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Climate and human impact during the past 2000 years as recorded in the Lagunas de Yala, Jujuy, northwestern Argentina

Liliana C. Lupo[a], María Martha Bianchi[b], Ezequiel Aráoz[c], Ricardo Grau[c], Christoph Lucas[d], Raoul Kern[d], María Camacho[e], Willi Tanner[f], Martin Grosjean[d,g,*]

[a]*CONICET, Palynology Laboratory Grupo Yavi, Universidad Nacional de Jujuy, Alberdi 49, 4600 Jujuy, Argentina*
[b]*CONICET- Universidad Nacional del Comahue, Quintral 1250 (8400) San Carlos de Bariloche, Argentina*
[c]*LIEY-UNT, CC 34, Yerba Buena, (4107), Tucumán, Argentina*
[d]*Department of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland*
[e]*IDGYM, Universidad Nacional de Jujuy, Av. Bolivia 1661, 4600 S.S. Jujuy, Argentina*
[f]*Institute of Plant Sciences, University of Bern, Altenbergstrasse 21, 3007 Bern, Switzerland*
[g]*NCCR Climate, University of Bern, Erlachstrasse 9a, 3012 Bern, Switzerland*

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Abstract

^{210}Pb, ^{137}Cs and ^{14}C dated sediments of two late Holocene landslide lakes in the Provincial Park Lagunas de Yala (Laguna Rodeo, Laguna Comedero, 24°06′S, 65°30′W, 2100 m asl, northwestern Argentina) reveal a high-resolution multi-proxy data set of climate change and human impact for the past ca. 2000 years. Comparison of the lake sediment data set for the 20th century (sediment mass accumulation rates MARs, pollen spectra, nutrient and charcoal fluxes) with independent dendroecological data from the catchment (fire scars, tree growth) and long regional precipitation series (from 1934 onwards) show that (1) the lake sediment data set is internally highly consistent and compares well with independent data sets, (2) the chronology of the sediment is reliable, (3) large fires (1940s, 1983/1984–1989) as documented in the local fire scar frequency are recorded in the charcoal flux to the lake sediments and coincide with low wet-season precipitation rates (e.g., 1940s, 1983/1984) and/or high interannual precipitation variability (late 1940s), and (4) the regional increase in precipitation after 1970 is recorded in an increase in the MARs (L. Rodeo from 100 to 390 mg cm^{-2} yr^{-1}) and in an increase in fern spores reflecting wet vegetation. The most significant change in MARs and nutrient fluxes (C_{org} and P) of the past 2000 years is observed with the transition from the Inca Empire to the Spanish Conquest around 1600 AD. Compared with the pre-17th century conditions, MARs increased by a factor of ca. 5 to >8 (to 800 $_{+130,\ -280}$ mg cm^{-2} yr^{-1}), PO_4 fluxes increased by a factor of 7, and C_{org} fluxes by a factor of 10.5 for the time between 1640 and 1930 AD. 17th to 19th century MARs and nutrient fluxes also exceed 20th century values. Excess Pb deposition as indicated by a significant increase in Pb/Zr and Pb/Rb ratios in the sediments after the 1950s coincides with a rapid expansion of the regional mining industry. Excess Pb is interpreted as atmospheric deposition and direct human impact due to Pb smelting.
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1. Introduction

One of the major challenges in ecosystem research is to determine to what extent current observed ecosystem changes are (1) the result of human impact, internal system dynamics, changes in the natural boundary conditions (such as climate) or a combination of these three factors, (2) if current changes exceed previous, i.e. pre-20th century changes both in terms of amplitude and rate of change, and (3) if current natural- and human-induced disturbance regimes are at levels where essential ecosystem services are or might be seriously affected on the long term.

In most case studies, including our work presented here, assessing these issues is not straight forward and challenged by two problems, i.e. shortcomings of the observational data sets and series, and missing knowledge about the baseline of natural dynamics and variability. Firstly, the period with direct observations of recent changes is generally very short, critical (geo)indicators are not defined and, except for a few hydro-climatological parameters, usually not monitored over longer periods. Thus the

*Corresponding author. Tel.: +41 31 631 31 47; fax: +41 31 631 43 38.
E-mail address: grosjean@giub.unibe.ch (M. Grosjean).

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significance of today's 'snapshots' in the context of the long-term ecosystem dynamics and perspective is not known. For this reason, the observational period has to be extended back in time by the use of environmental archives and reconstructions. Alternatively, well-calibrated and tested models may be used to run experiments and/or to explore projections into the future. Secondly, the baseline of natural ecosystem dynamics is mostly not known. This is particularly the case in areas with a very long history of human land use within different cultural and societal contexts, agricultural and land use practices. In the Americas and elsewhere, there is growing evidence for significant impacts of ancient cultures on vegetation cover and composition, on surface processes such as soil erosion, on hydraulic engineering and air pollution through metal smelting (O'Hara et al., 1993; Lenz, 2000; Abbott and Wolfe, 2003). In addition, paleoecological research may help in answering the question of how ecosystems would function without human intervention.

This is the general framework that stimulated our interdisciplinary paleoecological research in the area of the Lagunas de Yala, Provincia de Jujuy, northwestern Argentina (Fig. 1). We selected this area because (i) it is located in the upper montane forest belt of the Yungas, an ecosystem that is currently under pressure and, therefore a focal point for ecological research, (ii) it is located near San Salvador de Jujuy, a city with rapid growth and significant metal smelting industry, (iii) has a long tradition of human occupation that extends well beyond Colonial times, and (iv) hosts a series of landslide dammed lakes with sediments that may, in combination with regional dendro-ecological work (Villalba, 1995; Villalba et al., 1987, 1998 and references therein; Grau and Veblen, 2000; Grau et al., 2003) serve as paleoecological and paleoclimatic archives and thus provide insight into the multi-centennial ecosystem dynamics. We put particular emphasis on the fire history, vegetation changes, sediment accumulation rates and nutrient fluxes which are used as indicators for changes in the past disturbance regimes (Garralla et al., 2001; Lupo, 1990; Schäbitz et al., 2001). More specifically we addressed the following issues:

1. Can we determine the influence of cattle grazing, vegetation changes and climate on the sedimentation rates and sediment characteristics? We suspect that high cattle density results in increased soil erosion and eutrophication of the lakes.
2. Are the vegetation and land use changes such as deforestation and reforestation detectable in the pollen record, and can this information be extrapolated back to historic (last 400 years) and late Holocene times (ca. 2000 cal yr BP)?
3. How does the fire history as recorded in charcoal flux of lake sediments compare with the fire scars detected in

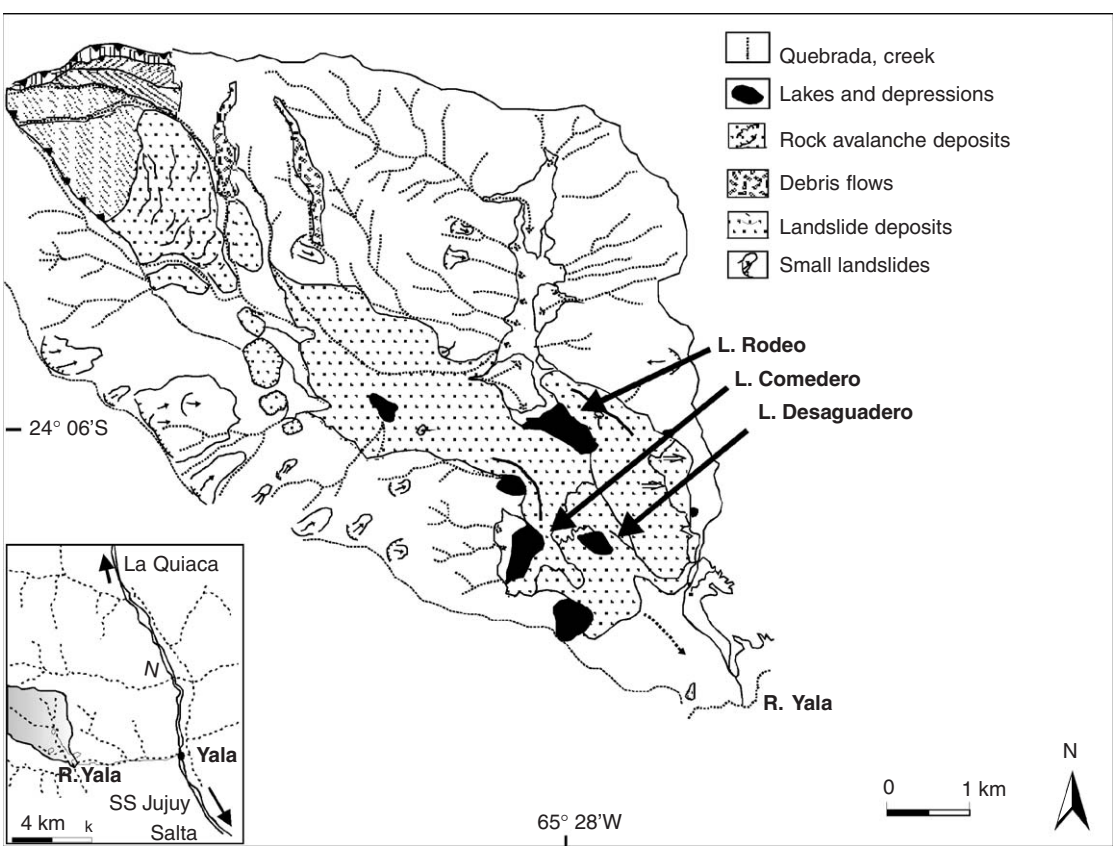

Fig. 1. Geomorphological map of the Lagunas de Yala catchment (after González Díaz and Mon, 2000).

dendro-ecological records, and can fires be related to climate and/or human interventions?

4. Does 20th Century atmospheric Pb deposition to lake sediments exceed natural background Pb levels, and can excess Pb be used as a proxy for metal smelting and industrialization?

In the following sections, we introduce the geo-biophysical setting of the study area, present and discuss the lake sediment parameters measured with the dendroecological studies from the catchment and instrumental meteorological data, and put the recorded changes of the 20th Century in the perspective of the last 2000 years.

2. The study area and geo-biophysical setting of the lakes

The Lagunas de Yala Provincial Park (24°06′S, 65°30′W, northwestern Argentina) is located in the foothill zone of the Eastern Cordillera de los Andes, province of Jujuy (Fig. 1). The steep catchment ranges from 1900 to 3100 m. Precambrian and Cambrian sediments, Miocene to Pliocene silt, sandstone, and conglomerates, and Middle to Upper Pleistocene-Holocene colluvial and alluvial sediments crop out in the upper catchment (González Díaz and Mon, 2000). The lower part of the catchment is filled with a large mid- to late Holocene (oldest lake sediments yielded an age of BC 2334–1886, Table 1, Camacho and Grosjean, 2004) landslide. Eight small shallow lakes including Laguna Rodeo and Laguna Comedero (this study) developed in the hummocky topography. These eight lakes have different geomorphological settings. With the large catchment and steep slopes ranging up to the high mountains, Laguna Rodeo acts mostly as a sediment trap for clastic material, while the lower lakes (Laguna Comedero) have small catchments and receive the water mostly from subsurface drainage through the landslide material.

The climate is subtropical humid with total annual rainfall around 1470 mm (nearest station Rodeo 1995 m, 1972–1990). Eighty six percent of the annual total precipitation falls during austral summer (October to March). Mean annual temperature is 15.9 °C. Winters are dry and cold with occasional frosts.

Fig. 2 shows the precipitation record from the nearby station Yala (1450 m, the nearest long record) and a regional record from four nearby stations for the years 1934 to 1989. The examination of these records indicates (i) a marked 50% regional precipitation increase from 1960 to 1985, (ii) dry conditions with high interannual variability and frequent very dry summers between 1934/1940 and 1948, and (iii) the exceptionally dry year of 1983/1984 that occurred within a relatively very humid period. Interannual and decadal-scale variability is remarkably high.

The natural vegetation cover is the upper montane forest of the Yungas that extends up to ca. 3000 m. In the upper treeline ecotone, *Alnus acuminata* (alder, 'aliso') and *Polylepis australis* ('queñoa') forests are followed by alpine Andean grasslands and meadows. Exotic species include *Digitalis purpurea, Duchesnea indica, Viola odorata, Primula malacoides*, and plantations of *Prunus* sp., *Pinus douglasiana* and *P. elliotis* from 1973 onwards.

The regional history of human occupation records a Formative Period with agro-pastoral settlements and pottery (between 700 BC and 300 AD, Fumagalli and Cremonte, 2002a), the 'Desarrollo Regional' Period (1000 to 1470 AD), the Inca Empire Period (1470–1550 AD) and, finally, the Colonial Period, which starts with the foundation of San Salvador de Jujuy in 1593 AD. Particularly during the Inca and Colonial periods, Jujuy was a point of strategic importance as it was the access to Potosí. Spanish control of the territory came to an end in 1813. Spaniards introduced new political regulations and land use practices. Cattle, sheep, goats and horses were also introduced during the Colonial time. The last 50 years saw a rapid growth of the metal industry, an expansion of agriculture, grazing land, and urbanism. The area of the Lagunas de Yala changed from private land into a Provincial Park in 1952. However, no changes in land use were reported at that time. A park ranger was appointed in 1986, together with a set of environmental measures to reduce grazing and fires (Mariani, personal communication, 2005).

The two selected lakes reflect different environmental settings. Laguna Rodeo (Fig. 1, 2150 m) is a 5 ha large, 3.4 m deep, polymictic, alkaline (pH 9.2), fresh (TDS 110 mg/l, EC 110 μS cm^{-1}) soft water lake (<1 mval $HCO_3^- l^{-1}$) with steep slopes and a flat bottom. Short-term fluctuations of the water level are significant and on the order of several meters. The water body is fed by a surface inflow that transports sediments and forms a delta in the NW sector of the lake. Subsurface seepage drains the lake, but at times of high water levels, surface discharge is also observed. Residence times of water are very short.

Table 1
^{14}C data of the Lagunas de Yala. Calibration is based on McCormac et al. (2004)

Lab no.	Sample ID	Sediment depth (cm)	Material	^{14}C yr BP (1 σ)	$\Delta^{13}C$ (‰)	Cal ^{14}C yr (2 σ)	Mid-point
Beta143808	Rodeo 1115	408–14	Terrestr. macrofossils	310±30	−26.4	1502–1668 AD	1640 AD
Poz11016	Rodeo 1115	429–430	Aquat. macrofossils	785±30	n.d.	1220–1299 AD	1278 AD
Beta-146731	Rodeo 1115	562–568	Aquat. macrofossils	1270±40	−28.2	685–895 AD	800 AD
Beta143809	Rodeo 1115	643–646	Aquat. macrofossils	1690±40	−25.2	328–540 AD	418 AD
Hv-22721	Desaguadero 1020	85–90	Aquat. macrofossils	2935±160	−25.8	1270–895 BC	1045 BC
Hv-22720	Desaguadero 1020	173–179	Aquat. macrofossils	3755±150	−25.6	2334–1886 BC	2045 BC

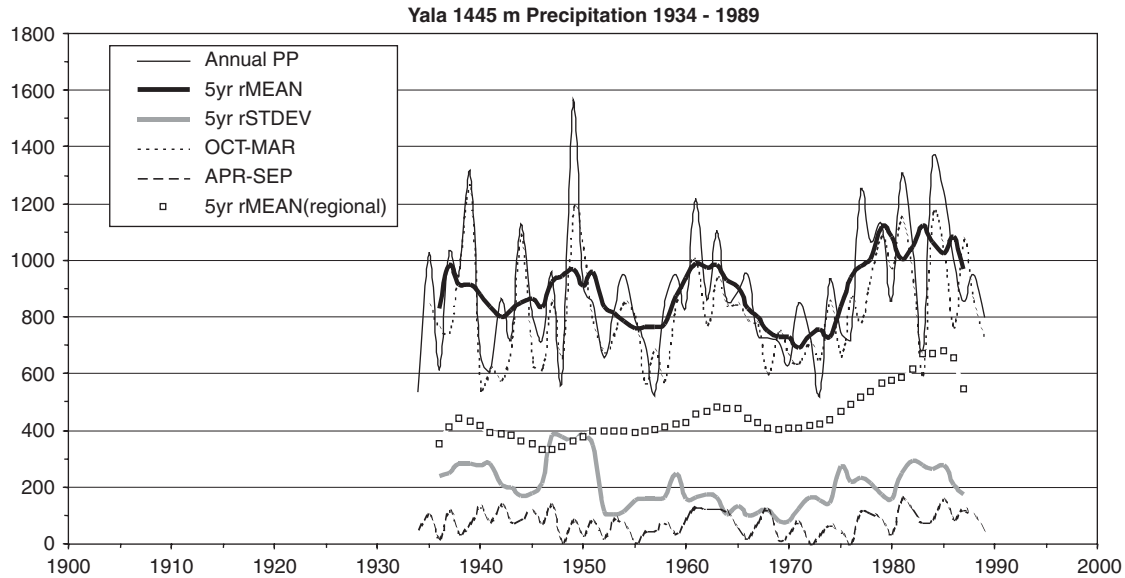

Fig. 2. 1934–1989 precipitation [mm] of station Yala (1445 m, nearest long record) showing the annual rainfall (black line, 5 yr running mean black bold line), summer (OCT–MAR, dotted line) and winter (APR–SEP, interrupted line), and the 5 yr running standard deviation (gray bold line). The regional 5 yr running mean annual precipitation (stations Volcán 2078 m, Leon 1622 m, SS Jujuy 1415 m, Yala 1445 m) are given for comparison. (Data: Bianchi and Yañez, 1992).

Laguna Comedero (Fig. 1, 2040 m) is a 3.5 ha large, 3.6 m deep, polymictic, alkaline (pH 9.7), fresh (TDS 118 mg/l, EC 118 $\mu S\,cm^{-1}$) soft water lake (<1 mval $HCO_3^-\,l^{-1}$). The chemical composition of the lake water is very similar to that of Laguna Rodeo, which is not surprising as the lake receives mostly subsurface seepage from the upslope areas and Laguna Rodeo. The catchment is very small and covered predominantly by forest (90%) and grazing lands (10%). The lake has two small sub-basins that are separated by a ridge ca. 2 m below the lake level.

3. Methods and materials

Short and long sediment cores were taken from the centers of both lakes using a Streiff-piston corer. We measured magnetic susceptibility in the field and cut the sub-samples of the short cores for ^{226}Ra, ^{210}Pb, ^{137}Cs profiles and geochemical analysis. Long cores were sealed and transported to the laboratory for non-destructive whole core measurements (magnetic susceptibility and γ-ray absorption using the Geotek MSCL at ETH Zurich) and subsampling.

Half-cores were photographed, macroscopically described (lithology, Munsell color, texture, bedding), and smear-slides and sub-samples were taken every 5–10 cm in the long cores. Short cores were sampled continuously at 1 cm slices, which corresponds to a resolution of 0.5–2 years in Laguna Comedero and 1–3 years in Laguna Rodeo. C_{org} and C_{inorg} were measured with Loss On Ignition LOI (Dean, 1974). Anions and cations were determined for the H_2O-soluble and 1 N HCl-soluble fraction (Anderson, 1976) with IC and ICP-OES. Grain size was measured on the organic matter-, metal oxide- and carbonate-free fraction using Micromeritics SediGraph 5100.

The age-depth model of the long core (Laguna Rodeo) is based on four AMS ^{14}C dates and the Southern Hemisphere calibration curve Calib 5.0.1 (McCormac et al., 2004; Stuiver et al., 2005), while the chronology of the short cores was established using ^{210}Pb activity profiles (Lucas, 1999). Because the appropriate choice of the calculation model is not a-priori known, ^{210}Pb ages were calculated with both the Constant Rate of Supply CRS model and the Constant Initial Concentration CIC model (Appleby, 2001 and references therein). Unsupported ^{210}Pb was determined with the level-by-level subtraction of ^{226}Ra, and the initial ^{210}Pb activity A_0 at the sediment-water interface was determined with an exponential function fitted through the uppermost four data points (Appleby, personal communication 1999). The ^{137}Cs peak of AD 1962/63 was used to validate the ^{210}Pb model age. Activity measurements were made using efficiency calibrated (IAEA Standards 135, 300 315) γ-decay counting.

Pollen samples were prepared using standard techniques (Faegri and Iversen, 1989). A minimum of 300 grains were counted per sample. Pollen was identified with the help of a reference collection and the publications of Heusser (1971), Markgraf and D'Antoni (1978), Moore et al. (1991) and Graf (1992). Preparation and analysis of charcoal samples, reported as particle concentrations at three fractions (>63, >125, and >250 μm) followed Gardner and Whitlock (2000) and Whitlock and Larsen (2002). Charcoal particles larger than 125 μm were interpreted as indicators of local fires. The fire history from charcoal particles was compared with the fire chronology based on tree-ring dating of scars

from *Alnus* cross sections (Grau and Veblen, 2000; Grau et al., 2003). Dates of *Alnus acuminata* establishment were based on tree ring counting of individual trees and used as an indicator of forest responses to large fires.

4. Results and discussion

4.1. Chronology: ^{210}Pb, ^{137}Cs, ^{14}C

The ^{210}Pb age profiles of Laguna Rodeo and Laguna Comedero are shown in Fig. 3.

For both profiles, atmospheric ^{210}Pb fluxes as derived from the initial activity A_0 (Comedero 125 Bq m^{-2} yr^{-1}; Rodeo 137.1 Bq m^{-2} yr^{-1}) and total unsupported ^{210}Pb activity (Rodeo 4410 Bq m^{-2}; Comedero 4010 Bq m^{-2}) are comparable and similar to results found in adjacent Bolivia (Pourchet et al., 1995). Bioturbation might play a role in both lakes since no ^{7}Be (half-life time of 53.3 days) could be detected in the top sediments, and a plateau of unsupported ^{210}Pb was found in the uppermost three samples of Laguna Comedero (cumulative dry mass 0.22 g cm^{-2}). Laguna Rodeo shows much larger down-core variability of unsupported ^{210}Pb activity (not shown), which reflects large interannual changes in the sedimentation rates (Fig. 3) and goes along with cm-scale upward graded beds (interpreted as rapid sedimentation, see Section 4.2) in the upper part of the sediment core. This clarifies the major discrepancies between the CRS and CIC model age profiles and explains the age inversions in the CIC model age profile. This is typical for variable admixtures of detrital terrigenous material to the sediments, a feature that is supported by the sedimentological analysis. In both lakes the CRS model ages reveal plausible results and are taken as the chronological frame for the further work presented here.

Laguna Comedero shows a clear ^{137}Cs increase and relative peak at 6.1 g cm^{-2} cumulative dry mass, which corresponds to the maximum atmospheric fallout in 1963 AD. This age corresponds well with both the CRS and the

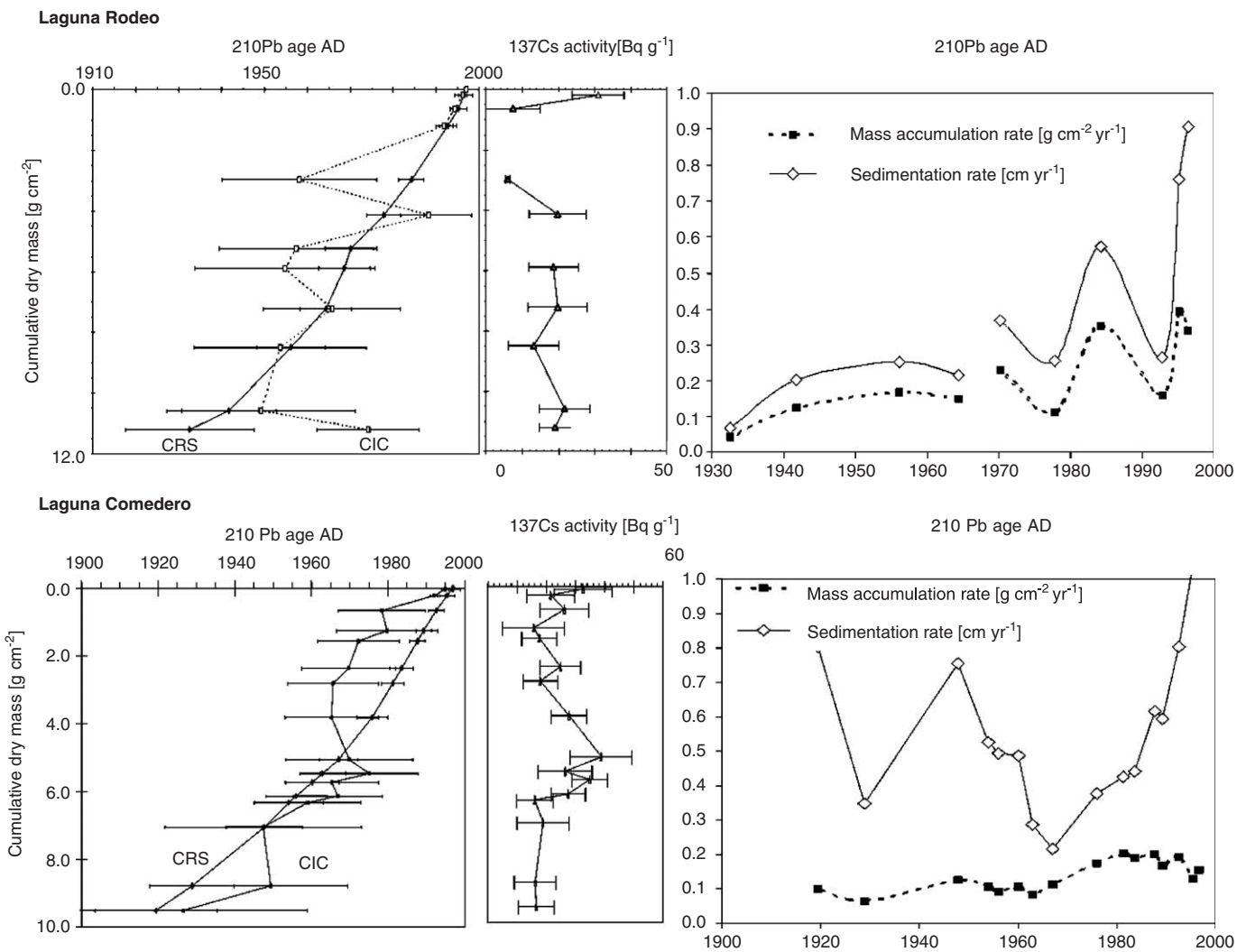

Fig. 3. ^{210}Pb age profiles calculated with the Constant Rate of Supply CRS and Constant Initial Concentration CIC models, ^{137}Cs profiles, mass accumulation and sedimentation rates as calculated from the CRS model for the short cores of Laguna Rodeo (above) and Laguna Comedero (below).

CIC age profile. As expected, Chernobyl ^{137}Cs could not be detected. A clear ^{137}Cs peak is not visible in Laguna Rodeo. This lake experienced at that time exceedingly high sedimentation rates (Fig. 3) which resulted possibly in the dilution of the ^{137}Cs activity peak. The dilution effect is also a possible explanation for the post-1963 peak in ^{137}Cs activities in Laguna Comedero, where sedimentation rates decreased significantly during the late 1960s through the 1970s (compared to the time around 1963 AD).

In summary the short core of Laguna Comedero (37 cm long, cumulative dry mass 9.5 g cm^{-2}) covers the time between 1919 ± 16 AD and 1998 AD (year of the coring), the short core of Laguna Rodeo (19 cm long, cumulative dry mass 11.2 g cm^{-2}) the time between 1933 ± 15 AD and 1998 AD.

Four ^{14}C ages encompass the age-depth model for the 735 cm long core of Laguna Rodeo (Fig. 4, Table 1). Given the water chemistry, the geology of the catchment, the short residence time of the water in the lake, and extrapolation of 20th Century sedimentation rates, we do not consider ^{14}C reservoir effects as likely. More likely are limitations due to reworked sediments and organic matter. Evidence for this effect can be found in the numerous cm- to dm-scale facies cycles (Section 4.2), which are interpreted as changes between rapid (maybe partly reworking) and slow sedimentation. Although the ^{14}C dates do not show age inversions, this potential effect cannot be fully ruled out or quantified with the number of dates available. Thus the age envelope around the ^{14}C data mid-points (Fig. 4) is kept conservative at the 2σ confidence interval for the calibrated ages.

In summary the core covers the last ca. 2000 years (735 cm sediment depth). The first ^{14}C age at 645 cm sediment depth confirms sediment ages between 330 and 540 AD.

4.2. Sedimentology of the lake deposits

The sediments of Laguna Rodeo consist of two Facies A and B that alternate at the centimeter to decimeter scale and build couplets (for details see Kern, 2001). The lower part of the couplet, Facies B, is composed of massive, (dark) gray to (reddish) brown (5–7.5 YR 4/1 to 4/3 Munsell color) silt and silty loam (mean grain size median 10.9 μm, $n = 6$). Beds of Facies B vary between 1 cm to more than a decimeter, show upward fining and start sometimes with an up to 0.5–1 cm thick loamy sand layer. C_{org} includes macroscopic plant debris and varies between 2% and 6% while $CaCO_3$ ranges between 3% and 8%. The overlying Facies A consists of massive to banded or cm and mm-scale laminated reddish brown, reddish gray to gray and yellowish brown (2.5–10 YR 5/1 to 5/4 Munsell color) silty clay and clay (mean grain size median 1.9 μm, $n = 6$), contain diatoms and are generally free of macroscopic plant debris. The reddish laminae exhibit aggregates, possibly metal oxides. C_{org} varies between 1% and 3% while $CaCO_3$ ranges between 3% and 9%. Clay minerals include illite (mean crystallinity 2.3 ± 0.5 2°Θ; $n = 13$) and

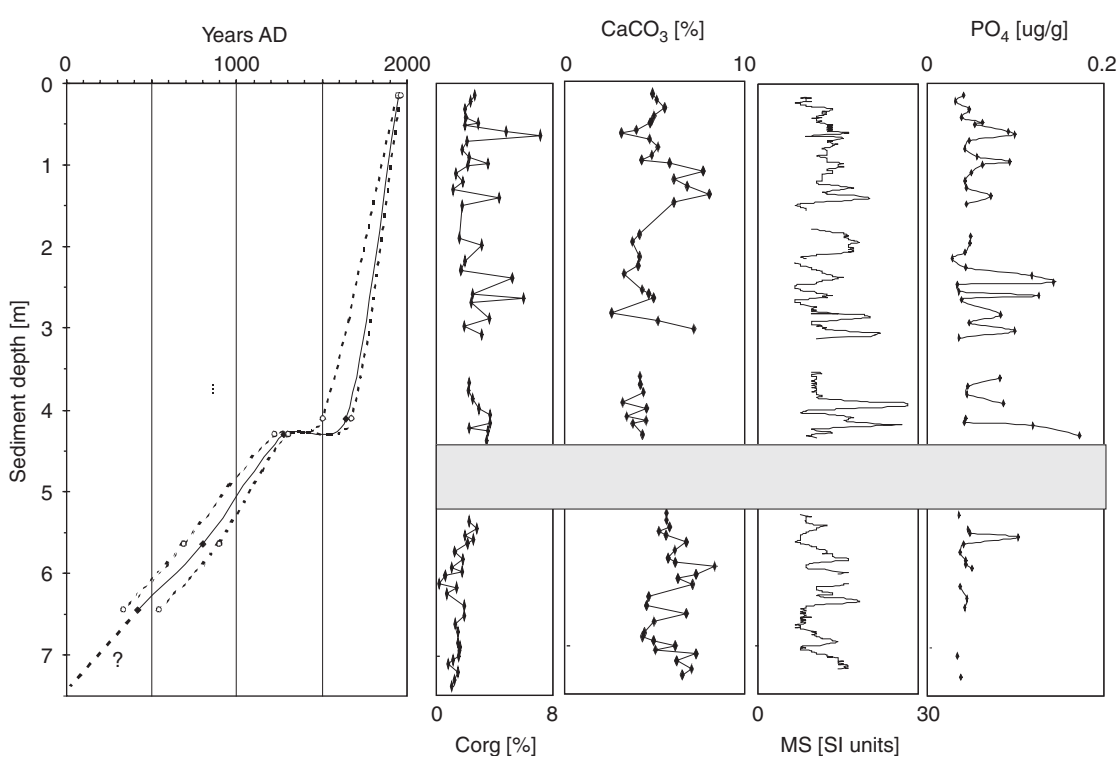

Fig. 4. ^{14}C age–depth model for the long core of Laguna Rodeo and selected sediment parameters (C_{org}, $CaCO_3$, magnetic susceptibility and phosphate. Gray shading: missing data).

chlorite (Camacho and Bossi, 2002). Based on data from the short core (19 cm, water content and cumulative dry mass accumulation) the density of the wet sediments is calculated to 0.59 g cm^{-3}. Contacts between Facies A and B are usually sharp; the basal contact of the sandy layers is mostly erosive.

We interpret Facies B as rapid, maybe event-based sedimentation with possible admixtures of reworked sediments from the delta area during times of heavy river runoff with high loads of suspended particles. Facies B includes small turbidites. Facies A reflects a gentle and slow sedimentation process.

Particularly at 400–440 cm sediment depth, the cycles are very dense with a series of cm-scale upward-graded beds (Facies B), which is reflected in maximum values of the magnetic susceptibility. The sedimentary process suggests that there is (unknown) potential for reworking of the organic material that was used for ^{14}C dating at 429–430 cm depth, which would translate into a too old age. Correcting for this hypothetical effect would largely smooth out the pre-1600 AD variability of the sedimentation rates and flux rates of chemical species (Fig. 5).

Sediments of the Laguna Comedero short core consist of (dark) olive gray, reddish brown and reddish gray, grayish brown (5Y 3/1, 5YR 5/3, 10YR 5/2) massive to banded silty clay. C_{org} content amounts to 9.3±2.3% with abundant plant debris, $CaCO_3$ concentrations are 8.4±2.2%, both indicative of higher biological activity compared with Laguna Rodeo. Clay mineralogy is very similar. However illite crystallinity is lower (3.2±1.1 2°Θ; $n = 9$), which is indicative of more advanced weathering in the catchment and lower admixtures of poorly weathered geologic debris as compared with Laguna Rodeo.

The 20th century mass accumulation rates are shown in Fig. 3. Mass accumulation rates are higher in Laguna Rodeo (210 mg cm^{-2} yr^{-1}; 680 mg cm^{-2} yr^{-1} if the exceptional value at 10.5 cm is included) compared with Laguna Comedero (134±42 mg cm^{-2} yr^{-1}), which reflects well the different sedimentary environments. Increasing mass accumulation rates are observed in both lakes since ca. 1960–1970 AD onwards (Comedero 173±24 mg cm^{-2} yr^{-1}, Rodeo 250 mg cm^{-2} yr^{-1}) and even more pronounced between 1980 and 1992 AD, which correlates well with enhanced precipitation rates (Fig. 2).

Fig. 5 shows the mass accumulation rates in Laguna Rodeo back to 400 AD. The age depth model is based on ^{14}C and ^{210}Pb dates, and calculations are made with 20th century specific sediment density. Errors due to these assumptions are minor since the sediment composition does not change much throughout the long core (Fig. 4).

Fig. 5 shows that 20th century MARs are significantly smaller than those during the 17th to 19th Century, but larger than the pre-1600 AD MARs. Given the caveats of the ^{14}C age–depth model it is not clear whether or not the pre-1600 AD variability is significant. MARs during the 17th to 19th century are by a factor of 5 to >8 higher compared with the pre-1600 AD period and about two to three times higher than the 20th century MARs.

The significant changes at the beginning of the 17th century (410 cm sediment depth) are also reflected in the increase of the PO_4 and C_{org} concentrations (Fig. 4) from an average 0.043 to 0.062 μgPO_4 g^{-1} (1.4 to 2.8% C_{org}), which translates into an increase in the PO_4 flux by a factor of 7 (increase in C_{org} flux: factor 10.5) when changing MARs are considered. The 20th century changes is the PO_4 flux as determined from the short core of Laguna Comedero (Fig. 6) suggest a further increase in the nutrient

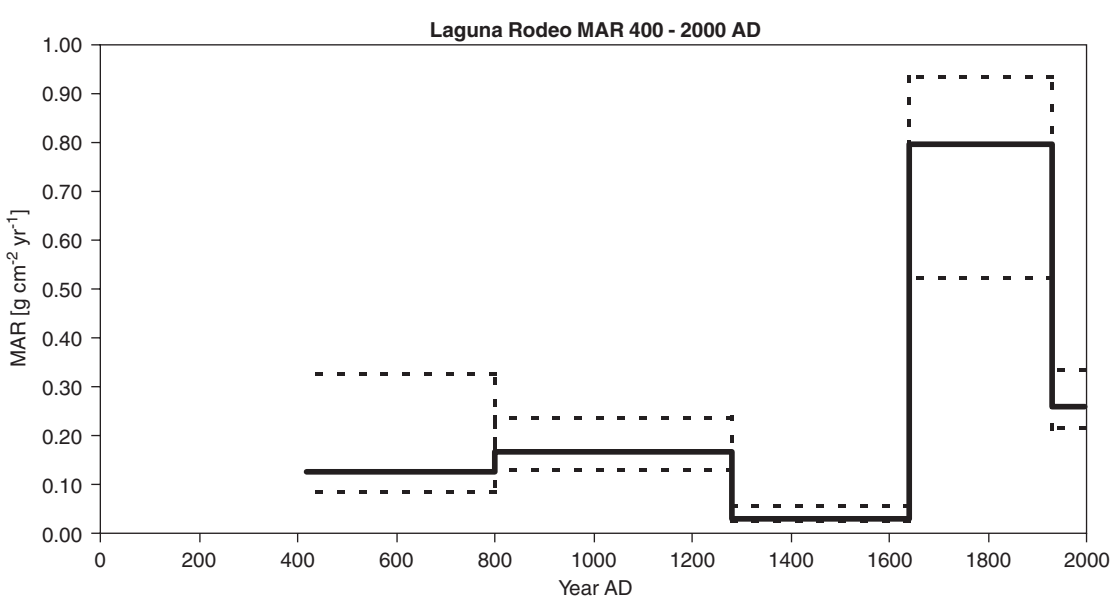

Fig. 5. Mass accumulation rates in Laguna Rodeo back to 400 AD. The solid line shows MARs calculated from the mid-point of the ^{14}C age-depth model (Fig. 4), the uncertainties (dotted line) show the MAR calculations with the 2σ ^{14}C calibration interval.

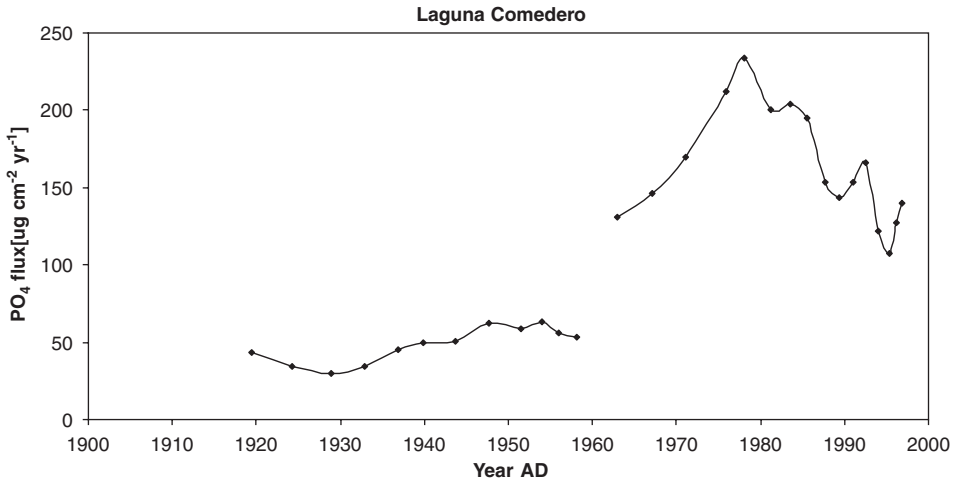

Fig. 6. The 20th Century PO_4 fluxes in Laguna Comedero.

supply after AD 1960, which is mainly attributed to animals in the catchment, particularly in the near-shore pastures.

4.3. Vegetation cover and land use

Fig. 7 reflects the 20th century vegetation composition (pollen percentage) in the catchments of both lakes. Alder (*Alnus acuminata*), the main forest species amounts to 40–60% of the total pollen, whereas herb and shrub taxa, indicative of pastures (Poaceae and Asteraceae), make 20–40%. According to Braun Wilke et al. (1995), *Acacia, Plantago, Satureja* and *Urtica* are interpreted as fire indicators, while *Urtica* and *Plantago* are also indicative of the presence of cattle (nutrients and soil compaction). The sum of Cyperaceae and Juncaginaceae indicate near-shore wetlands, and ferns (mainly Monolete spores) are interpreted in terms of atmospheric moisture.

The results of both profiles are highly consistent showing the statistically largest change during the 1960s (Zones I to II), when ferns increase. This is in line with the increase in regional precipitation (Fig. 2). The onset in Laguna Comedero is slightly earlier (1960) than in Laguna Rodeo (1969) which may partly be due to the ^{210}Pb dating uncertainty of ± 6 years at that age. The pollen spectra reflect the 20th Century mixed forest–pasture land-use pattern. Long-term trends of the forest to grassland pollen proportions are not observed, which suggests a stable vegetation composition through the 20th century. However, variability at the (sub-) decadal scale is remarkable as indicated by the varying proportions of trees versus shrubs and herbs taxa. As expected, both groups are inversely correlated, and mirror interannual variations in climate and the fire disturbance regime as it is also recorded in the charcoal flux (Fig. 8) and the frequency of fire scars in living *Alnus* trees (Fig. 9; see below). In Laguna Comedero, *Alnus* pollen shows a positive trend between 1930 and 1950 (Zone I-B) which is synchronous with a negative trend in the frequency of fire scars. In Laguna Rodeo (Zone II-A) and to some extent in Laguna Comedero (Zone II-B), *Alnus* peaks between mid-1970 to 1982 which correlates with the period of least frequent fires.

4.4. Fire disturbance regime

The 20th century fire disturbance regime is inferred from charcoal flux in the lake sediments as well as fire scars and population dynamics of *Alnus acuminata*, the dominant tree species. Fig. 8 displays the fluxes of coarse (125–250 μm) and fine (>63 μm) charcoal particles. The data of all fractions reveal a quasi-identical structure suggesting that the charcoal particles are mostly related to local fires and/or that the local fire history is well representative for the regional history. This in turn would enhance the significance of the local fire signal as recorded in the fire scars from the Laguna Rodeo catchment. Highest charcoal fluxes are observed between 1925 and >1950 AD with a maximum between 1945 and 1950 (and 1925 AD for the coarse fraction), and a second maximum starting 1984 and ending 1991. Charcoal fluxes between 1960 and 1983 AD remain constantly very low.

The fire scar history and population dynamics as indicated in the recruitment of *Alnus acuminata* (Fig. 9) is based on 405 sampled living trees from 50 places in the catchment of Laguna Rodeo. At least six trees were sampled at each site and a total of 80 fire scars was counted. Several scars in the same year at the same site were treated as one fire, and the fire history is reported in % of tree rings with scars from the total population of potential recorder trees.

The fire scar data show frequent fires during 1933–1960 AD and from 1984–1989 AD, and a minimum 1960–1975. Peaks are recorded during the period of 1956–1959 and 1984–1987. Periods with frequent fire scars are very much in line with relative *Alnus* pollen minima (Compositae maxima) pollen minima (maxima), with charcoal flux

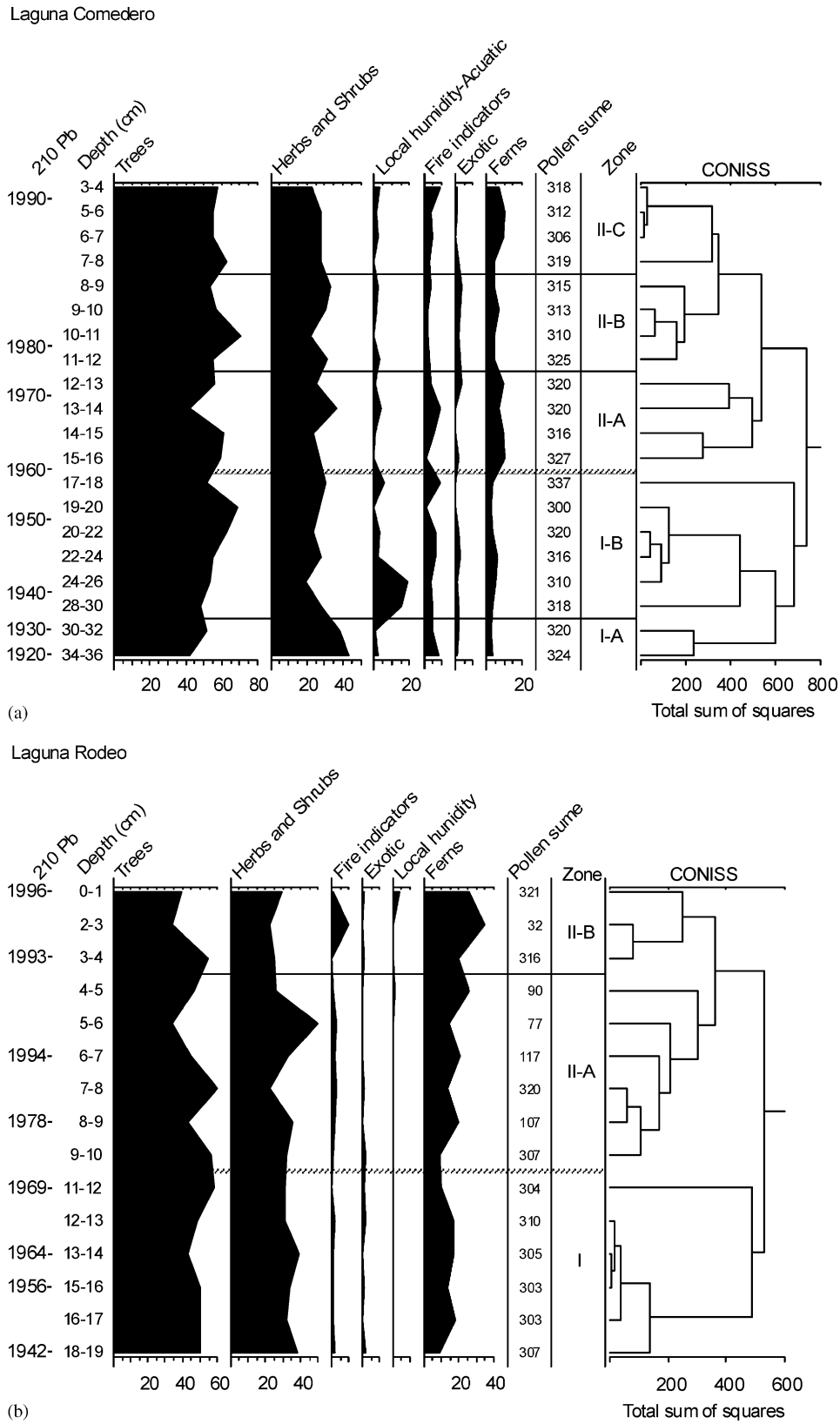

Fig. 7. Pollen (percentage) of the major groups in the short cores of Laguna Rodeo and Laguna Comedero.

(except the 1956–1959 fires which are not recorded in the charcoal data), and with years of extremely low wet-season (October–March) precipitation rates and large interannual precipitation variability (Figs. 2, 7–9). Although the fire season is usually the dry season, low wet-season precipitation rates seem to be the key meteorological predisposition.

Individual dry years (e.g. 1984) or couplets of dry years (1940–1948, 1956–1959) are well visible in the scar and charcoal data suggesting that the proxy data used here are suitable fire indicators at the interannual resolution.

The fire history is very well backed up by the population dynamics of *Alnus*. Tree recruitment (Fig. 9) is pronounced in the years subsequent to intense fires (from 1950 AD). However, the most significant increase in alder recruitment after 1955AD coincided also with the change from private ownership of the land to a Provincial Park. Thus an anthropogenic effect cannot be ruled out.

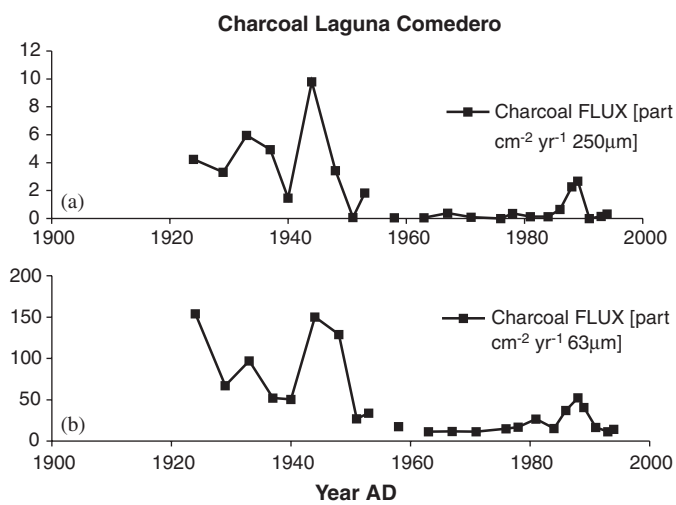

Fig. 8. Charcoal particle fluxes [particles $cm^{-2} yr^{-1}$] of the coarse (>250 µm, top) and the fine (>63 µm, bottom) fraction from Laguna Comedero.

4.5. Atmospheric Pb deposition

The last indicator of human impact studied in the Laguna Comedero concerns atmospheric Pb deposition. We use relative changes in Pb/Zr and Pb/Rb ratios as a proxy for excess (atmospheric) Pb deposition assuming that admixtures of unweathered geologic material has constant Pb/Zr/Rb ratios. Increasing Pb/Zr and Pb/Rb ratios reflect Pb enrichment from non-geologic sources, i.e. atmospheric Pb deposition (approach similar to Shotyk et al., 1998).

Fig. 10 shows the data for the short core Laguna Comedero. Pb/Zr and Pb/Rb ratios are consistent ($r = 0.77$). For both ratios, the values for the sediments deposited between 1950 and 1998 AD (Pb/Zr $= 0.513 \pm 0.151$; Pb/Rb $= 0.380 \pm 0.060$) are significantly above the 19th century values (Pb/Zr $= 0.241 \pm 0.040$; Pb/Rb $= 0.209 \pm 0.027$, $n = 4$; data not shown), suggesting that Pb is enriched and there is a significant non-geological (atmospheric) Pb source in the second half of the 20th century.

5. Discussion

Before conclusions on the climatic and environmental history are drawn, the following questions are to be assessed: (1) what is the quality and consistency of our data set? (2) Which of the measured parameters are suitable for reconstructing changes in climate, human impact on the environment, or a combination of both, and what can we learn from the data recorded during the 20th century? (3) How does our data set and its interpretation compare with other regional proxy data for climatic changes and with the

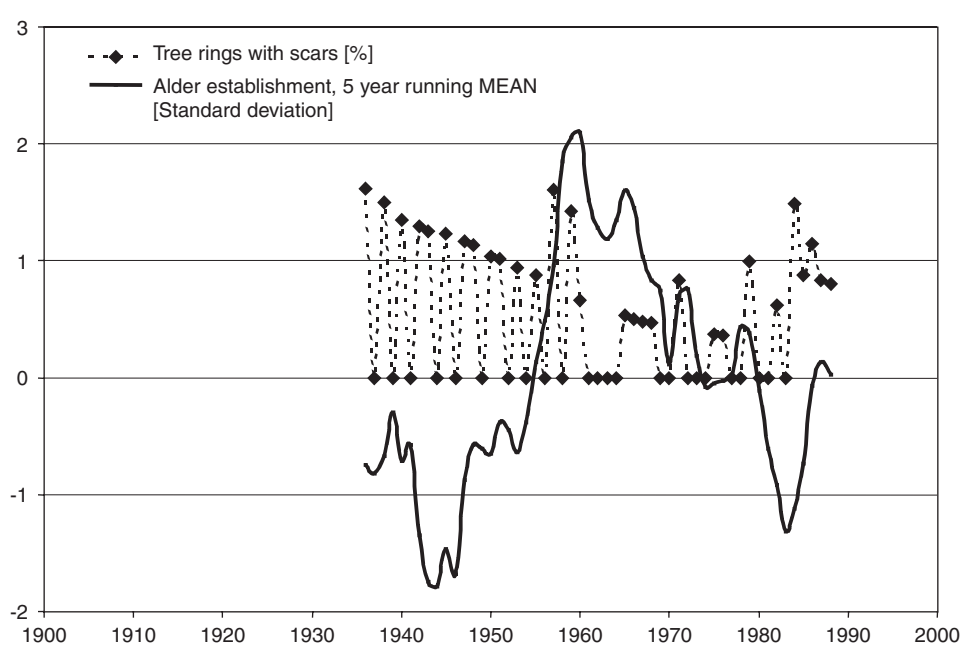

Fig. 9. Fire scar frequency (in % of *Alnus* tree rings with scars, dotted line) and alder recruitment (normalized values, 5 yr moving average, black line) in the catchment of Laguna Rodeo, Potrero de Yala.

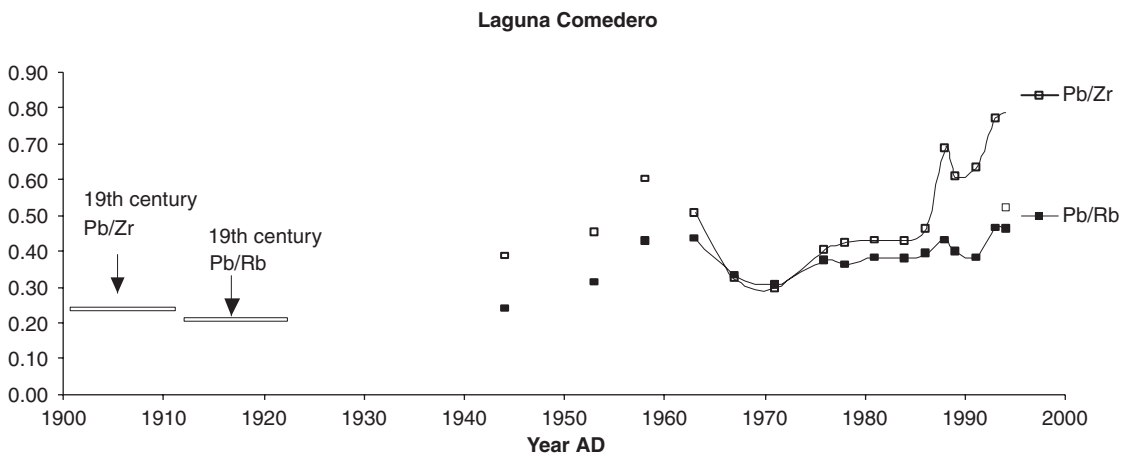

Fig. 10. Pb/Zr and Pb/Rb ratios in the short core of Laguna Comedero between 1940 and 1998 AD.

history of land-use and human impact as revealed in documentary and archaeological data for the past?

The quality (consistency of parameters and chronology) of the data set is assessed by comparison of the lake sediment data with independent and precisely dated dendro-ecological records (fire scars with yearly resolution), meteorological time series (precipitation with monthly resolution), and data on atmospheric Pb deposition and chronicles for metal production (yearly resolution). The common period among these variables is 1934–1998.

Coincidences between peaks in charcoal from lake sediments and fire scars from *Alnus* trees (1940–1948, 1984–1987, Figs. 8 and 9) suggest that (1) the charcoal flux reflects the local fires and (2) the lake sediment ^{210}Pb chronology (as calculated with the CRS model) is in line with the dendro-chronological and calendar time-scale. Comparison between the fire history (charcoal and fire scars) and the vegetation composition (pollen percentage profile, Fig. 7) reveals that frequent fires coincide with relative vegetation changes, whereby tree pollen decrease and Poaceae pollen increase. Trees need some time to recover. Dendro-ecological data (Fig. 9) further corroborate that, subsequently to longer periods of frequent fires, new-growth of alder is enhanced, suggesting that open space is re-colonized. The fire history (at interannual resolution), the main change in vegetation composition (around 1960, Fig. 7) and the increase in mass accumulation rates after ca. 1965 is well in line with the interannual precipitation series (Fig. 2). It is shown that (1) large fires occur after dry wet-season conditions in a regime with generally high interannual precipitation variability, (2) ferns, as indicators of wet vegetation, reflect the increase in regional precipitation (5 years moving average) after 1960, (3) enhanced mass accumulation rates after 1965, interpreted as enhanced erosion in the catchment, coincided with and are mostly explained by increased regional rainfall during that time, given that the Provincial Park was established in 1952 and no major human land use changes occurred since then. In summary, we conclude a high internal consistency within our data set, and a high confidence in the chronological model of the lake sediments.

Of the parameters measured in the lake sediments, charcoal indicating fires, fern pollen indicating wet vegetation, and mass accumulation rates indicating erosion rates in the catchment may potentially be used as proxies for (wet season) precipitation. While fern pollen is the most direct proxy, fires and soil erosion may also be induced by human activity. Given that the area was transformed into a Park in 1952 and the coincidence with the regional precipitation changes, we attribute most the variability in mass accumulation rates (range Rodeo: 0.1–0.4 $g\,cm^{-2}\,yr^{-1}$) and charcoal flux during the second half of the 20th century to climate variability overriding the background fluxes that correspond to the current land use and management practices. This is consistent with the dendroclimatological studies of Villalba et al. (1998) suggesting that the last three decades in the 20th century and those from 1850 to 1880 were the wettest and driest during the past ca. 200 years. As the short cores from Laguna Comedero and Laguna Rodeo encompass the whole range of climate fluctuations of the last 200 years, mass accumulation rates exceeding this range may largely be attributed to human impact and land use changes.

This later line of argument comes into play when the mass accumulation rates, C_{org} and phosphorus fluxes are assessed over longer time scales back to 2000 BP (Figs. 4 and 5). While the pre-1640 MAR fluctuations may, to some extent, also be an artifact due to ^{14}C dating uncertainties, the 17–19th century increases in MARs (factor 5 to >8), in C_{org} flux (factor 10.5) and in phosphorus flux (factor 7) are the most significant changes during the last 2000 years, which are mostly attributed to human impact.

During the Formative and the Desarollo Regional Periods (ending 1470 AD), agro-pastoral activities are documented from several archaeological sites nearby the lake catchments (Fumagalli and Cremonte, 2002b).

Subsequently, during the 15th/16th centuries, MARs and human impact decrease compared with the previous centuries, which is in line with the human activities and the spatial organization reported for this area during the Inca Empire (1450–1570 AD). The interest in exploitation of natural resources and possibly agro-pastoral activities in the Yungas environment was marginal. Most of the activities were of strategic nature and oriented towards securing the trade and traffic routes towards Potosí and the highlands of the Altiplano. Forts, tambos, roads and sanctuaries witness the (architectural) priorities, and reflect the principle of Inca governance, the political organization of the space, and the structuring of the society (Núñez et al., 2005). However, to the south of the lake catchments, small enclaves with agricultural production were present. MARs are relatively low and on the same order of magnitude as MARs between 1930 and 1960 (100–200 $mg\,cm^{-2}\,yr^{-1}$). However, because soil erosion is a combination of erosivity of the precipitation and erodibility of the soil (as a function of the soil properties, vegetation, and land management, among other factors), we are not able to discriminate the human impact from the climate impact at that fine scale. MARs increased significantly by an order of magnitude with the Spanish Conquest at the beginning of the 17th century, when exploitation of natural resources, mainly agriculture, cattle raising, pasture and forest products became very important. The valley of San Salvador de Jujuy was an important route for cattle to Potosí. Production of timber and fuel wood for the mining industry was significant, as witnessed by agreements (e.g. 1636), contracts (e.g. 1638) and money sent for forest products (1647) in historical documents (Arzans de Orsua y Vela, 1970). New domestic animal species (sheep, goats, cattle and horses) with different grazing habits and diets were introduced, and new agricultural techniques and management systems were implemented. This had an impact on vegetation and land cover, nutrient cycles (e.g. phosphorus), and land surface processes such as soil erosion and MARs. In summary, we attribute the 17th to 19th century increase in MAR, P and C_{org} fluxes to the impact of colonial land use and management practices. However, with respect to MARs, it has to be recognized that the erodibility of the soil in the freshly clear-cut areas was likely much higher that it is today.

Although metal mining and smelting was historically very important (particularly during the Colonial time), the big boost with large plants for Pb and Ag smelting took place in the 1950s and 1960s. Seven large plants were installed in the area, some of them (Martin Munster SA, Cuprifera Argentina) in the immediate vicinity of the lakes (10 km). Measurements of Pb concentrations in the air at three stations in Río Blanco (24°12′S/65°13′W), Parque Industrial, and Industrial Palpala (24°16′S, 65°10′W) revealed values as high as 22.9 $\mu gPb/m^3$ air (mean of 81 samples taken between 1987 and 1990; Territorial, 1990). The significant increase in Pb deposition after 1950 AD, as observed in the short core from Laguna Comedero (Fig. 10), reflects anthropogenic emissions and atmospheric deposition from the regional metal industry.

6. Conclusions

Late Holocene sediments from two small lakes in the biosphere reserve 'Lagunas de Yala', Yungas montane forest, NW Argentina provide insights on the paleoenvironmental changes during the past centuries. The internally-consistent, multi-proxy data set from the lake compares well with independent dendro-ecological and instrumental climate records over the common time interval 1938–1998.

The flux of charcoal particles (three different fractions) to the lake compares well with the frequency of fire scars as recorded in alder trees in the lake catchment area. Both parameters show frequent fires in the 1940s and 1984–1987, which coincides with low wet-season (i.e. austral summer) precipitation and high interannual variability. In light of the reduced land use and vegetation cover changes (as revealed by the pollen percentage profile) during that time, the fire history over this period is mostly explained by precipitation variability.

Increasing precipitation rates at the multi-annual to decadal scale (e.g. after 1960) is consistent with larger fern presence in the pollen spectra. Relative changes between tree and Poaceae pollen (inversely correlated) at the sub-decadal scale are related to local and regional fire history, which in turn depends on climate variability.

Sediment mass accumulation rates (MARs) increase after 1960 by a factor of 1.5–4 reflecting the regional increase in precipitation. Changes in land use over that time were reduced suggesting a dominant effect of climate variability on lake processes.

MARs, C_{org} and phosphorus fluxes over the last 2000 years reveal information about land use and land cover changes, nutrient cycling and eutrophication of the lake for historical and pre-historical times. Nutrient fluxes and erosion rates remain relatively low up to 1640 AD, when new domesticated animals, land use and management practices arrived with the Spanish Conquest, and the pressure on exploitation of agro-pastoral and forest products increased. Concomitant pressure on the Yungas montane forest ecosystem resulted in land degradation, enhanced soil erosion and accelerated nutrient fluxes.

In this study, we put emphasis on the 20th century high resolution records since, at this stage of our research, the principal question is: What is recorded in the lake sediments?, and can this information be used for paleoclimatic studies and the history of human impact? Our data show that the Lagunas de Yala records are suitable for the reconstruction of past environmental and anthropogenic changes in the region. In addition, the preliminary dating of the long core show the potential of these records for a detailed reconstruction of paleoenvironmental and land use changes during the past millennia.

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References

Abbott, M.B., Wolfe, A.P., 2003. Intensive pre-incan metallurgy recorded by lake sediments from the Bolivian Andes. Science 301, 1893–1895.

Anderson, J.M., 1976. An ignition method for determination of P tot in lake sediments. Water Research 10, 329–331.

Appleby, P.G., 2001. Chronostratigraphic techniques on recent sediments. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Basin Analysis, Coring, and Chronological Techniques, vol. 1. Kluwer Academic Publisher, Dordrecht, pp. 171–203 (Chapter 9).

Arzans de Orsua y Vela, B., 1970. Anales de la Villa Imperial de Potosí. Ministerio de Educación y Cultura, Fondo Nacional de Bolivia, 119pp.

Bianchi, A.R., Yáñez, C., 1992. Las precipitaciones del Noroeste Argentino. Instituto Nacional de Tecnología Agropecuaria, Salta, Argentina, 383pp.

Braun Wilke, R., Canelada, A., Chalabe S., Picchetti, L., 1995. Diagnostico Ambiental del Eje San Salvador de Jujuy-Palpala. Colección Arte-Ciencia. Serie: Jujuy en el presente. Universidad Nacional de Jujuy—Agua de Los Andes.

Camacho, M., Bossi, G.E., 2002. Mineralogía de los depósitos del Holoceno Medio Tardío-Reciente de las Lagunas de Yala: Rodeo y Comedero en el Valle de San Salvador de Jujuy, Noroeste de Argentina. In: Actas II de XV Congreso Geológico Argentino, Calafate, pp. 603–608.

Camacho, M., Grosjean, M., 2004. The Late-Holocene (3755 ± 150 ^{14}C yr BP) Sedimentary Sequence of the Yala Lakes, Jujuy, NW Argentina. In: Actas I de X Reunion Argentina de Sedimentologia, San Luis, pp. 37–38.

Dean, W., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44, 242–248.

Faegri, K., Iversen, J., 1989. Textbook of Pollen Analysis. Cuarta Edición por Fraegri, K., Kaland, P.E., Krywinski, K., Chichester.

Fumagalli, M.G., Cremonte, M.B., 2002a. Ocupaciones Agropatoriles Tempranas al Sur de La Quebrada de Humahuaca (Jujuy, Argentina). Chungara Revista de Antropología Chilena 34 (1), 35–52.

Fumagalli, M.G., Cremonte, M.B., 2002b. Camino a Las Yungas. El Sur de la Quebrada de Humahuaca. Un Espacio Diferente. PACARINA Arqueología y Etnografía Americana II (2), 93–101.

Gardner, J.J., Whitlock, C., 2000. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. The Holocene 11 (5), 541–549.

Garralla, S., Muruaga, C., Herbst, R., 2001. Lago El Rincón, Holoceno del Departamento de Tafí del Valle, Provincia de Tucumán (Argentina): palinología y facies sedimentarias. Ameghiniana. 8, 91–99 (Publicación Especial).

González Díaz, E.F., Mon, R., 2000. El origen de las lagunas de Yala, Provincia de Jujuy (24°05′ de Latitud Sur y 65°28′ de Longitud Oeste). In: Actas IV de XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, pp. 209–217.

Graf, K. 1992. Pollendiagramme aus den Anden: eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physiche Geographie 34.

Grau, H.R., Veblen, T.T., 2000. Rainfall variability, fire and vegetation dynamics in neotropical montane ecosystems of north-western Argentina. Journal of Biogeography 27, 1107–1121.

Grau, H.R., Easdale, T.A., Paolini, L., 2003. Subtropical dendroecology-dating disturbances and forest dynamics in northwestern Argentina montane ecosystems. Forest Ecology and Management 177, 131–143.

Heusser, C.J., 1971. Pollen and Spores of Chile. University of Arizona Press, Tucson.

Kern, R., 2001. Paläolimnologische Untersuchungen an Sedimentkernen aus zwei Seen in der Provincia de Jujuy, NW-Argentinien und deren Verwendung als spätholozäne Klimaarchive. Diplomarbeit Universität Bern.

Lenz, D., 2000. Imperfect balance: landscape transformations in the precolumbian Americas. The Historical Ecology Series. Columbia University Press, New York.

Lucas, C., 1999. ^{210}Pb Datierungen von Sedimenten aus vier Seen in NW Argentinien. Diplomarbeit Universität Bern.

Lupo, L. C., 1990. Palinología de una secuencia del Holoceno en el Valle de Tafí, provincia de Tucumán, Argentina. FACENA 8, Serie Ciencias Naturales, Corrientes, Argentina, pp. 87–98.

Markgraf, V., D'Antoni, H.L., 1978. Pollen Flora of Argentina. The University of Arizona Press, Tucson.

McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere Calibration 0–11.0 cal kyr BP. Radiocarbon 46, 1087–1092.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis, Segunda edición. Blackwell Scientific Publications, London.

Núñez, L.A., Grosjean, M., Cartajena, I., 2005. The Expansion of the Inca Empire into the Atacama Desert, northern Chile, In: Smith, M., Hesse, P., (Eds.), 23° South: The Archaeology and Environmental History of the Southern Deserts. National Museum of Australia, Canberra, pp. 324–332 (Chapter 23).

O'Hara, S.L., Street-Perrott, F.A., Burt, T.P., 1993. Accelerated soil erosion around a Mexican highland lake caused by prehispanic agriculture. Nature 362, 48–51.

Pourchet, M., Mourguiart, P., Pinglot, J.-F., Preiss, N., Argollo, J., Wirrmann, D., 1995. Evaluation des vitesses de sédimentation récente dans les hautes vallées des Andes boliviennes. Son Intérêt dans l'estimation des paléo-pollutions atmosphériques. Comptes Rendues de l' Académie Science 320 (t II), 477–482.

Schäbitz, F., Lupo, L., Kulemeyer, J.J., Kulemeyer, J.A., 2001. Variaciones de la vegetación, el clima y la presencia humana en los últimos 15.000 años en el Borde Oriental de la Puna, provincias de Jujuy y Salta, Noroeste Argentino. Ameghiniana 8, 125–130 (Publicación Especial).

Shotyk, W., Weiss, D., Appleby, P.G., Cheburkin, A.K., Frei, R., Gloor, M., Kramers, J.D., Reese, S., van der Knaap, W.O., 1998. History of atmospheric lead deposition since 12,370 ^{14}C yr BP from a peat bog, Jura Mountains, Switzerland. Science 281, 1635–1640.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2005. CALIB 5.0. http://radiocarbon.pa.qub.ac.uk/calib/calib.html

Territorial, C., 1990. Informe sobre contaminacion atmosférica del Departemento de Calidad Ambiental. 19 July 1990.

Villalba, R., 1995. Estudios dendrocronológicos en la selva subtropical de montaña, implicaciones para su manejo y conservación. In: Brown, A.D., Grau, H.R. (Eds.), Investigación, conservación y desarrollo en selvas subtropicales de montaña. Universidad Nacional de Tucumán, Argentina, pp. 9–68.

Villalba, R., Boninsegna, J., Ripalta, A., 1987. Climate, tree growth and site conditions in subtropical northwestern Argentina. Canadian Journal of Forest Research 17, 1527–1539.

Villalba, R., Grau, H.R., Boninsegna, J., Jacoby, G., Ripalta, A., 1998. Tree-ring evidence for long-term rainfall changes in subtropical South America. International Journal of Climatology 18, 1463–1478.

Whitlock, C., Larsen, C.P.S., 2002. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking environmental Change Using Lake Sediments. Biological techniques and Indicators, Vol. 2. Kluwer Academic Publishers, Dordrecht, pp. 85–97.