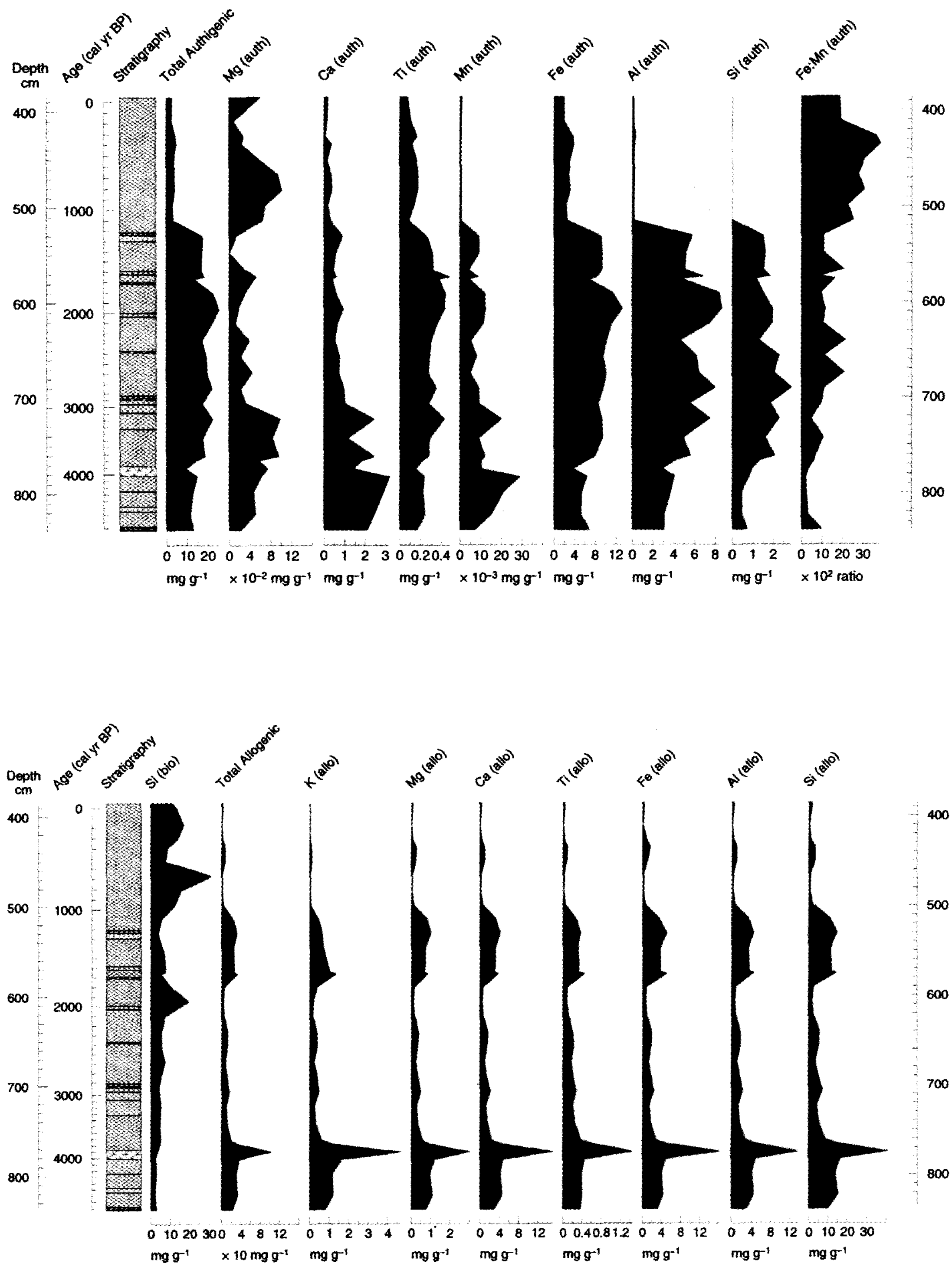

Fig. 4. Sediment chemistry of Laguna Miranda samples against lake depth and inferred age (note independent scaling for each element). a) Authigenic fraction, b) Biogenic and Allogenic fraction.

Química sedimentaria de muestras de Laguna Miranda contra profundidad del lago y edad inferida obsérvese la escala independiente para cada elemento). a) Fracción autígena, b) Fracciones biogénicas y alogénicas.

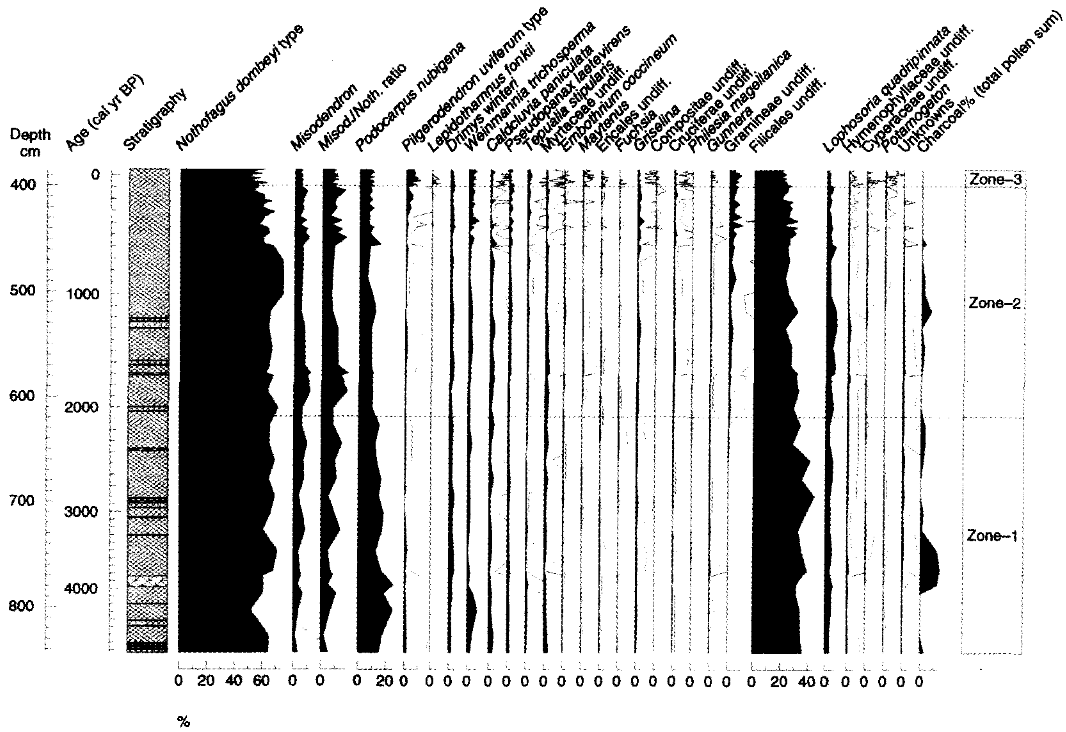

Fig. 5. Pollen percentage diagram of combined cores from Laguna Miranda against depth and inferred age. Pollen counts are expressed as percentages of the total pollen sum, excluding pollen of aquatic vascular plants and all spores. Selected taxa percentages are drawn with an exaggeration of x10 (single line). *Nothofagus* to *Misodendron* ratio as an indicator of relative *Nothofagus* infestation. Charcoal is expressed as a percentage of the total pollen sum. For explanation of sedimentary column see Fig. 2a.

El diagrama de porcentajes de polen de columnas combinados de Laguna Miranda contra profundidad y edad inferida. El conteo se expresa como porcentajes de la suma total de polen, excluyendo el polen de plantas acuáticas vasculares y todas las esporas. Los porcentajes de toxones seleccionados se sacan con una exageración de x10 (línea singular). La proporción de *Nothofagus* a *Misodendron* indica una infestación relativa de *Nothofagus*. El carbón vegetal se expresa como un porcentaje de la suma total de polen. Ver Fig. 2a para una explicación de la columna sedimentaria.

type towards the top of the zone. The ratio between *Misodendron* and *Nothofagus* continues to show only minor fluctuations. Microscopic charcoal remains very low.

Zone 3 (ca 200 cal yr BP to present): *Pilgerodendron uviferum* pollen becomes important in this zone. *Tepualia stipularis*, *Maytenus* and *Lepidothamnus fonkii* show slight increases in representation. Microscopic charcoal is very low.

Principal Components Analysis (PCA): The major patterns of variation in the pollen data were summarised by means of PCA, with pollen taxa accounting for significant sample variance displayed as a biplot (Fig. 6). The sample distribution shows a U-shaped shift through time showing the three phases of vegetation change: (i) early dominance of *Nothofagus* forest with *Podocarpus*, and to a lesser extent *Weinmannia* and *Pilgerodendron* important taxa, (ii) reduced influence from all forest taxa except *Nothofagus* under the influence of increased Gramineae, and (iii) the shift to *Nothofagus* forest including *Pilgerodendron* and *Weinmannia* as important components of the forest. High negative loadings for *Nothofagus* and *Misodendron* in axis 2 reflect changes in the forest dominant *Nothofagus*, and the close correspondence between abundance of the semiparasitic plant *Misodendron* and its host *Nothofagus*.

Interpretation

The lake sediment record begins around 4800 cal yr BP at which time a North Patagonian rainforest, including a mixture of shade-tolerant and shade-intolerant species, was already established around the lake. Burning appears to have been minimal throughout the record. Between 4800 - 2100 cal yr BP very little change is evident in the forest composition, though there is a gradual decline in

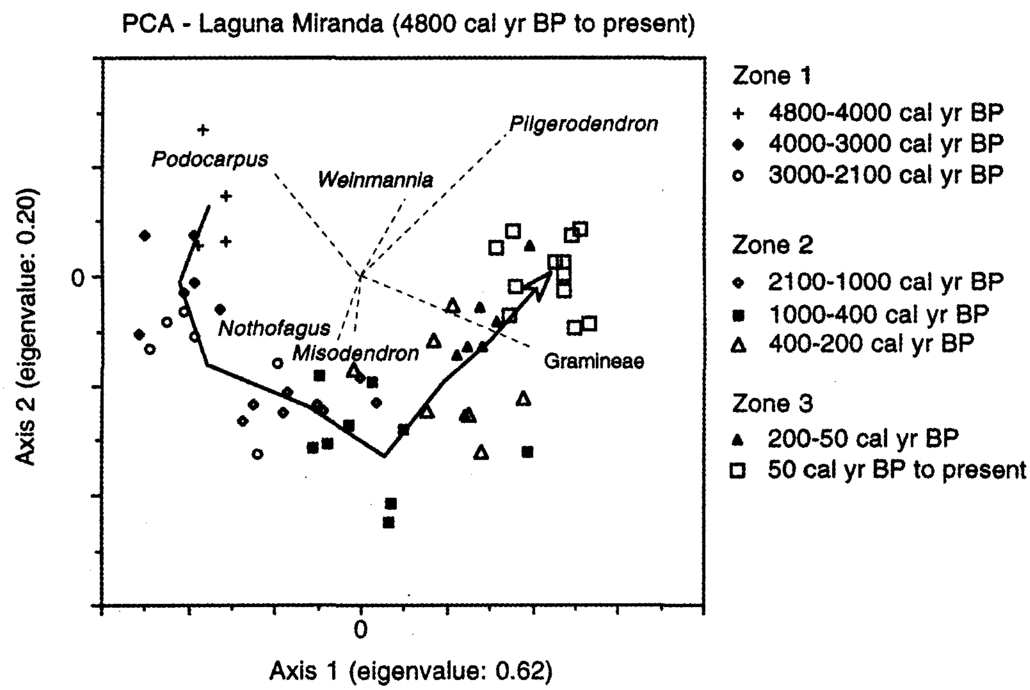

Fig. 6. Principal Components Analysis of pollen data from Laguna Miranda (taxa with relative abundance of <5% were excluded from the analysis). Eigenvalues are expressed as proportions of total variation with axis scale linear and plot centred on origin. The two dimensional representation accounts for around 82% of the original variability (Axis 1 = 62%, Axis 2 = 20%). The samples are identified according to their respective zone and the midpoint of samples from a single zone (mean of principal components) are joined up in stratigraphic order (thick stippled line). The directions of influence for each pollen taxa used in this analysis are overlain on the stratigraphic sample data in this diagram.

Análisis de los integrantes principales del polen de Laguna Miranda (taxones con una abundancia relativa de <5% no se incluyeron en el análisis). Los valores característicos se expresan como proporciones de variación total con escala axial lineal y plano bidimensional centrados en origen. La representación bidimensional supone alrededor del 82% de la variabilidad original (Eje 1 = 62%, Eje 2 = 20%). Las muestras se identifican según las zonas respectivas y el punto medio de muestras de una sola zona (media de componentes principales) se hallan unidos en correlación estratigráfica (línea de puntos gruesos). Las direcciones de influencia por cada taxón de polen usado en este análisis van sobrepuestas a los datos estratigráficos de la muestra en este diagrama.

Podocarpus over this time and a reduction in the importance of *Weinmannia trichosperma* after 4000 cal yr BP. High allogenic inputs into the lake, particularly prior to 4000 cal yr BP, are probably derived from direct airfall of tephra and subsequent inwashing and reworking via overground water flow. Similarly, authigenic minerals formed in the waterlogged organic catchment soils, and mobilised by eluvial processes, are likely to have been derived from weathered products of older tephra deposits. The concentration of biogenic Si is at its lowest during this period, despite the high mineral inputs from tephra airfall events. Biogenic Si tends to be negatively correlated with total allogenic inputs suggesting the addition of tephra derived minerals resulted in an aquatic environment that was relatively poorly suited for the growth of diatoms and other aquatic organisms.

Between 2100 - 200 cal yr BP there are important changes in both the vegetation and geochemical record. Gramineae appears around 2400 cal yr BP and becomes increasingly important after 2100 yr BP. These changes may relate to the earlier rise in authigenic minerals, particularly Fe and the Fe:Mn ratio, indicative of reduced soil redox conditions during the development or expansion of waterlogged soils (Mackereth 1966, Pennington et al. 1972, Engstrom & Wright 1984). With continued addition of mineral nutrients to the environment from tephra fall and high levels of disturbance, there would have been an increase in the availability of sites for invasion. *Nothofagus* and Gramineae (likely the *Chusquea* bamboo) may have been best suited to take advantage of the disturbance regime and changing soil conditions.

The striking reduction in total authigenic elements in the sediment after 1200 cal yr BP coincides with a sharp reduction in the addition of tephra to the sediment. The increases in Cyperaceae and *Potamogeton*, around the edge of the lake, are indicative of progressively shallow lake margin and possibly marginal peat development. This is also supported by the rise in Fe:Mn ratio in response to a further reduction in soil redox conditions. The development of a lake margin peat, today occupied by *Chusquea* bamboo and the tree taxa *Pilgerodendron* and *Tepualia*, may also have contributed to the reduction in both total authigenic and allogenic elements by restricting mobility of inwashing allogenic and authigenic minerals. Dense growth of *Chusquea* bamboo may have acted as a filter to inwashing minerals and also utilised authigenic minerals in plant growth. Lake productivity increases during this period as biogenic Si concentrations reach a maximum. The last 200 cal years sees a rise in *Pilgerodendron*, presumably expanding around the lake margin as open sites become available for tree growth. There are no marked changes in sediment chemistry or microscopic charcoal to suggest a possible cause for this change. Szeicz (unpublished results) has examined this period in high resolution, comparing *Pilgerodendron* tree-rings analysis to determine stand age and pollen results over the last 400 years, and suggests that the most recent expansion of *Pilgerodendron* at the northern and eastern margins of this site may be a response to periodic tectonic induced watertable changes or is part of a long-term trend in gymnosperm growth around a shallowing lake margin. Fluctuations in pollen taxa percentages over this time may suggest that periodic disturbance still plays an important part in local vegetation dynamics, despite the lack of erosion or tephra evident in the lake sediment record.

DISCUSSION AND CONCLUSIONS

This study has focussed on late Holocene environmental change recorded in a lake catchment with minimal human disturbance. Despite the long history of human occupation in southern Chile that reaches into at least the late glacial transition (Dillehay 1989) the influence of fire, which in this high rainfall environment is most likely associated with human activity, is negligible in the Laguna Miranda record (low charcoal levels throughout). The occupation of the channel islands by amerindians (Chono or Wayteca), whose subsistence was based primarily on fishing and coastal resource exploitation, appears to be relatively late, with sparse archaeological remains dating to no earlier than 5800 cal yr BP (Cardenas et al. 1993). Amerindian impact on this environment may have been focussed on the coastal margins and occasional excursions to the interior of the islands of the Taitao-Chonos region. Lake sediments under investigation from the northern Chonos islands show high levels of charcoal over at least the last 4000 years, suggesting much greater impact from human activity and possibly higher populations living in this environment relative to the Taitao Peninsula region (Haberle, unpublished results). Currently, human settlement is very sparse and clearance for grazing or agriculture is non-existent, though some areas have been burnt over the last 150 years for the purpose of timber extraction. So, what was the role of natural disturbance, in the absence of human activity, on the vegetation and sediment history of Laguna Miranda over time scales of several millennia?

Sources of instability in the catchment include volcanic and tectonic disturbance, changes due to disease, fire, and climate induced changes from drought and wind. The site is prone to earthquakes as it lies close to the main Liquiñe-Ofqui fault system, where evidence for uplift rates of around 10 m per 1000 years have been recorded around Chiloé Island for the late Holocene (Hervé & Ota 1993). Mass movement scars and drowned forests around Laguna San Rafael (Reed et al. 1988), and throughout south-central Chile (Veblen & Ashton 1978), attest to the capacity of tectonic movement to impact forests within the area. The absence of significant eroded soils in the Laguna Miranda sediment demonstrate that no widespread slope failures have taken place during the recorded history of the catchment.

The record of tephra layers found at Laguna Miranda represent only a partial record of the sequence of tephra eruptions at Hudson Volcano during the last 5 millennia. It is likely that there were additional eruptions of Hudson Volcano during this period that were not recorded in the Laguna Miranda sequence, either because the eruptions were small and deposition was not sufficient to be visible in this analysis, or because tephra dispersal was in a different direction during the eruption. The predominant winds in the region favour dispersal in an easterly direction, away from Laguna Miranda, so the tephras record at Laguna Miranda can only be considered to represent a minimum estimate of eruption frequency. Indeed, it is important to note that the lack of tephra layers after 1200 cal yr BP in Laguna Miranda may be a function of dominant dispersal direction rather than lower eruption frequency or magnitude.

What is the impact of tephra deposition on the vegetation around Laguna Miranda? Observations from the forested slopes of Hudson Volcano after the 1991 eruption showed that most of the plants in the *Nothofagus* forest community survived up to 100 mm thick tephra deposits, though with thicker deposits plant mortality increased (Vogel 1996). Complete destruction of the forest only appeared to occur when buried by more than 1,80 m of tephra. Most of the Laguna Miranda tephra layers are very thin (<80 mm), suggesting thickness of deposits in the catchment and impact from burial may have been minimal. The long-term shift to *Nothofagus* dominance from 4800 to 1200 cal yr BP is here considered to be a response to periodic volcanic disturbance, in which shade-intolerant *Nothofagus* species are best adapted. By contrast, if the absence of tephra layers after 1200 cal yr BP in the Laguna Miranda record is taken to indicate a period of relative volcanic, if not tectonic stability, then it is possible that the shift to a more mixed forest with a reduced *Nothofagus* component was the product of a long period of stability. This appears to be consistent with the response observed in other Chilean *Nothofagus* communities subjected to variable disturbance regimes (Veblen et al. 1996).

The addition of thin layers of tephra to the Laguna Miranda catchment may have caused damage to vegetation through mechanical and chemical processes, such as defoliation and subsequent prolonged absence of leaves (Rees 1979) or noxious gases and acid-bearing rains (Thorarinsson 1979). Fires associated with volcanic activity may have been a contributory factor to vegetation change, though there is no evidence to support this in the Laguna Miranda record. Disease and dieback are also known to affect *Nothofagus* forest structure in southern Chile, and in many cases large areas of canopy tree mortality have been observed (Veblen et al. 1996). The infestation of individual *Nothofagus* trees by the semi-parasitic plants *Misodendron* appears to have been a persistent feature in the Laguna Miranda catchment. Minor increases in *Misodendron* infestation may have been due to periodic disturbance events, such as tephra-tectonic activity, climatic variability, natural successional changes and human activity, that may have increased the susceptibility of individual *Nothofagus* trees to infestation for short periods of time.

Edaphic conditions may change with the addition of mineral nutrients and sand/silt sized particles after tephra deposition, altering the nutrient balance within the forest and influencing regeneration. Rapid rates of sedimentation of around 1 m per 1000 years and the development of waterlogged soils and peats around the margins of Laguna Miranda are likely to be a response to frequent renewal of nutrients from tephra deposition. Some support for this is evident in a comparison of sedimentation rates from a similar lake basin in a more remote region some 120 km from Hudson Volcano. The sedimentation rate at Laguna Stibnite on the Taitao Peninsula is around 28 cm per 1000 years, one quarter the rate recorded for Laguna Miranda (Lumley & Switsur 1993), which may reflect a relatively poor supply of nutrients to the catchments there.

Is there evidence that climatic fluctuations have influenced vegetation dynamics during the late Holocene? Previously investigated pollen profiles from the region have been interpreted to indicate vegetation responding to changes from warmer-drier to cool-moist conditions during the late Holocene (Heusser 1964, Markgraf 1989). Neoglacial advances have also been proposed for the southern Chilean region, culminating 5750-4450 cal yr BP, 3200-1950 cal yr BP, 1250-950 cal yr BP and 700-50 cal yr BP (Clapperton & Sugden 1988), and suggesting that climates where variable during the mid to late Holocene. The complicated dynamics of tide-water glaciers, such as the San Rafael Glacier some 50 km to the south of Laguna Miranda, make the interpretation of glacial fluctuations in the Laguna Miranda region highly problematic. In the Laguna San Rafael region, high abundance of *Weinmannia* in the lower levels of Ismo de Ofqui I site and the Interfluctuational section is considered to represent a warmer climate phase following neoglacial retreat from the sites (Heusser 1964). The sites are fragmentary and the dating is highly problematic (Clapperton & Sugden 1988); but, stratigraphic indications from each site point to disturbance, from both volcanic eruptions and nearby physical influences from glacial meltwater flooding, as possible significant factors in local vegetation change during the high *Weinmannia* phase. *Weinmannia trichosperma* is a relatively shade-intolerant species that is able to readily invade disturbed sites in much the same way as *Nothofagus*. Clearly caution must be exercised when inferring climate change from a single species such as *Weinmannia*, as it may be responding to changing disturbance regimes as much as climate variables.

Over shorter time scales of years to decades, climate variability may have been high during the late Holocene due to an increase in ENSO (El Niño-Southern Oscillation) climate events (Markgraf et al. 1992), though the southwestern region of Chile may not have been as strongly influenced by ENSO events as the subtropical-tropical regions (Ortlieb & Macharé 1993). The impact of these short-term fluctuations on vegetation are poorly understood, though over longer time scales the cumulative impact may be to increase the success of species adapted to frequent disturbance. There is no conclusive evidence of climatically induced forest change at Laguna Miranda. This raises the possibility that short-term climatic disturbances may produce similar responses in the pollen record as does volcanic or tectonic activity.

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APPENDIX 1

List of all fossil pollen and spore taxa (family in brackets, undiff. = undifferentiated) identified from the Laguna Miranda core (Fig. 5). Taxa are grouped into plant habit categories

Lista de todos los taxones de polen y esporas fósiles (familia entre paréntesis, undiff. = no diferenciados) identificados en la columna sedimentaria de Laguna Miranda (Fig. 5). Los taxones están agrupados por categorías de plantas según sus hábitos

Tree and Shrub pollen	Herb pollen:
Caldcluvia paniculata [Cunoniaceae]	Compositae undiff.
Drimys winteri [Winteraceae]	Cruciferae undiff.
Embothrium coccineum [Proteaceae]	Gramineae undiff.
Ericales undiff.	*Gunnera* [Haloragaceae]
Fuchsia {Onagraceae]	*Philesia magellanica* [Liliaceae]
Griselinia [Cornaceae]	
Lepidothamnus fonkii [Podocarpaceae]	Ferns:
Maytenus [Celastraceae]	*Lophosoria quadripinnata* [Cyathaceae]
Misodendrum [Misodendronaceae]	Hymenophyllaceae undiff.
Myrtaceae undiff.	Filicales undiff.
Nothofagus dombeyi-type [Fagaceae]	
Pilgerodendron uviferum-type [Cupressaceae]	Aquatic taxa
Podocarpus nubigena [Podocarpaceae]	Cyperaceae undiff.
Pseudopanax laetevirens [Araliaceae]	*Potamogeton* [Potamogetonaceae]
Tepualia stipularis [Myrtaceae]	
Weinmannia trichosperma [Cunoniaceae]	Unknowns

APPENDIX 2

Abundances of major elements in glass shards extracted from Laguna Miranda tephra samples. Tephra glass geochemistry is expressed as percentage weight, normalised to 100 wt%. Analysis was performed at the Department of Earth Sciences, University of Cambridge, using a Cameca SX50 spectrometer microprobe, an electron microscope with three wave dispersive spectrometers and a LINK AN10000 energy dispersive spectrometer running PAP matrix correction software. The probe operated at 20kV, using a 10nA beam current and a 10μm defocused beam to minimise loss of Na and K (50s count time). A mixture of minerals, natural oxides and pure metals were employed as standards that were periodically checked in order to verify internal consistency of the results

Abundancia de elementos principales en fragmentos de cristales extraídos de las muestras de tefra de Laguna Miranda. La geoquímica del cristal de tefra se expresa como peso porcentual, con normalidad de 100 wt%. El análisis se realizó en el Departamento de Ciencias de la Tierra (Department of Earth Sciences), Universidad de Cambridge, usando un espectrómetro microsonda Cameca SX50, un microscopio electrónico con tres espectrómetros dispersores de ondas y un espectrómetro LINK AN1000 dispersor de energía utilizando software PAP de matriz correctora. La sonda operaba a 20kV, usando una corriente de haz de 10nA y un haz desviado de 10μm para minimizar pérdida de Na y K (50s tiempo controlado). Se empleó una mezcla de minerales, óxidos naturales y metales puros como patrón, verificándolos periódicamente a fin de comprobar la consistencia interna de los resultados

Mir-1											
SiO_2	65.998	66.439	66.280	67.709	66.831	66.461	66.382	66.478	65.817	65.121	65.198
TiO_2	1.213	1.298	1.299	1.168	1.403	1.241	1.223	1.265	1.245	0.900	1.235
Al_2O_3	16.627	16.564	16.646	16.391	16.065	16.694	16.495	16.590	16.461	18.610	16.337
FeO	5.051	4.746	4.772	4.326	5.085	3.851	4.779	4.595	4.956	3.106	4.674
MnO	0.199	0.199	0.119	0.160	0.108	0.112	0.129	0.182	0.166	0.023	0.052
MgO	1.517	1.369	1.493	1.001	1.414	1.072	1.495	1.386	1.481	0.756	1.419
CaO	3.531	3.375	3.441	3.061	2.961	3.402	3.430	3.351	3.248	4.462	5.055
Na_2O	3.019	2.925	3.160	3.173	3.067	5.012	3.203	3.282	3.534	5.070	3.277
K_2O	2.746	2.977	2.668	2.889	3.049	2.077	2.772	2.794	3.020	1.890	2.667
Cl	0.094	0.112	0.121	0.117	0.123	0.075	0.094	0.073	0.074	0.089	0.135
Total	100	100	100	100	100	100	100	100	100	100	100
Mir-1 cont.											
SiO_2	65.948	66.807	66.213	66.051	66.208	66.180	66.669	65.753	65.818	66.738	66.175
TiO_2	1.334	1.284	1.289	1.241	1.282	1.298	1.302	1.235	1.372	1.218	1.261
Al_2O_3	16.628	16.750	16.494	16.686	16.727	16.712	16.576	16.542	16.553	16.593	16.573
FeO	5.000	4.565	4.961	4.930	4.793	4.569	4.608	5.044	5.056	4.572	4.948
MnO	0.206	0.114	0.143	0.207	0.201	0.233	0.115	0.160	0.157	0.199	0.110
MgO	1.623	1.420	1.386	1.598	1.572	1.572	1.432	1.580	1.503	1.399	1.526
CaO	3.574	3.241	3.440	3.355	3.354	3.438	3.413	3.455	3.572	3.198	3.498
Na_2O	2.965	2.974	3.325	3.110	3.047	3.231	3.034	3.371	3.164	3.072	3.221
K_2O	2.598	2.773	2.677	2.731	2.743	2.657	2.729	2.734	2.675	2.874	2.684
Cl	0.121	0.071	0.071	0.090	0.078	0.108	0.122	0.127	0.124	0.135	0.115
Total	100	100	100	100	100	100	100	100	100	100	100
Mir-2											
SiO_2	55.655	55.498	55.779	55.155	55.777	56.626	52.993	55.610	55.805	55.893	
TiO_2	1.680	1.766	1.782	1.779	1.839	1.561	1.579	1.829	1.981	1.880	
Al_2O_3	16.368	15.499	15.739	14.789	15.177	16.664	16.105	15.756	14.949	15.378	
FeO	8.378	9.288	8.678	9.101	9.237	8.234	10.025	8.953	9.653	9.189	
MnO	0.146	0.222	0.091	0.255	0.236	0.121	0.243	0.217	0.197	0.206	
MgO	4.200	4.608	4.883	5.694	4.545	3.961	4.985	4.492	4.081	4.467	
CaO	8.295	8.064	8.001	8.060	8.015	7.298	8.396	7.977	7.897	7.827	
Na_2O	3.978	3.438	3.669	3.660	3.592	3.960	4.367	3.597	3.748	3.589	
K_2O	1.204	1.499	1.371	1.414	1.472	1.501	1.238	1.472	1.586	1.473	
Cl	0.098	0.119	0.102	0.089	0.112	0.077	0.072	0.101	0.106	0.096	
Total	100	100	100	100	100	100	100	100	100	100	
Mir-3											
SiO_2	60.985	57.385	55.607	56.248	57.992	56.527	57.425				
TiO_2	1.803	2.416	1.955	1.712	2.525	2.109	2.347				
Al_2O_3	16.709	13.512	13.636	17.325	13.701	14.965	14.127				
FeO	6.836	10.876	11.228	8.107	10.502	9.503	10.279				
MnO	0.159	0.221	0.306	0.160	0.317	0.286	0.210				
MgO	2.453	3.439	5.917	3.224	3.170	3.799	3.327				
CaO	4.789	6.719	6.230	7.529	6.475	7.000	6.886				
Na_2O	3.920	3.422	3.314	4.141	3.248	3.822	3.396				
K_2O	2.210	1.912	1.687	1.463	1.957	1.858	1.899				
Cl	0.135	0.092	0.117	0.090	0.110	0.128	0.103				
Total	100	100	100	100	100	100	100				