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Paleolimnological assessment of human impacts in Lake Blanca, SE Uruguay

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Abstract

Paleolimnological techniques were used to assess human impacts on Lake Blanca, a small (0.6 km^2), coastal fresh waterbody in southern Uruguay, which is the drinking water source for ~100,000 local residents. We retrieved a core that extends to about 1100 ^{14}C yr BP. ^{210}Pb ages, organic mater, CO_3, total carbon, nutrients, fossil pigments and diatoms allowed us to establish limnological conditions before and after cultural impacts. Soil removal (1880–1960) and intensive cattle and sheep grazing (1943–1966) led to gully formation in the catchment. This watershed erosion resulted in increased sedimentation rates. The aquatic system appeared to be mesotrophic with dominance of epibenthic diatoms until ~1966, at which time eutrophication intensified with forestry activities. Increases in nutrients, as well as blooms of planktonic diatoms, were observed. During the last decade, tourist/urban development as well as high drinking water demand caused a reduction in lake area. Subsequent marked increases in rainfall led to further phytoplankton blooms and macrophyte proliferation.

Introduction

Lake Blanca is a coastal fresh waterbody in SE Uruguay that is a drinking water source for local residents. Several recent eutrophication episodes and a reduction in lake area led to a decrease in drinking water production. This situation became particularly problematic in 1998/99, when the agency in charge of producing drinking water could no longer supply the local population. As a consequence, local authorities sought a remedy for the situation. To assist managers we started this research program to: 1) establish when the system started to experience strong eutrophication events, 2) determine how frequently they occurred, 3) assess the magnitude of eutrophication episodes, and 4) establish the possible causes of eutrophication. Because long-term limnological data are unavailable for Lake Blanca, paleolimnological methods were used to infer past trophic state (Smol 1990, 1992), and assess the effect of human impacts on the lake (Hodgson et al. 1996; Pan and Brugam 1997; Kamaleldin et al. 1997; Kaushal and Binford 1999; Kaupplia et al. 2002; Miettinen et al. 2002). We reconstructed paleolimnological conditions in Lake Blanca to evaluate predisturbance conditions, document the changes that have occurred, and try to correlate those limnological changes with human activities in the watershed.

Study area

Lake Blanca lies at 34° 53′ S; 54° 50′ W, on the southern coast of Uruguay (Figure 1). The lake forms part of a series of coastal aquatic systems that originated about 6000 yr BP, after the first large Holocene marine transgression (Martin and Suguio 1992; Angulo and Lessa 1997). The lake area is 0.6 km^2, maximum depth is 4 m and the catchment area is 7.5 km^2. The lake is freshwater and is separated from the ocean by a 1.5-km-wide sand bar, on which a holiday resort was built. Recent sediments consist mainly of clay and silt. Surrounding vegetation is dominated by extensive meadows and both *Eucalyptus* sp. and *Pinus pinaster* forests. By ~1880, soil removal in the catchment for road building and home construction, had began. Soil removal lasted until about 1960. In 1943 intensive cattle and sheep grazing activities were undertaken in the north section of the catchment. Grazing led to gully formation (Figure 1A). These gullies were even bigger by 1967 (Figure 1B) as a consequence of erosion. After intensive grazing activities ended in 1966/67, gullies were forested with *Eucalyptus* sp. Since 1969/70 the lake has been a source of drinking water, during which time it has been subjected to human impacts including farming, urban development, and tourism. Recently, the littoral zone has been invaded by *Egeria densa* Planchon (Figure 1C).

Materials and methods

A 150-cm-long core (LBL1, Figure 1) was taken in Lake Blanca in May 2000 with the aid of a 5-cm-diameter piston corer. The sampling station was located at the maximum depth in the lake. After retrieval, the core was immediately sealed and kept in the dark at 4°C, prior to laboratory analyses.

Lithological units were described based on colour, grain size and texture. Aliquots of ~50 g were dried at 80°C for 48 hours and then treated with 30% H_2O_2 and HCl to remove organic matter and CO_3 respectively. Dry samples were sieved with an electrical sieve. Sediment size was expressed as percentage of ϕ-units [i.e., ϕ = log 2 (grain size, mm)].

Sediment age at 140–145 cm was determined by conventional ^{14}C on bulk sedimentary organic matter. Samples were treated with dilute HCl to remove CO_3. Bulk organic material was converted to benzene and its ^{14}C activity was measured with a Packard Tri-Carb 2560 TR/XL liquid scintillation spectrometer. Age is expressed in conventional ^{14}C yr BP, corrected for isotopic fractionation by normalising $\delta^{13}C$ values to −25‰. Quoted error ($\pm 1\sigma$) includes uncertainties in counting statistics.

Sediments were also dated by ^{210}Pb (excess) technique (Appleby and Oldfield 1992). The core was cut in 5-cm sections from the surface to 30 cm depth. Below 30 cm, only three samples (i.e., 56–60 cm, 91–95 cm, and 108–112 cm) were measured. Samples were dried for 48 hr at 60°C. Radioactivity was measured with a gamma spectrometer of a high-purity germanium (HPGe) coaxial low energy n-type detector, using a 39 cm^3 cylindrical capsule and a Be-window of 0.5 mm. The detector was calibrated with certified reference material of the International Atomic Energy Agency (IAEA), and the Canadian Certified Reference Materials Project (reference britholite ore OKA-2). Dates were calculated using the CRS model (Appleby and Oldfield 1992). The ^{210}Pb ages were related to historical information on the chronology of human impacts in the catchment. Historical information was obtained from the National Direction for Mining and Geology, and conversations with local people. ^{137}Cs was also measured in an effort to identify the period of maximum fallout from atmospheric nuclear weapons testing and to corroborate ^{210}Pb dates.

Total carbon, total nitrogen and total phosphorus were determined according to standard methods of the German Institute for Standardisation (DIN: *Deutsches Institut fuer Normung*) and the International Standard Organisation (ISO). For total phosphorus (DIN 38414, 1986), samples were treated with NH_4NO_3, HCl and allowed to stand for 15 min. Then, 100 ml of this solution were treated with p-nitrophenol, NaOH, H_2SO_4, $KMnO_4$ and allowed to stand for 15 min. Finally, the samples were treated with ascorbic acid, molybdate reagent and absorbances were read with a UV/VIS spectrophotometer at 880 nm. For total carbon and nitrogen (International Standards Organisation 1984), samples were measured with a vario-EL-CNS elemental analyzer (*Elementar Analysesysteme GmbH*, Jena, Germany). Organic matter was determined by weight loss on ignition (LOI) at 550°C for two hours. Subsequently the CO_2 mass evolved from carbonate was determined by LOI at 880°C for two hours, and the CO_3 content was calculated by multiplying the weight loss by 1.36 (Heiri et al. 2001). The non-carbonate inorganic fraction of the

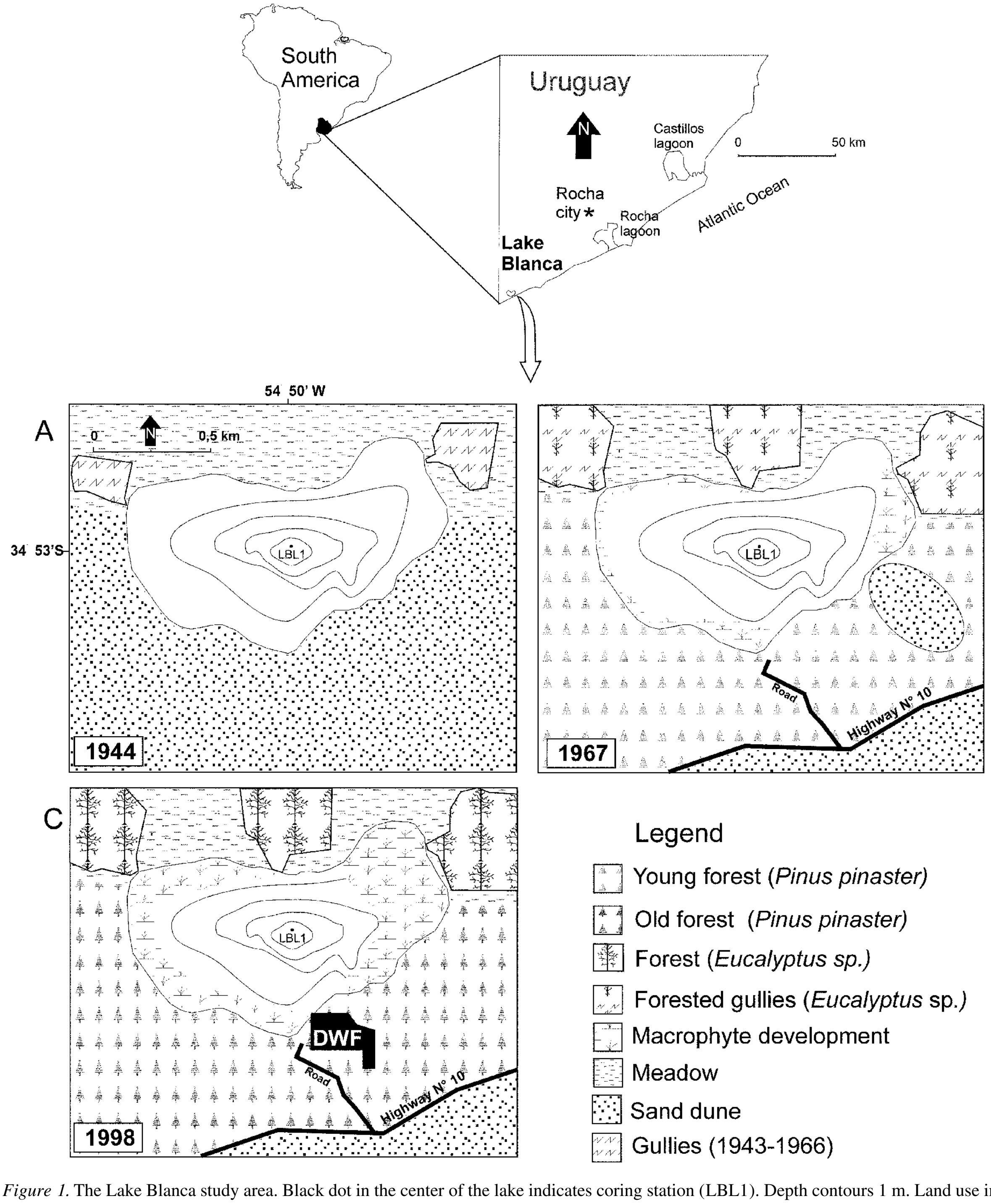

Figure 1. The Lake Blanca study area. Black dot in the center of the lake indicates coring station (LBL1). Depth contours 1 m. Land use in the catchment area is illustrated for 1944 (A), 1967 (B) and 1998 (C). DWF = Drinking Water Facility.

sediment was figured as the residue after subtraction of present organic matter and carbonate (as $CaCO_3$).

Chlorophyll derivatives were extracted with 96% ethanol for 24 hours according to Nusch (1980). After extracting pigments, samples were centrifuged at 1000 g for 10 min and the supernatant was filtered with glass-fibre filters. Absorbances were read with a UV/Vis spectrophotometer at 665 nm for pigments and 750 nm to correct for turbidity. The method of Nusch (1980) was developed to measure chlorophyll-a in water samples, but García-Rodríguez (1993) showed that this method may be also useful to estimate chlorophyll derivatives in sediment samples.

Samples for diatom counting and identification were treated with 35% HCl for 24 hours to eliminate carbonates, and then rinsed four times with distilled water. Next, 10 ml of 30% H_2O_2 were added to eliminate organic matter, and then the samples were boiled for four hours and rinsed five times with distilled water. Permanent slides were mounted in Naphrax® for counting and identification. A minimum of 400 valves was counted at 1250x magnification in each sample. Species were identified according to Lange-Bertalot (2001), Witkowski et al. (2000), Rumrich et al. (2000), Metzeltin and Lange-Bertalot (1998), Krammer (2000), Krammer and Lange-Bertalot (1991a, 1991b, 1988).

Rainfall data for the Rocha station located in Rocha city (Figure 1), were obtained from the National Institute of Meteorology. Aerial photographs from 1944, 1967, and 1998 were purchased from the Uruguayan army to establish the history of land use in the lake catchment.

Results

Seven lithological units were identified according to sediment colour (Figure 2). Grain size composition showed no major changes throughout the core, being dominated by silt/clay grains (ϕ-4 ~20%, ϕ-5 ~40% and ϕ-6 ~40%).

Figure 2 shows ^{210}Pb activities and corresponding ages. Supported ^{210}Pb in each sample was assumed to be in equilibrium with the in situ ^{226}Ra, and unsupported ^{210}Pb was calculated by subtracting ^{226}Ra activity from total ^{210}Pb. ^{226}Ra values ranged between 25 and 46 Bq kg^{-1}, and the supported/unsupported boundary was reached at 56–60 cm (i.e., five half lives ago) corresponding to the end of the 19th century (~1890 AD). Total ^{210}Pb activity declined significantly between the section 0–5 cm (156 Bq kg^{-1}) and 5–10 cm (71 Bq kg^{-1}). From 5–10 cm to 15–20 cm, no significant difference in ^{210}Pb-activity was detected. The peak of ^{210}Pb activity, observed at 20–25 cm (326 Bq kg^{-1}), was followed by a new decline in activity below. A significant difference between activity at 20–25 cm and 25–30 cm depths was observed. From 25–30 cm to 56–60 cm, ^{210}Pb activity decreased. ^{137}Cs did not display a maximum bomb peak and activity values did not allow reliable age calculations. Sediment age at 140–145 cm was 1020 ± 60 ^{14}C yr BP.

Sedimentation rates are shown in Figure 2. The lowest sedimentation rate was observed in units VII, VI and V (0.98 mm yr^{-1}). Sedimentation rate increased in unit IV (3.51 mm yr^{-1}), and even higher values were observed for the top 25 cm (upper section of units IV, III, II and I), with values ranging from 5.55 mm yr^{-1} to 9 mm yr^{-1}.

Chemical variables display fluctuations over the length of the core (Figure 3). At the base of the core, in lithological unit VII, relatively high concentrations of organic matter (~25%), CO_3 (~4%), total carbon (~120 mg g^{-1}), and total nitrogen (~11 mg g^{-1}) were observed. Total phosphorus concentrations were about 0.4 mg g^{-1}, pigment values were always close to 2 μg g^{-1} O.M., while ratios C/N were ~9. The non-carbonate inorganic fraction of the sediment accounted for ~75%. In unit VI, there was high variability in organic matter and CO_3, and both total carbon and nitrogen decreased. Total phosphorus and pigment concentrations remained similar to those values of unit VII, and ratios C/N decreased to ~7. The non-carbonate inorganic fraction of the sediment increased to 85%.

Lithological units V and IV exhibited little change in all variables, with highest values of total carbon, total nitrogen and total phosphorus at 90 cm. Organic matter percentages were always close to 8%, apart from the minimum recorded at 47 cm. CO_3 content displayed values of ~2%, excluding the maximum peak observed at the boundary of units V and IV, and the minimum at 47 cm. The non-carbonate inorganic fraction of the sediment reached values of ~90%. Fossil pigment concentrations were ~2 μg g^{-1} O.M., except at 60, 27 and 25 cm depths, where concentrations were ~5 μg g^{-1} O.M. Total nitrogen in zones V and IV showed no major changes, with concentrations close to 2.5 mg g^{-1}. Total phosphorus exhibited a slight decrease from the bottom of unit V to the top of unit IV. C/N ratios decreased to ~6 at 60 cm depth and then increased to about 7.5 at the top of unit IV.

From unit IV to III, all variables increased, which were associated with a decline in the non-carbonate inorganic fraction of the sediment. C/N ratios remained close to 7.5. Peaks of organic matter, CO_3, total carbon and pigments were observed in the mid-

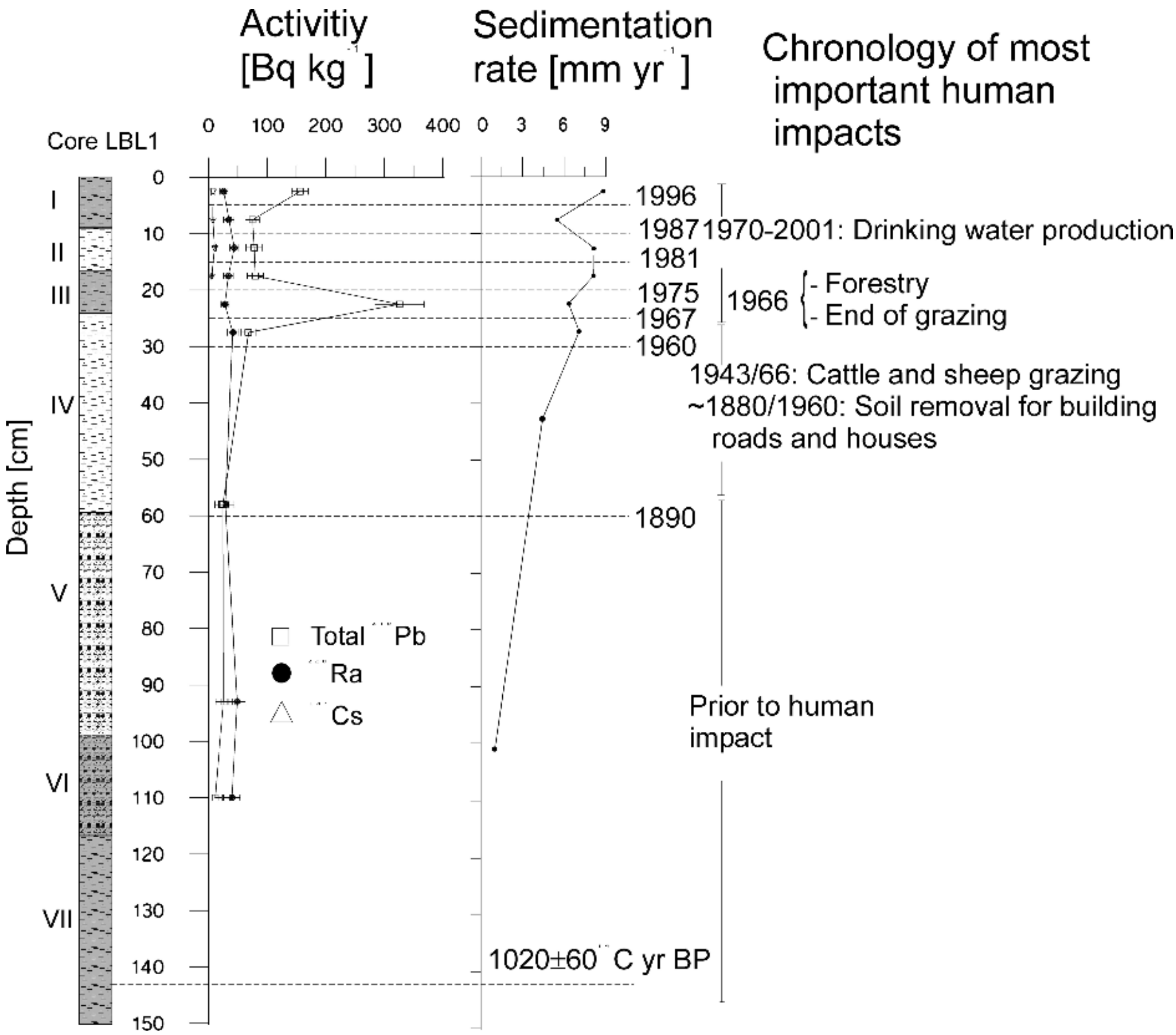

Figure 2. Vertical distribution of total ^{210}Pb activity, ^{226}Ra, ^{137}Cs, calculated bulk sedimentation, and chronology of human impacts in the catchment.

dle of unit III. CO_3 content, however, continued to increase until the 17 cm depth. Total carbon, total nitrogen and total phosphorus showed a maximum peak at the bottom of unit III, and then decreased towards the top of the unit.

From unit III to the middle of unit II, organic matter and CO_3 decreased, and then showed an increasing trend above. The non-carbonate inorganic fraction increased to reach values close to 90%. Pigment concentration exhibited a maximum value at 14 cm and then decreased. Total nitrogen and phosphorus values increased from the bottom to the top of unit II. From unit II to I, all variables increased except for the non-carbonate inorganic fraction that decreased.

One hundred and twenty-nine diatom taxa were identified, and the relative abundance of the 17 most common taxa [>2% in at least three sediment intervals (Karst and Smol 2000)], are shown in Figure 4. The core was co-dominated by epibenthic species (i.e., *Fragilaria* spp. *Navicula peregrinopsis*, *Epithemia adnata*, *Mastogloia smithii var. smithii*, *Nitzschia denticula* and *Pinnularia* spp.), which accounted for ~70%. Planktonic species represented about 27% of diatoms. Only at 125, 68 and 48 cm;

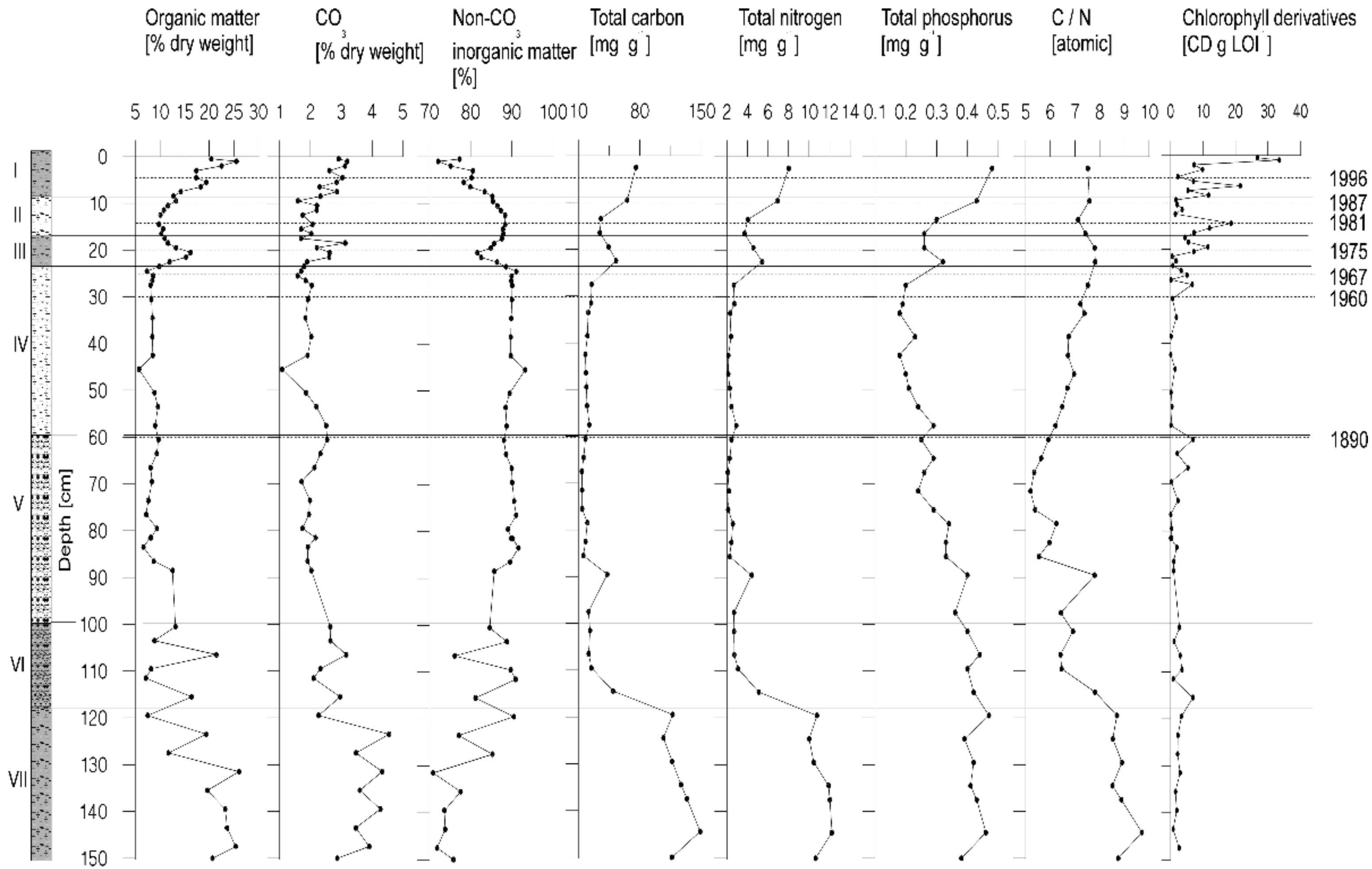

Figure 3. Vertical distribution of chemical variables. Lithological units are indicated with Roman numerals. ^{210}Pb dates are presented to the right of the plot.

however, planktonic species *Aulacoseira granulata* and *Cyclotella meneghiniana* combined to account for ~65%, 44% and 48% respectively. In addition, in the section 17-14 cm *Aulacoseira granulata* and *Actinocyclus normanii* accounted for 45%.

Total rainfall for the last 70 years is expressed on an annual and monthly basis (Figure 5). Maximum total annual rainfall values (~1800 mm yr^{-1}) were observed in 1940, 1986, and 2000. Minimum values (~650 mm yr^{-1}) were recorded in 1931, 1962, and 1965. Mean total rainfall for the last 70 yr was 1100 mm yr^{-1}. Total rainfall per month ranged from 10 to 400 mm, with an average value of 118 mm.

Discussion

The core retrieved from Lake Blanca extends to about 1100 ^{14}C yr BP (Figure 2), which corresponds to the time of regional transition from a semiarid to a temperate/subtropical climate (García-Rodríguez et al. 2001). The basal 33 cm (i.e., 150-117 cm, unit VII) consisted of dark-grey sediments with low concentrations of pigments, high values of organic matter, total carbon, total nitrogen and phosphorus. C/N ratios were ~9, which suggests that aquatic organisms, especially macrophytes, were the main source of sedimentary organic matter (Müller and Mathesius 1999). The diatom community (Figure 4) was dominated by epibenthic *Fragilaria* spp. and *Nitzschia denticula* (Figure 4), except at 125 cm where *Aulacoseira granulata* was the most abundant species. Therefore (except for 125 cm depth), microbenthic primary producers and macrophytes have probably accounted for most of the primary productivity. The relatively low values of fossil pigments indicate poor conditions for pigment conservation. This may be because, first, Lake Blanca is a coastal shallow system influenced by wind, and therefore the water column might have exhibited mixing conditions. Second, solar radiation probably reached the sediment surface, where photosynthesis maintained oxygen in deep waters, inhibiting fossil pigment preservation before permanent burial (Leavitt 1993). Hence, it is likely that the water column exhibited mesotrophic conditions.

The change in lithology in VI is reflected in the increases in the non-carbonate inorganic fraction of the sediment (Figure 3). A decrease in total C, total N and carbonates was also observed. C/N ratios reached values between 5 and 7, in the range of benthic microalgae and phytoplankton (Müller and Mathesius 1999). It is likely that primary productivity was even lower than that of unit VII, due to a decrease in nutrient input. C/N ratios indicate that the macrophyte biomass decreased, and primary productivity was dominated by epibenthic species, which accounted for about 80% of fossil diatoms (Figure 4). Low concentrations of chlorophyll derivatives (Figure 3) indicate poor conditions for fossil pigment preservation before permanent burial. Mixing of the water column (by strong winds), and solar radiation reaching the sediment surface probably maintained oxygen concentrations in deepwater (Leavitt 1993).

Lithological unit V and IV showed no major changes and chemical variables remained fairly constant (Figure 3), except for total phosphorus that showed a slight decrease. Diatom community composition in unit V was similar to that of units VII and VI (i.e., dominated by epibenthic diatoms) (Figure 4). There was, however, a significant change in diatom composition from unit V to IV (at 60 cm depth). There was a sharp decrease in the relative percentages of *Fragilaria brevistriata*, *F. pinnata* and *F. construens* (which were the most abundant species), and a concomitant increase in relative percentages of *Epithemia adnata*, *Mastogloia smithii var. smithii* and *Gyrosigma acuminatum*. In addition an increase in sedimentation rate was also recorded from unit V to IV (Figure 2).

The layer 56–60 cm was estimated to have an age of 1890 AD (Figure 2), and corresponds to a change in land use within the lake catchment. During the last two decades of the 19th century, soil removal began in the north section of the catchment. It was used for constructing roads and houses. This could explain the changes in lithology (Figure 2) and in diatom composition (Figure 4) observed by 60 cm depth. In addition, the high percentages of the non-carbonate inorganic fraction of the sediment in these zones (Figure 3) also indicate an increase in watershed erosion. By 1943 intensive cattle and sheep grazing had began, which, together with soil removal, might have led to gully formation in the north section of the watershed (Figure 1A), thus increasing sedimentation rate (Figure 2). However, no evidence of major changes in chemical variables related to grazing and soil removal were observed within units V and IV (Figure 3).

A further change in lithology (Figure 3) and sedimentation rates (Figure 2) were observed by 25 cm (transition between units IV and III). The non-carbon-

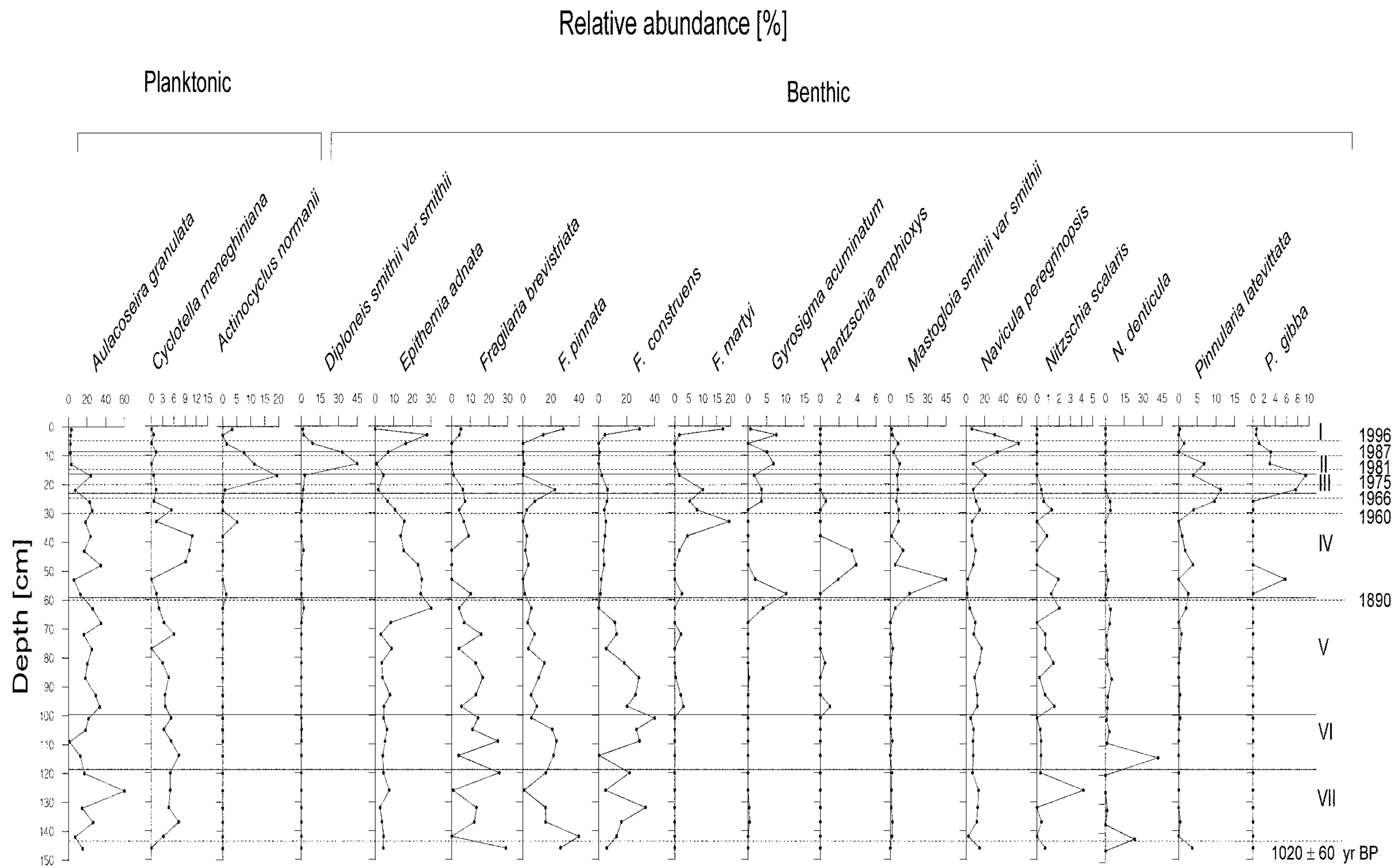

Figure 4. Relative abundances of the most common diatom taxa versus depth. Lithological units are indicated with Roman numerals. ^{210}Pb dates are presented to the right of the plot.

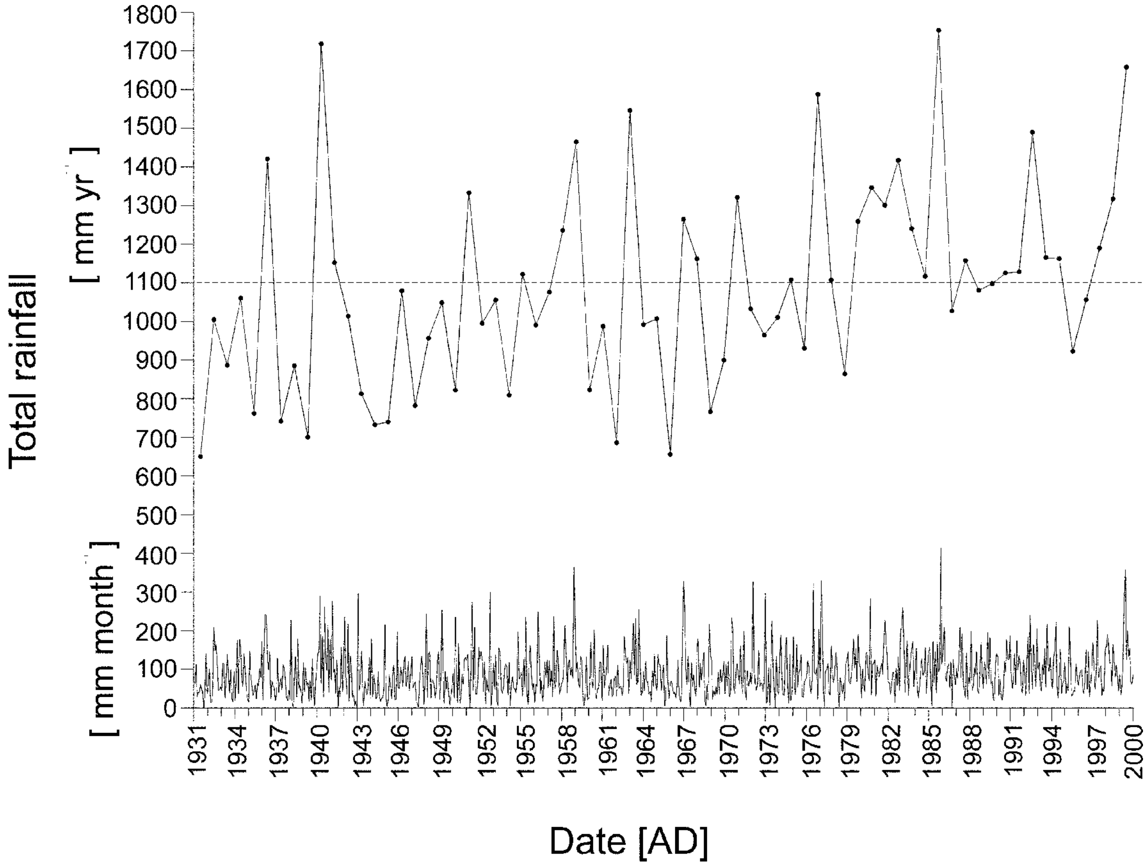

Figure 5. Monthly and annual rainfall (mm) for the Rocha station over the last 70 years. Broken line indicates long-term mean historical annual rainfall. For location of Rocha station, see Figure 1.

ate inorganic fraction of the sediment also showed a sharp decrease (Figure 3). The 27 cm depth yielded a date of 1960 AD, while the 22 cm depth was 1967 AD (Figure 2). By 1966, there was a significant change in land use within the watershed. Cattle and sheep grazing ended, the sand dune was forested with *Pinus pinaster* (Figure 1A), the gullies of the north section of the watershed were forested with *Eucalyptus* sp.

Forestry led to two major changes in limnological conditions. First, *P. pinaster* forests stabilised the sand dune which separates the lake from the Atlantic Ocean, and therefore it constituted a barrier that changed wind pattern circulation and dune movement. Consequently, the lake may have begun to stratify thermally. Littoral expansion and macrophyte invasion were observed in the aerial photograph from 1967 (Figure 1B). Second, *Eucalyptus* forestry north of the lake required fertilisation with phosphorite (National Geological Survey, pers. commun.). A standard amount of 250 kg per hectare is commonly used for such plantations in Uruguay. The permeable sandy-silty and organic-poor nature of the soils of the watershed, would have promoted phosphate leaching and transport into the lake. Furthermore, just after forestry activities began, high values of total rainfall in 1967/68 [both per year (~1200 mm) and month (~350 mm), Figure 5], contributed to phosphorite-leaching and runoff processes. This would also explain the peak of ^{210}Pb activity observed by the 22 cm depth (Figure 2), because ^{210}Pb is a daughter isotope of ^{238}U (average value in shales and sand-stones 3.5‰, Krauskopf (1982): 482), which are the predominant soils within the watershed. Therefore, the peak of ^{210}Pb would correspond to an input of ^{238}U into the lake, as natural phosphorite has average U-concentration of 120 ppm, which is 35 times higher than that of shales and sand-stones. Sedimentation rates remained fairly constant within this section (i.e., about 6 mm yr^{-1}, Figure 2), thus allowing us to use the CRS model (Appleby and Oldfield 1992). Peaks of organic matter, CO_3, total carbon, pigments and nutrients (Figure 3) were also detected in the section 20–22 cm. The increases in relative percentages of epibenthic diatoms (i.e., *Pinnularia latevittata*, *Pinnularia gibba* and *Fragilaria pinnata*, Figure 4) also indicate inputs from the catchment. Macrophyte proliferation along the lake's littoral zone is also supported by the increase in C/N ratios (close to 8, Müller and Mathesius (1999)).

The peak observed by 20–22 cm was followed by a decrease in organic matter, nutrients (Figure 3) and ^{210}Pb (Figure 2). The latter may be because once the *Eucalyptus* forests matured and grasses colonised the soils, phosphorite-rich soils were fixed, and inputs from the watershed may have decreased. In addition, low values of total rainfall were recorded in 1969/70 (Figure 5). Both CO_3 and pigment content (Figure 3), as well as the relative percentages of *Aulacoseira granulata* and *Actinocyclus normanii* (Figure 4), displayed a further peak by 17–18 cm, which may suggest phytoplankton blooms. From 18 cm to surface, planktonic diatoms accounted for $<14\%$ (Figure 4), and the lake was dominated by epibenthic diatoms.

From the middle of unit II to the surface (after *ca* 1985) corresponds to the period of tourist and urban development. During the past 15 years, many houses and holiday resorts were built close to the shore of the lake. Human impacts such as sewage and garbage disposal probably occurred, as reflected by changes in chemical variables (Figure 3). By ~1986/87 a strong eutrophication event was detected (Figure 3), as reflected in maximum peaks of organic matter and pigments. This could have been a consequence of increased total rainfall (Figure 5), as the maximum value, both per month (~400 mm) and per year (~1700 mm), was observed in 1986. Increases in sedimentation rates were observed in unit II (after 1975 and before 1987, Figure 2). The high values of the non-carbonate inorganic fraction of the sediment (Figure 3) also indicate erosion in the watershed. This could be explained by the high values of total rainfall (Figure 5), because, except for 1979, higher values than the historical average were observed. Furthermore, in 1986 the highest total precipitation [per month (~400 mm) and per year (~1700 mm)] were observed. After 1987, rainfall decreased (Figure 5) and a lower sedimentation rate (Figure 2) was observed.

The last eutrophication episode in the lake's history was in 1997/98. Severe drought and high water consumption reduced lake area by about 30%, so drinking water could no longer be withdrawn. In addition, low values of total rainfall registered in 1996/97 (Figure 5) contributed to a decline in lake surface area. Since 1998, total rainfall values increased contributing to lake refilling. The high sedimentation rate observed in this section (~9 mm yr^{-1}), may be due to increases in total rainfall since 1998 (Figure 5), and lake refilling. After the lake re-filled, phytoplankton blooms occurred, as indicated by the peak in pigments just below the sediment surface (Figure 3). Authorities in charge of producing drinking water observed that the water had very low transparency. However, the high pigment values below surface may be due to a diagenetic artefact. Low percentages of planktonic diatoms below the sediment surface indicate that these diatoms probably did not bloom. Instead, blooms of other microalgae probably occurred. Phytoplankton blooms were followed by explosive proliferation of *Egeria densa* (*ca* 30% of the lake surface, Figure 1C). This macrophyte may explain peaks of organic matter just below the sediment surface.

Summary

Although our paleolimnological data cannot identify all possible causes for environmental changes, we note shifts in chemical variables and diatom composition that coincide with changes in land use within the watershed and rainfall data. Three main stages in Lake Blanca's history were identified. The first, from 150 to 117 cm (lithological unit VII), was characterised by high values of organic matter, total carbon and nutrients, but low concentrations of pigments. The system may have had high transparency (i.e., mesotrophic conditions) and well oxygenated bottom waters, thus leading to poor fossil pigment conservation (Leavitt 1993). Both macrophytes and epibenthic diatoms were the most important contributors to primary production. During the second stage (lithological units VI, V and IV), all measured variables showed low values, and the non-carbonate inorganic fraction of the sediment accounted for more than 90% of the sediment mass. Sedimentation rates increased from unit V to IV because of soil removal and grazing in the watershed. Water transparency should have been high enough to impede fossil pigment preservation before permanent burial. The most recent stage (lithological units III, II and I) began by the middle 1960s with the end of cattle grazing, beginning of forestry, and drinking water withdrawal, at which time the system started to increase in trophic state. This situation worsened between 1998 and 2000, because of lake area reduction. Drinking water could no longer be removed, because of phytoplankton blooms and the proliferation of *Egeria densa* along the shoreline. A recent study (Mazzeo et al. 2001) determined that *Egeria densa* should not be removed from the lake, because phytoplankton and macrophytes compete for nutrients, and macrophyte removal may lead to further phytoplankton blooms (Carpenter and Pace 1997; Scheffer 1998; Scasso et al. 2001).

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