The last two centuries of environmental history in Picos de Europa National Park as assessed from sediments of a mountain lake (Lago Enol, N Iberia)

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Abstract

We present a multi-proxy study of two short sediment cores recovered in Lago Enol located in the Picos de Europa National Park (Cantabrian Mountains, North of Iberia), based on the integration of geochemical and biological (pollen and diatoms) proxies in a ^{210}Pb chronological framework together with the temperature and precipitation reconstruction using instrumental data collected since 1871 in several meteorological stations in N Iberia. The record provides evidence of environmental changes during the last 200 years. During the end of the Little Ice Age (~1800-1875 AD) this region was characterized by an open landscape. Long-term use of the area for mixed livestock grazing in the mountains, and cultivation of rye during the 19th century contributed to the expansion of grassland at the expense of forest. After this period the lake responds to warmer temperatures since the end of the 19th century with a change in the diatom assemblage, and the development of the native forest. Socioeconomic transformation during the 20th century, such as changes in the type of livestock related to a dairy specialization, afforestation with non-native tree species, mining activities, and the park management since the creation of the National Park in 1918, caused profound changes in the catchment area and in the lake ecology. The last years (~1970-2007 AD) recorded in Lago Enol sediments are strikingly different from previous periods, indicating lower runoff and increasing lake productivity, particularly since 2000 AD. Nowadays, the increase of visitors to the lake area appears to be one of the most important impacts in this ecosystem.

Keywords Picos de Europa National Park, Anthropogenic impact, Little Ice Age, Geochemistry, Pollen, Diatoms.

Introduction

Reconstructing recent environmental changes, whether triggered by climate shifts and/or human-induced changes, is required for deciphering the importance of those changes as forcing drivers of the present environmental conditions. Particularly important for contextualizing the impact of recent anthropogenic activities and global warming observed during the 20th century is the need to extend the geographic coverage of the recent high-resolution paleorecords. The Iberian Peninsula is located in a region at risk regarding future impacts of global warming (IPCC 2007), so performing high-resolution environmental reconstructions of last centuries is an interesting and necessary topic.

In fact, several climate reconstructions have been done during the last decades in different areas of the Iberian Peninsula using different methodologies. Agustí-Panareda and Thompson (2002) reconstructed the temperature of two Spanish alpine lakes located in the Pyrenees and Gredos Range from 1781 to 1997 AD using long instrumental climate records in lowlands and correcting them with vertical temperature gradients. In the Pyrenees, performing a tree-ring research, Büntgen et al. (2008) reconstructed summer temperature variations of the last millennia. In the Xistral Mountains and using geochemical data, Martínez Cortizas et al. (1999) inferred the temperatures for the last millennia in NW Iberia. Multi-proxy studies have also been developed in Iberia covering the last centuries, such as Zoñar Lake in southern Iberia (Martín-Puertas et al. 2008), Estanya Lake in the Pre-Pyrenees (Morellón et al. in press), and Taravilla Lake in the Iberian Range (Moreno et al. 2008), among others. All these studies detected the cold Little Ice Age (LIA) phase and the current climate warming trend. The transition from the LIA to the observed warming trend of the 20th century is also shown in the Spanish Temperature Record (Brunet et al. 2007), which estimates the observed temperature change from 1850 to 2005 over mainland Spain.

But climate variability is not the only variable shaping the environmental conditions, so especial emphasis has to be done identifying human disturbances, being the last centuries a period with a strong increase of anthropogenic activities. In this sense, knowledge of past land use is essential to understand the relationship between human activities and environmental variables in order to underpin strategies to properly manage natural areas. In our study zone, the creation of the National Park had profound implications in shaping the landscape of this area. Since the creation of Covadonga National Park in 1918 -the first one in Spain- there have been different stages of conservation management policies. According to García Dory (1977), the history of the National Park can be divided in three periods, and a fourth period is detected during the last decades. The first one covers the years 1918-1936, since the establishment of the Park to the start of the Spanish Civil War. In this period some measures of protection were adopted, which prohibited the exploitation of several natural resources, i.e. mineral and timber. The second period coincides with the Civil War (1936-1939), and witnessed a great reduction of fauna, including bear, wolf, chamois, bearded vulture and golden eagle. The third period covers General Franco's Dictatorship (1939-1975), characterized by the increasing human activities allowed within the Park, i.e. opening of mines, exploitation of water and timber resources, expansion of non-native plantations, and the promotion of tourism. The last period from 1975 to 2007 saw some conservation procedures implemented, i.e. reforestation with native species. In 1995 the Spanish authorities expanded the boundaries of Covadonga National Park to create the current Picos de Europa National Park (PENP). Tourism in the area remains very important today, and hampers further conservation policies (Suárez Antuña et al. 2005).

Thus, acquiring new information about the long-term environmental changes, both climate- and/or human-induced, in protected areas such as PENP will be crucial to develop new conservation strategies. However, due to the strong human-environment interaction during the last centuries, it is not easy the separation of climate and anthropogenic influences on the available proxy records. This makes disentangling the main forcing mechanisms that trigger the environmental lacustrine changes especially challenging.

This study provides an environmental reconstruction based on the paleolimnological study of short sediment cores from Lago Enol covering the last 200 years and the instrumental data of temperature and precipitation collected since 1871 in several meteorological stations in N Iberia. We have followed a multi-proxy strategy, including sedimentological, geochemical and biological (diatoms and pollen) proxies, with the objective of detecting environmental changes acting on the environment of Lago Enol during the last two centuries.

Study area and site characteristics

Lago Enol (43º16'N, 4º59'W, 1070 m asl; Fig.1A) is located in the western Massif of the Picos de Europa Mountains, in the eastern Cantabrian Mountain Range (N Spain), and included in a protected area established as a National Park since 1918 AD. Lago Enol has a water surface area of 12.2 ha and a maximum depth of 22 m and its small watershed (1.5 km^2) is located over Carboniferous formations. The lake is fed by laminar (unconfined) runoff but groundwater inputs and outputs are key factors to the hydrological balance. The lake is monomictic, with waters characterized as oligotrophic (8 µg Total Phosphorous, TP L^{-1} ; Velasco et al. 1999), although no information has been collected for the last decade and the TP value corresponds to a single measurement in June 1992. Lake waters are moderately hard (alkalinity 2.4 meq l^{-1}; 29 mg Ca l^{-1}) and carbonate and calcium-rich ($[HCO_3^{2-}] > [Ca^{2+}] > [SO_4^{2-}]$) with a conductivity of 202 µS cm^{-1} (Moreno et al. 2010). $\delta^{18}O$ and $\delta^{13}C$ (in dissolved inorganic carbon, DIC) isotopic ratios measured during summer 2007 and winter 2008 do not show high variability through the water column and are indicating dilute waters in both seasons (averaged values of -7.01‰ and -6.58‰ for $\delta^{18}O$ and -10.23‰ and -6.9‰ for $\delta^{13}C$ (DIC), in summer and winter respectively).

The climate of the study area is oceanic, characterized by high annual precipitation (>1000 mm) that occurs mostly in late autumn and early winter, associated with mid-latitude storms from the Atlantic Ocean. The annual average temperature is 13°C. In terms of vegetation, the study area is located within the biogeographical Eurosiberian region, dominated by deciduous forest with *Quercus robur, Betula alba, Corylus avellana, Fraxinus excelsior, Alnus glutinosa* and *Acer* sp., together with scrubland of Ericaceae and Fabaceae within Poaceae pasturelands. Small patches of Mediterranean formations with mainly evergreen *Quercus, Olea europaea*, etc., are also present in sunny and sheltered areas. During pre-historical and historical times, the watershed and the wider region have been subjected to intense anthropogenic activity, leading to deforestation and resulting in a landscape of alpine pasturelands (Montserrat and Fillat 1990).

Material and methods

Core retrieval and analysis

Two short cores were retrieved from Lago Enol in July 2007, using a UWITEC gravity corer (Fig. 1B). The cores ENO07-1A-1M (31 cm long) and ENO07-1C-1M (38 cm long) were obtained from the deepest central area of the basin. Core ENO07-1A-1M was sub-sampled in the field every 1 cm for ^{210}Pb analyses by gamma ray spectrometry performed at the St. Croix Watershed Research Station (Science Museum of Minnesota, USA). The remaining sediment was stored and later prepared for diatom analyses and for carbon content. The TC, TS and TOC were analyzed with a LECO 144DR elemental analyser. TIC values were obtained by subtracting TOC values from corresponding TC values. The second core, ENO07-1C-1M, was split longitudinally and sampled at 2 cm intervals for pollen and carbon content analyses. The archive half-core was measured at 1-mm resolution for major and trace elements (Si, K, Ca, Ti, V, Cr, Mn, Fe, Rb, Sr, Y, Zr, Ba and Pb) using a ITRAX XRF core scanner (Duluth Large Lakes Observatory, University of Minnesota, USA) with a 30 seconds count time, 30 kV X-ray voltage and an X-ray current of 20 mA. Only significant elements are selected based on their intensity, together with the incoherence/coherence ratio. The ratio is a measure of the relationship between the incoherent scatter from the Mo tube (Compton scattering or inelastic scattering) and the coherent scatter (Raleigh scattering or elastic scattering), i.e. an indicator of the primary radiation from the X-ray tube that is scattered in the sample and thereby affected by the sample composition (Croudace et al. 2006). In some sediments, the inc/coh ratio serves as a measure of the organic content (Sáez et al. 2009).

A total of 27 samples were taken from the core ENO07-1A-1M and processed for diatom analysis. Diatom slides were prepared following standard procedures (Battarbee et al. 2001) and at least 400 diatom valves were counted per slide. Counting was performed on random transects, and taxonomic identification followed standard flora classification (Krammer and Lange-Bertalot 1986-1991; Lange-Bertalot and Metzeltin 1996). Diatom zones were constructed on the basis of stratigraphically constrained agglomerative cluster analysis (CONISS, Grimm 1987), after the square root transformation of the data. The diatom diagram was prepared using the computer software package C2 version 1.5 (Juggins 2007). A Principal Component Analyses (PCA) was carried out to explore the main gradients of community variation and to infer the main factors influencing the sediment core diatom assemblages through time. An exploratory Detrended Correspondence Analysis (DCA) revealed a gradient length <2 sd units indicating that the PCA was appropriate. Data were square root transformed and PCA analysis was performed on the co-variance matrix and undertaken using the CANOCO version 4.5 (ter Braak and Šmilauer 2002). Only taxa with an abundance >1% in at least one sample was included in the analysis (17 taxa).

A total of 19 samples were analyzed palynologically from ENO07-1C-1M core. The classic chemical methodology based on Moore et al. (1991) was applied to obtain pollen and non-pollen palynomorphs (NPP), with concentration in dense liquid (Goeury and Beaulieu 1979). The pollen sum was around 500-600 palynomorphs, excluding hydro-hygrophytes and NPP and expressed as percentages of the pollen sum. Palynological identification and counting was aided by the reference collection of the Laboratory of Archaeobiology at the CCHS (Madrid). Pollen diagram was drawn using Tilia 2.0 and TGView programs (Grimm 1992, 2004). Pollen zones were constructed on the basis of agglomerative cluster analysis (CONISS) (Grimm 1987).

Temperature and precipitation data

In order to develop regional temperature and precipitation time series representative of the climate variability over the central Cantabrian region, a dataset of raw monthly maximum and minimum temperature and precipitation records was selected and compiled from the Spanish Climatological Bank at the Agencia Estatal de Meteorología (AEMET). The rationale for selecting the network (Fig. 1C) was based on the temporal and spatial coverage, long-term records, data completeness and potential data quality. The dataset is composed of twenty-five monthly precipitation and thirteen monthly temperature long records. An extra set of five daily adjusted temperature time series from the Spanish Daily Adjusted Temperature Series (SDATS) developed by Brunet et al. (2006, 2008) have been used in order to optimize the homogenisation process, but are not included either in the analysis or in the development of the regional series. The modified data were quality controlled following the procedures recommended by Brunet et al. (2008). The Regional Central Cantabrian precipitation and temperature time series for the period 1871-2007 were created by averaging monthly anomalies and then adding back the base-period mean (1961-1990), following the method of Jones and Hulme (1996) of separating climatological values into its two components: the climatology and the anomaly. To account for the variance bias present in regional time series, associated over time with varying sample size, the Osborn et al. (1997) method has been applied to the regional time series. Linear trends fit over the entire period and several subperiods have been calculated on an annual basis by using the nonparametric Mann-Kendall test (Kendall 1976) and adapting Sen's (1968) estimator of the slope.

Results

Chronology and cross-dating

Dating of the Lago Enol sediments was based on ^{210}Pb measurements in core ENO07-1A-1M. Total ^{210}Pb activity in core ENO07-1A-1M was relatively high with near-surface values of 10-12 pCi g^{-1}. Supported ^{210}Pb was estimated at 1.8909 ± 0.0395 pCi g^{-1} (Fig. 2A). Constant rate of supply (CRS) modelling of the ^{210}Pb profile gave a lowermost date of ~1840 AD (± 27 years) at 20 cm (Fig. 2B). In the absence of other reliable chronological information we extrapolated the average sedimentation using the cumulative dry mass to ~1800 AD at 23 cm. Thus, from core ENO07-1A-1M we discuss the data of the period ~1800-2007 AD. The sediment accumulation profile displayed low Sedimentation Accumulation Rate (SAR) up to ~1930 AD, a rising trend with a sharp increase after ~1960 AD, highest values around ~1970-1980 AD and a small decline afterwards (Fig. 2C).

The two sediment cores provide very similar geochemical signatures and comparable total carbon. This similarity enabled correlation between cores and application of the chronology established for ENO07-1A-1M to the adjacent core ENO07-1C-1M (Fig. 3). Four tie points were obtained from the detailed correlation of the two carbon records and transferred to ENO07-1C-1M (grey arrows in Fig. 3). The first tie point lies in the transition towards minimum organic carbon values; while the second tie point is the minimum value. The third tie point indicates the maximum of organic values and the fourth tie point was the following minimum value. The age model for ENO07-1C-1M is a 200 yr-long sequence too, from ~1800 AD to 2007 AD (Fig. 3).

Sedimentology and geochemical content

Both short cores were composed of brown to dark-brown, massive to faintly banded carbonatic silts to silty-sands (up to 60% carbonate content) with abundant amorphous organic matter (25%) and siliciclastic particles (up to 20%), mainly in the clay fraction. Elements such as Si, Ti or Fe are enriched in the clay fraction while Ca is present in calcite (Fig. 3). The sedimentary units have been defined following compositional criteria, mainly the organic and inorganic carbon content and the amount of the siliciclastic fraction. Three sedimentological units were defined for the last 200 years (Fig. 3). Below these units, an interval of 10 cm in ENO07-1A-1M core is characterized by the highest values in total (6-10%), organic (4-8%) and inorganic (2%) carbon but the chronology cannot be precisely established because of an extrapolation of ^{210}Pb model would include an error of more than ±30 years. Unit 3 (~1800-1875 AD) represented contrasting conditions to the basal sediments since it is defined by the minimum values in total (4-6%), inorganic (1-1.8%) and organic (3-4%) carbon. Ca counts reached the minima while Si, Ti and Fe values were the highest of the sequence pointing to the presence of organic-poor, siliciclastic sediment. After this minimum in organic matter and carbonates, there was a clear trend towards higher values of both inorganic and organic carbon and steadily decreasing Si, Ti and Fe values along Unit 2 (~1875-1970 AD). Unit 1 (~1970-2007 AD) is characterized by increasing organic and decreasing inorganic carbon for the first time in the sequence (Fig. 3): organic matter increased while there was a decrease in Ca values. Unit 1 was also marked by an increase in Fe that is usually related to increase in bottom-water oxygen content that allow fixation of Fe forming oxides (De Lange et al. 1994).

Diatoms

In ENO07-1A-1M core of Lago Enol, the diatom assemblages are characterised by the high abundance of planktonic taxa present throughout the last 200 years with low levels of benthic diatoms. Most common diatom taxa are plotted stratigraphically in Figure 4. Three diatom zones (DAZ) have been identified.

DAZ-3 (23-19.5 cm, ~1800-1850 AD): This diatom zone is characterized by the dominance of planktonic *Cyclotella ocellata* Pantocsek. However, the assemblage is characterized by its gradual decrease and a concurrent increase in the benthic species abundances, primarily small Fragilarioid species.

DAZ-2 (19.5-9.5 cm, ~1850-1965 AD): Diatom assemblages in this zone are characterized by the high abundance in Fragilarioid taxa while the planktonic *C. ocellata* experiences a steady increase in abundance from ~20 to 60% at the top of the zone.

DAZ-1 (9.5-0 cm, ~1965 AD-present): The uppermost diatom zone is characterized by the most substantial shifts in diatom composition along the record. This zone is initially characterized by the demise of *Cyclotella ocellata* and the rise of the also planktonic *Cyclotella radiosa* (Grunow) Lemmermann. The last 10 years are characterized by a further increase in Fragilarioid species, concurrent with the virtual disappearance of *Cyclotella* species. Changes in the abundance of benthic *Cavinula scutelloides* (W.Smith) Lange-Bertalot and *Naviculadicta vitabunda* (Hustedt) Lange-Bertalot are also noticeable, increasing and peaking at the top of the core.

The samples scores on PCA-axis 1 and axis 2 are also plotted stratigraphically in Fig. 4. High sample score values on axis-1, which explains 47% of the variance, are positively associated with species such as *Cyclotella ocellata*, while low sample scores are negatively associated with *Staurosira construens* var. *construens*, *Cyclotella radiosa* and *Naviculadicta vitabunda* (Table 1). Axis-1, therefore, appears to reflect a trophic status gradient, and contrasts assemblages typical of oligotrophic conditions with those of more nutrient rich conditions. On axis-2, which explains 17% of the variance, high sample scores are associated with *Staurosirella pinnata*, *Cavinula scultelloides* and *Naviculadicta vitabunda*, while low sample scores were associated with species such as *C. radiosa* and *C. ocellata* (Table 1). High samples scores on axis-2 are most strongly correlated to plankton: periphyton ratio. Axis-2 hence appears to be a gradient of littoral development, and contrasts benthic species to species associated with pelagic habitats. Over the length of the Enol core, PCA1 shows the most striking changes occurring at ~20 cm while PCA2 shows the largest change occurring at ~3 cm (Fig. 4). The pronounced and clear shift in diatom community composition at DAZ-1 is represented by the sudden increase in PCA2 (at ~3 cm) while PCA1 remains stable. This change is related to the sudden increase in small productive benthic Naviculoid taxa (Fig. 4).

Pollen and non-pollen palynomorphs

Two main pollen zones (PZ) were distinguished in ENO07-1C-1M. Each pollen zone could be divided into two distinct pollen sub-zones (Fig. 5).

PZ-2 (38-22.5 cm, ~1800-1905 AD): This pollen zone is characterized by the lowest tree percentages of the sequence (<35%) indicative of a regional landscape characterized by open vegetation dominated by herbs. During the sub-zone PZ-2B (38-28.5 cm, ~1800-1875 AD) the tree component (~20%) principally consists of mesophilous taxa (deciduous *Quercus*, *Fagus*, *Corylus*, *Castanea*, *Betula* and *Alnus*). *Pinus* also appears, mainly *Pinus sylvestris* type, with low but constant percentages, as well as some thermophilous elements such as evergreen *Quercus* and *Olea europaea*. The shrub component is not well developed (<10%). Herbaceous elements are dominated by Poaceae, *Plantago* and Compositae. Some nitrophilous taxa such as *Rumex acetosella* and *Urtica dioica* also appear. Rye pollen (*Secale cereale*) is present. Hydro-hygrophytes are well represented with Cyperaceae, ferns and *Ranunculus*. *Botryococcus* has relatively low values. Among the other NPP the most important feature is related to the presence of coprophilous fungi such as *Sordaria*, *Podospora* and *Sporormiella,* and the occurrence of chlamydospores of *Glomus*. During the sub-zone PZ-2A (28.5-22.5 cm, ~1875-1905 AD), a slight increase of the tree percentages (35%) is observed, as both mesophilous (deciduous *Quercus*, *Fagus*, *Corylus*, *Castanea*, *Betula* and *Alnus*) and thermophilous (evergreen *Quercus* and *Olea europaea*) taxa increase. Consequently, herbaceous percentages decrease, mainly Compositae, while Poaceae and *Plantago* still remain important. *Secale cereale* is also detected. The hydro-hygrophytes, coprophilous fungi and *Glomus* maintain their presence in this sub-zone while *Botryococcus* percentages increase.

<u>PZ-1 (22.5 cm-top, ~1905 AD-present)</u>: This pollen zone is characterized by higher tree values (>40%) than in the previous zone. Sub-zone PZ-1B (22.5-10.5 cm, ~1905-1970 AD) shows an increase of the tree values to 40-50%, which could be attributed to two paralell processes. One of them, and similar to PZ-2A, is the increase of meso-thermophilous taxa; and the other one is the regional afforestation with non-native species of *Pinus* (Other *Pinus* in Fig. 5) and *Eucalyptus*. Herbaceous taxa percentages decrease although Poaceae remains relatively high (~20%). *Rumex acetosella* increases but *Plantago* and Compositae decrease. The lower values of the hydro-hygrophytes are also notable. Coprophilous fungi and *Glomus* percentages decrease or even disappear in the sub-zone. *Botryococcus* increases significantly at the beginning of PZ-1B. Finally, sub-zone PZ-1A (10.5-top, ~1970 AD-present) is very similar to the previous one although there are higher percentages of deciduous *Quercus* and the expansion of *Cytisus/Ulex* is evident. Finally, hydro-hygrophytes increase while *Botryococcus* is less abundant.

Climate data

Statistically significant warming of about 0.55ºC is evident in the regional temperature time series over the last 137 years (Fig. 6). However a period of decreasing and/or stagnant temperatures (1960-1973 AD) is evident. The most striking feature of the data is the recent warming period (1973-2007 AD), as it has seen the highest increase (0.29ºC/decade at α=0.01 level of significance); whereas during the first warming phase (1880-1960 AD), the trend was much lower (0.11ºC/decade at α=0.05). In the period 1960-1973 AD the trend was -0.29ºC/decade, but this was not statistically significant. These sub-periods were determined by visually inspecting the annual Gaussian low-pass filter of 13 terms (not shown) and they are consistent with the findings of Brunet et al. (2007) for mainland Spain and with the general pattern shown by Northern Hemisphere temperature reconstructions (Jones and Mann 2004).

Trend estimation and inspection of the interannual evolution of the developed Regional Central Cantabrian precipitation anomaly series show, first, two distinctive periods characterised by increasing and decreasing trends: a significant (α=0.01) increase (16.9 mm/decade) in precipitation for the period 1871-1976 and a decreasing, but not significant, trend from 1977 to 2007. Second, it also shows the corresponding interannual variability characterising the Atlantic/Oceanic/Asturias-Cantabrian climate type (de Castro et al. 2005), in which there seems to be some sort of cyclicity apparent during the first increasing period and absence during the recent decreasing period in precipitation. Another striking feature is the contrasting trends in the precipitation and temperature data post-1977 AD, in which the observed warming is accompanied by a decrease in precipitation.

Environmental changes in Picos de Europa National Park during the last 200 years

The end of the LIA is commonly located around the second half of 19th century (i.e. Jones et al. 2001; 2009). During the last phase of the LIA (~1800-1875 AD), palynological data reflect a landscape characterized by open vegetation. The low percentages of thermophilous elements, such as evergreen *Quercus* or *Olea europaea*, point to a consequence of the cold conditions associated with the end of the LIA (Fig. 5). However, they can also be the consequence of intense human activities near the site. In fact, palynological data, i.e. coprophilous fungi, indicated the presence of livestock in the study area since the beginning of the sequence. In an area intensely modified by human activities such as Picos de Europa, it is very difficult to attribute environmental changes detected in the landscape definitively to climate or anthropogenic causes. Therefore, although the interplay of climate and human influences on the landscape is evident, discriminating the importance of both factors for that time period remains unsolved.

After the end of this phase, the tendency towards an increase of the temperatures in the second half of the 19th century reconstructed from instrumental records. In fact, there is a statically significant warming phase during 1880-1960 AD with an increase of 0.11ºC/decade (Fig. 6), trend also found in other climate series (Agustí-Panareda and Thomposon 2002; Büntgen et al. 2008). This trend is also reflected in the geochemical data with steady increase in both organic and inorganic carbon during Unit 2 (Fig. 3). At this particular lake site, since the carbonate found in the sediments is mostly detrital, low rainfall resulted in decreased delivery of sediments from the catchment, which is dominated by limestones while cold climate will be conducive to lower lake productivity. Both are climatic parameters that decrease the amount of organic matter (terrestrial and aquatic) in the sediments (Moreno et al. in press). Therefore, carbonate is considered here a proxy for erosion processes while organic matter points to the combined effects of erosion and lake productivity (Fig. 3). In addition to the carbon content, the recovery of the native forest in meso-termophilous taxa during ~1875-1905 AD (PZ-2A, Fig. 5) is another indicator of improved temperatures. The recovery of the native forest continued during ~1905-

1970 AD (PZ-1B), but non-native species such as *Pinus* (other *Pinus* in Fig. 5) and *Eucalyptus* also increased during that period. Thus, the first arboreal expansion immediately after the LIA was a reflection of the climate improvement detected in the instrumental record and geochemical features. Nevertheless, the second arboreal expansion during ~1905-1970 AD, when both native and non-native species increased their values, was more related to the creation of the National Park in 1918 AD and the well-known regional afforestation with pines and eucalypts.

The most important change detected in the Lago Enol palynological record during last 200 years was related to pastoral activity. Shepherding has been, and it continues being, one of the main economic bases of the Cantabrian region (Dominguez Martín and Puente Fernández 1995; Mayor López 2002). Indicators of this activity have some differences when comparing the 19th and the 20th centuries. During the 19th century coprophilous fungi were very abundant. On the contrary, during the 20th century, although anthropozoogenous taxa remained important, coprophilous fungi presence was greatly reduced (Fig. 5). This contrasting pattern is related to widespread transformation in the type of livestock during the 20th century in the Cantabrian Mountains. The change is linked to dairy specialization, consisting of the replacement of native cattle, mostly used for meat, by other breeds that are major producers of milk (Suárez Antuña et al. 2005). Another important transformation was the decline in minor livestock (sheep and goats). The new introduced breeds spent long periods housed in the valleys and not grazing in the mountains (Rodríguez Castañón 1996; Suárez Antuña et al. 2005) and this probably lead to the reduction of coprophilous fungi and the expansion of Atlantic bushes of *Erica* and *Cytisus/Ulex*, as the high-altitude pasturelands have been partially abandoned (Rodríguez Castañón 1996).

Together with pastoral activity, cultivation of *Secale cereale* is another indicator of anthropogenic activity. Besides, *Eucalyptus* was planted in the second half of the 19th century in NW Iberia as an ornamental and decorative tree (Sande Silva 2007), but the first appearance in the Lago Enol record is during the 20th century, reflecting the period of more extensive cultivation.

It is interesting to point out the alternation between rye and eucalypt crops during the 20th century indicating changes in land use (Fig. 6).

Concerning hydrological conditions, the higher values of *Botryococcus* between ~1875 and 1970 AD (Fig. 5) may point to environmental fluctuations. Changes in *Botryococcus* values have been related to changes in water levels (i.e. Carrión 2002; Sáez et al. 2007), nutrients and temperature (i.e. Rull et al. 2008; Huber et al. 2010). According to the instrumental record, this period was characterized in this region by a generally warm climate and an increase in precipitation (Fig. 6). Therefore, it was possible that both higher temperatures and precipitation had an impact on Lago Enol limnology leading to an increase in *Botryococcus* percentages. However, it is also possible to ascribe the changes in this chlorophyte to enhanced nutrient enrichment in Lago Enol as a consequence of anthropogenic disturbances in the landscape. Similarly, diatom changes during this period (DAZ-2: ~1850-1965 AD), particularly the increase of Fragilarioid taxa while planktonic species diminished (Fig. 3), could also be linked to both climate and/or human impact. Fragilarioid species are related to high lake water alkalinity, with relatively high optima to limnological variables related to ionic composition, i.e. conductivity, alkalinity, DIC, concentration of major ions, etc. In mountain lakes, the increase in alkalinity has been essentially attributed to the reduction in the renewal rate of the basin water (Schindler et al. 1990) and to the increasing weathering of easily soluble salts such as calcium and magnesium sulphate from the catchment basin, due to increasing temperature and reduced snow cover (Rogora et al. 2006). Therefore, these changes can be attributed mainly to the effects of climate warming and/or modifications in the lake level and the lake-water residence time. Additionally, human impact on the lake catchment may not just modify catchment hydrology but could also influence biogeochemical processes such as rates of mineral weathering, dissolved organic carbon production, and nutrient and alkalinity generation. The systematic exploitation of Buferrera mine (north of Lago Enol, Fig. 1A) began in the 1870s finishing mostly in the 1930s although some work was still carried out until the 1950s or even the 1970s (Rodríguez Terente et al. 2006). Although, mining activities did not develop principally within the lake catchment, the waters of Lago Enol and nearby Ercina were used to produce power, likely affecting their hydrology, i.e. a 1.5 m tall dike was built at one end of Ercina Lake to create a reservoir, thereby doubling the original size of the lake. The workforce changed over time, reaching approximately five hundred workers in the late 19th century and during the summer seasons. Since part of the water inputs into Enol are from underground waters, a direct impact of mining on Lago Enol water quality and water levels is possible. Accordingly, considering the observed changes in diatoms and *Botryococcus* during last half of the 19th century and first half of the 20th century, we propose that variability in the Lago Enol record is also connected with the exploitation of Buferrera mine. Thus, the changes in the biological communities could be a consequence of climate improvement detected in the instrumental record but could also result from catchment disturbance related to mining activities. Again, this observed variability in the Lago Enol record highlights the concomitant influences of both climate and human factors.

According to the instrumental record, after the short period of stable or slightly decreasing temperatures (1960-1973 AD), temperature increases with a trend of 0.29°C/decade during 1973-2007 AD and precipitation diminishes since 1976 AD (Fig. 6). This last period in the Lago Enol record is clearly differentiated by the hydrological and limnological indicators. Thus, DAZ-1 (~1965-2007 AD) is initially characterized by the demise of planktonic *Cyclotella ocellata* and the rise of *Cyclotella radiosa* (Fig. 4), which has a higher optimum for silica than *C. ocellata*. In the EDDI combined TP dataset *C. radiosa* is found in meso- to eutrophic lakes and has an optimum for TP of ~27mg L^{-1}. Maximum abundances of *C. radiosa* are coincident with the highest precipitation. *C. radiosa* is a species which blooms preferentially in late-summer at the onset of the autumn circulation period (i.e. Morabito et al. 2002; Kienel et al. 2005). Its development suggests higher nutrient concentration and turbulence during the late-summer and autumn. This was possibly related to a more intense mixing period during this time interval. The subsequent decrease in rainfall would have reduced inputs of nutrients into the lake and, thus, leading to the decline in *C. radiosa* populations. Similarly, depletion of nutrients during summer stratification is likely to be stronger and longer with the recent warming trend. Under these circumstances, in low productive temperate lakes such as Enol the mid-summer phytoplankton maximum will be reached earlier, during spring, depleting the lake of nutrients during the summer period and limiting the development of *C. ocellata*. A second phytoplankton peak would take place later associated to the autumn overturn, enabling *C. radiosa*, a late-summer blooming species, to thrive during the autumn overturn. Consequently, longer growing seasons will eventually lead to a reduction in *C. radiosa* abundances. Both lake processes can also be responsible for the shift in the diatom community experienced in Lago Enol in last decades and would decrease the ability of *Cyclotella* spp. to survive and grow in the water column (Reynolds 2006).

Divergent trends in organic and inorganic carbon for the first time at the end of the sequence suggest a change in depositional environmental dynamics. One possible factor could be the reverse pattern of regional precipitation (decrease) and temperature (increase) reconstructions since 1973 AD to present-day (Fig. 6). The observed tendency towards less precipitation in the area may have resulted in lower erosion and lower delivery of detrital carbonate in the lake. Lower sediment accumulation rates were detected for this period (~1980-2007 AD; Fig. 2C) supporting this interpretation. On the other hand, recent higher values of organic carbon would be in association to increasing lake benthic bioproductivity. In addition, the increase of the Fe, and particularly the Fe/Ti ratio, at the top of the sequence points to an increase of phosphorus that would be trapped from the water column into the sediments (Fig. 3). Low numbers of planktonic diatoms and increasing abundance of benthic species may be related to low water levels. However, water transparency can increase as a result of the reduced weathering limiting catchment inputs into the lake thus favoring periphytic diatoms even under deep water conditions.

In contrast to these important changes detected in the diatoms and in the dynamics of the depositional environment, the palynological spectra show a relatively well-established forest since ~1920 AD. The stability of the forest is likely more related to anthropogenic factors, especially to several conservation policies in the PENP. Thus, the top samples of the Enol record show a decrease non-native species indicating that recent park management policies aim to preserve and restore native forest (Fig. 5).

Diatom assemblages switch to primarily benthic production for the last ten years, reflecting better light conditions and/or a predominantly littoral system. The increase of Naviculoid species during last decade also indicates a change towards more productive conditions. *Naviculadicta vitabunda* and *Cavinula scutelloides* are cosmopolitan diatoms quite frequent in mesotrophic to eutrophic waters (Krammer and Lange-Betalot 1986-1991). The presence of these diatoms may be explained by the local disturbance caused by human activities, such as tourism concentrated in the lake area or the recent increase in livestock in the catchment. The number of visitors to the PENP and lakes of Enol and Ercina increased by 50% between 2003 and 2004 exceeding two million visitors in 2004 and remains at about 1.8 million visitors since then (source: http://www.mma.es). These data clearly show the high levels of human impact on the lake which puts pressure on natural resources.

It is thus difficult to determine to what extent the described changes in the ecological trajectory of Lago Enol have been affected by climate change either directly or indirectly or by human stressors. In any case, this record represents an interesting interplay of climate and human forcing in a recent period.

Conclusions

The Lago Enol paleoenvironmental reconstruction, together with the reconstructed climatic parameters throughout instrumental data, exhibited a complex pattern of climate and human impact during the last 200 years in the PENP. In fact, the present-day landscape is the result of a long-term evolution where climate process and different land uses interacted. The strong interplay between both forcing mechanisms makes it very difficult to separate the origin of some changes recorded in Lago Enol record, but it seems that the end of the LIA and the following climate improvement, the agropastoral transformations between 19th and 20th centuries, some impact of mining activities in Buferrera, and the creation and management of the National Park together with the current high human impact due to touristic activities were the main factors shaping the current landscape and lake features.

Multidisciplinary studies focusing on recent lacustrine records allow an understanding of environmental changes on the evolution of both the catchment area and the lake system. Thus, since the current state of the environment is the result of those influences, this type of study will be useful for implementing new policies of conservation within the National Park.

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References

Agustí-Panareda A, Thompson R (2002) Reconstructing air temperatures at eleven remote alpine and artic lakes in Europe from 1781 to 1997 AD. J Paleolim 28: 7-23.

Battarbee RW, Jones VJ, Flower RJ, Cameron NG, Bennion H, Calhalho L, Juggins S (2001) Diatoms. In: Smol JP, Birks HJB, Last WM (eds) Tracking environmental change using lake sediments, vol 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, 155-202.

Brunet M, Saladié O, Jones P, Sigró J, Aguilar E, Moberg A, Lister D, Walther A, Almarza C (2008) A case-study/guidance on the development of long-term daily adjusted temperature datasets. WMO-TD-1425/WCDMP-66, Geneva.

Brunet M, Jones PD, Sigró J, Saladie O, Aguilar E, Moberg A, Della-Marta PM, Lister D, Walther A, López D (2007) Temporal and spatial temperature variability and change over Spain during 1850-2005. J Geophys Res 112: D12117, doi:10.1029/2006JD008249.

Brunet M, Saladié O, Jones PD, Sigró J, Aguilar E, Moberg A, Lister D, Walther A, López D, Almarza C (2006) The development of a new dataset of Spanish daily adjusted temperature series (SDATS) (1850-2003). Intl J Climatol 26 (13): 1777-1802.

Büntgen U, Frank D, Grudd H, Esper J (2008) Long-term summer temperature variations in the Pyrenees. Clim Dyn 31: 615-631.

Carrión JS (2002) Patterns and processes of Late Quaternary environmental change in a montane region of southwestern Europe. Quat Sci Rev 21: 2047-2066.

Croudace IW, Rindby A, Rothwell RG (2006) ITRAX: Description and evaluation of a new multifunction X-ray core scanner. In: Rothwell RG (ed.) New Techniques in Sediment Core Analysis. Geological Society, London, Special Publications, 267: 51–63.

de Castro M, Martín-Vide J, Alonso S, 17 contributing authors (2005) The climate of Spain: Past, present and scenarios for the 21st century. In: Impacts of climate change in Spain, Publicaciones Ministerio de Medio Ambiente, Madrid, 207-218. ISBN: 84-934207-0-0.

De Lange GJ, Van Os B, Pruysers PA, Middelburg JJ, Castradori D, Van Santvoort P, Müller P, Eggenkamp H, Prahl F (1994) Possible early diagenetic alteration of paleo proxies. In: Zahn R (ed) Carbon Cycling in the Glacial Ocean: Springer-Verlag. NATO ASI Series, 225-257.

Domínguez Martín R, Puente Fernández L (1995) Condicionantes e itinerarios del cambio técnico en la ganadería cántabra, 1750-1930. Historia Agraria 9: 69-86.

García Dory MA (1977) Covadonga National Park, Asturias, Spain. Its history, conservation interest and management problems. Biol Cons 11: 79-85.

Goeury C, Beaulieu JL de (1979) À propos de la concentration du pollen à l'aide de la liqueur de Thoulet dans le sédiments minéraux. Pol Spor 21: 239-251.

Grimm EC (1987) CONISS: a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Comp Geosci 13: 13-35.

Grimm EC (1992) Tilia version 2. Springfield. IL 62703. Illinois State Museum. Research and Collection Center, USA.

Grimm EC (2004) TGView. Illinois State Museum, Springfield.

Huber K, Weckström K, Drescher-Schneider R, Knoll J, Schmidt J, Schmidt R (2010) Climate changes during the last glacial termination inferred from diatom-based temperatures and pollen in a sediment core from Längsee (Austria). J Paleolim 43: 131-147.

IPCC (2007). Summary for Policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernamental Panel on Climate Change. Cambridge University Presss, Cambridge, 1-142.

Jones PD, Hulme M (1996) Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. Int J of Climatol 16: 361-377.

Jones PD, Mann ME (2004) Climate over past millennia. Rev Geophys 42, doi: 10.1029/2003RG000143.

Jones PD, Osborn TJ, Briffa KR (2001) The evolution of climate over the last millennium. Science 292: 662-667.

Jones PD, Briffa KR, Osborn TJ, Lough JM, Ommen TD, Vinther BM, Luterbacher J, Wahl ER, Zwiers FW, Mann ME, Schmidt GA, Ammann CM, Buckley BM, Cobb KM, Esper J, Goosse H, Graham N, Jansen E, Kiefer T, Kull C, Küttel M, Mosley-Thompson E, Overpeck JT, Riedwyl N, Schulz M, Tudhope AW, Villalba R, Wanner H, Wolff E, Xoplaki E (2009) High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. Holocene 19: 3-49.

Juggins S (2007) C2 Software for Ecological and Palaeoecological Data Analysis and Visualisation. User Guide, Version 1.5. Newcastle University, Newcastle upon Tyne, UK.

Kendall S (1976) Time Series. Oxford University Press (2nd edition), New York.

Kienel U, Schwab MJ, Schettler G (2005) Distinguishing climatic from direct anthropogenic influences during the past 400 years in varved sediments from Lake Holzmaar (Eifel, Germany). J Paleolim 33, 327-347.

Krammer K, Lange-Bertalot H (1986–1991) Bacillariophyceae. In: Ettl H, Gerloff J, Heynig H, Mollenhauer D (eds) Süßwasserflora von Mitteleuropa. Stuttgart: Fischer.

Lange-Bertalot H, Metzeltin D (1996) Indicators of Oligotrophy. 800 taxa representative of three ecologically distinct lake types: Carbonate buffered-Oligodystrophic-Weakly buffered soft water. Konigstein: Koeltz Scientific Books.

Martín-Puertas C, Valero-Garcés BL, Mata P, González-Sampériz P, Bao R, Moreno A, Stefanova V (2008) Arid and Humid Phases in Southern Spain during the last 4000 Years: The Zoñar Lake Record, Córdoba. Holocene 40: 195-215.

Martínez Cortizas A, Pontevedra Pombal X, Nóvoa Muñoz JC, García-Rodeja E, Shotyk, W. 1999. Mercury in a Spanish peat bog: archive of climate change and atmospheric metal deposition. Science 284: 939-942.

Mayor López M (2002) Landscapes of northern Spain and pastoral systems. In: Redecker B, Finck P, Härdtle W, Riecken U, Schröder E (eds) Pasture Landscapes and Nature Conservation. Springer, Heidelberg, Berlin, Germany and New York, 67-86.

Montserrat P, Fillat F (1990) The systems of grassland management in Spain. In: Breymeyer A (ed) Managed Grasslands 17, 37-70. Elsevier Science, Amsterdam.

Moore PD, Webb JA, Collinson ME (1991) Pollen analysis. Blackwell Scientific Publications (2nd edition), London.

Morabito G, Ruggiu D, Panzani P (2002) Recent dynamics (1995–1999) of the phytoplankton assemblages in Lago Maggiore as a basic tool for defining association patterns in the Italian deep lakes. J Limnol 61: 129-145.

Morellón M, Valero-Garcés B, González-Sampériz P, Vegas-Vilarrúbia T, Rubio E, Rieradevall M, Delgado-Huertas A, Mata P, Romero Ó, Engstrom DR, López-Vicente M, Navas A, Soto J (in press) Climate change and human activities recorded in the sediments of Lake Estanya (NE Spain) during the Medieval Warm Period and Little Ice Age. J Paleolim, doi: 10.1007/s10933-009-9346-3.

Moreno A, Valero-Garcés BL, González-Sampériz P, Rico M (2008) Flood response to rainfall variability during the last 2000 years inferred from the Taravilla Lake record (Central Iberian Range, Spain). J Paleolim 40: 943-961.

Moreno A, Valero-Garcés BL, Jiménez Sánchez M, Domínguez MJ, Mata P, Navas A, González-Sampériz P, Stoll H, Farias P, Morellón M, Corella P, Rico M (2010) The last deglaciation in the Picos de Europa National Park (Cantabrian Mountains, Northern Spain). J Quat Sci 25 (7): 1076-1091.

Moreno A, López-Merino L, Leira M, Marco-Barba J, González-Sampériz P, Valero-Garcés B, López-Sáez JA, Santos L, Mata P, Ito E (in press) Revealing the last 13,500 years of environmental history from the multiproxy record of a mountain lake (Lago Enol, northern Iberian Peninsula). J Paleolim, doi: 10.1007/s10933-009-9387-7.

Osborn TJ, Briffa KR, Jones PD (1997) Adjusting variance for sample-size in tree-ring chronologies and other regional mean time series. Dendrochronologia 15: 89-99.

Reynolds CS (2006) Ecology of Phytoplankton. Cambridge University Press, Cambridge.

Rodríguez Castañón AA (1996) La producción de vacuno con rebaños de Asturiana de la Montaña: Ganadería extensiva en la Cordillera Cantábrica. Agricultura 764: 214-217.

Rodríguez Terente LM, Luque Cabal C, Gutiérrez Claverol M. 2006. Los registros mineros para sustancias metálicas en Asturias. Trabajos de Geología 26: 19-55.

Rogora M, Mosello R, Arisci S, Brizzio MC, Barbieri A, Balestrini R, Waldner P, Scmhidt M, Stähli M, Thimonier A, Kalina M, Puxbaum H, Nickus U, Ulrich E, Probst A (2006) An overview of atmospheric deposition chemistry over the Alps: present status and long-term trends. Hydrobiologia 562: 17-40.

Rull V, López-Sáez J, Vegas-Vilarrúbia T (2008) Contribution of non-pollen palynomorphs to the paleolimnological study of a high-altitude Andean lake (Laguna Verde Alta, Venezuela). J Paleolimnol 40: 399-411.

Sáez A, Valero-Garcés BL, Giralt S, Moreno A, Bao R, Pueyo JJ, Hernández A, Casas D (2009) Glacial to Holocene climate changes in the SE Pacific. The Raraku Lake sedimentary record (Easter Island, 27°S). Quat Sci Rev 28: 2743-2759.

Sáez A, Valero-Garcés BL, Moreno A, Bao R, Pueyo JJ, González-Sampériz P, Giralt S, Taberner C, Herrera C, Gibert RO (2007) Lacustrine sedimentation in active volcanic settings: the Late Quaternary depositional evolution of Lake Chungará (northern Chile). Sedimentology 54: 1191-1222.

Sande Silva J (2007) Pinhais e eucaliptais. A foresta cultivada. Público, Comunicação, S.A. Fundação Luso-Americana para o desenvolvimento, Lisboa.

Schindler DW, Beaty KG, Fee EJ, Cruickshnak DR, DeBruyn ER, Findlay DL, Linsey GA, Sheare JA, Stainton MP, Turner MA (1990) Effects of climate warming on lakes of the Central Boreal Forest. Science 250: 967-970.

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63: 1379-1389.

Suárez Antuña F, Herrán Alonso M, Ruiz Fernández J (2005) La adaptación del hombre a la montaña. El paisaje de Cabrales (Picos de Europa). Ería 68: 373-389.

ter Braak CJF, Smilauer P (2002) CANOCO. Reference manual and CanocoDraw for Windows user´s guide: software for canonical community ordination (version 4.5). Microcomputer Power (Ithaca, NY, USA) 500pp.

Velasco JL, Araujo R, Álvarez M, Colomer M, Baltanás A (1999) Aportación al conocimiento limnológico de ocho lagos y lagunas de montaña de Asturias (España). Bol R Soc Esp Hist Nat (Biol) 95: 181-191.

Figure and table captions

Fig. 1 (A) Location of the study area. (B) Position of the short cores in Lago Enol. (C) location map of the meteorological stations used in this study.

Fig. 2 Chronological framework of core ENO07-1A-1M. (A) Total ^{210}Pb activities of supported (dashed line) and unsupported (continuous line) lead. (B) Constant rate of supply model of ^{210}Pb values. (C) ^{210}Pb based sediment accumulation rate.

Fig. 3 Correlation between short cores ENO07-1A-1M (^{210}Pb dated) and ENO07-1C-1M (cross-dating) based on the content on total carbon (TC), organic carbon (TOC) and inorganic carbon (TIC). The incoherence/coherence ratio (inc/coh) is interpreted here as an indirect indicator of the amount of organic matter in the sediments. Arrows indicate the tie points used to construct the age model of core ENO07-1C-1M. Geochemical profiles of short core ENO07-1C-1M (Si, Ti, Ca and Fe in counts per second, and the Fe/TI ratio) measured by the ITRAX XRF Core Scanner are also plotted. Sedimentological units are indicated on the right and the age in yr AD on the left.

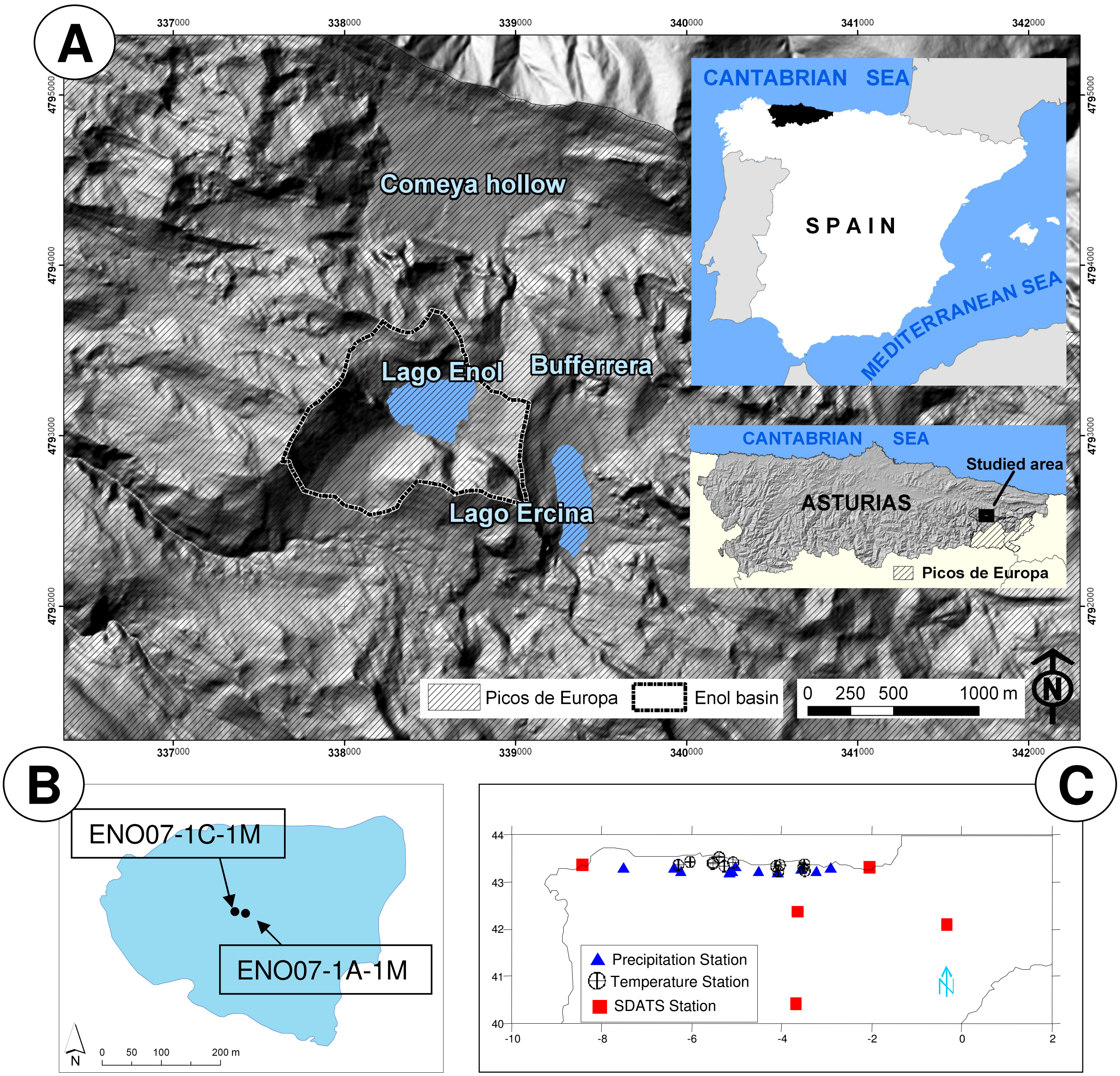
Fig. 4 Diatom summary diagram of selected taxa from core ENO07-1A-1M plotted against depth and age in yr AD. Diatom zones are indicated on the right. PCA axis 1 and 2, and Plankton: Periphyton ratio, are also plotted.

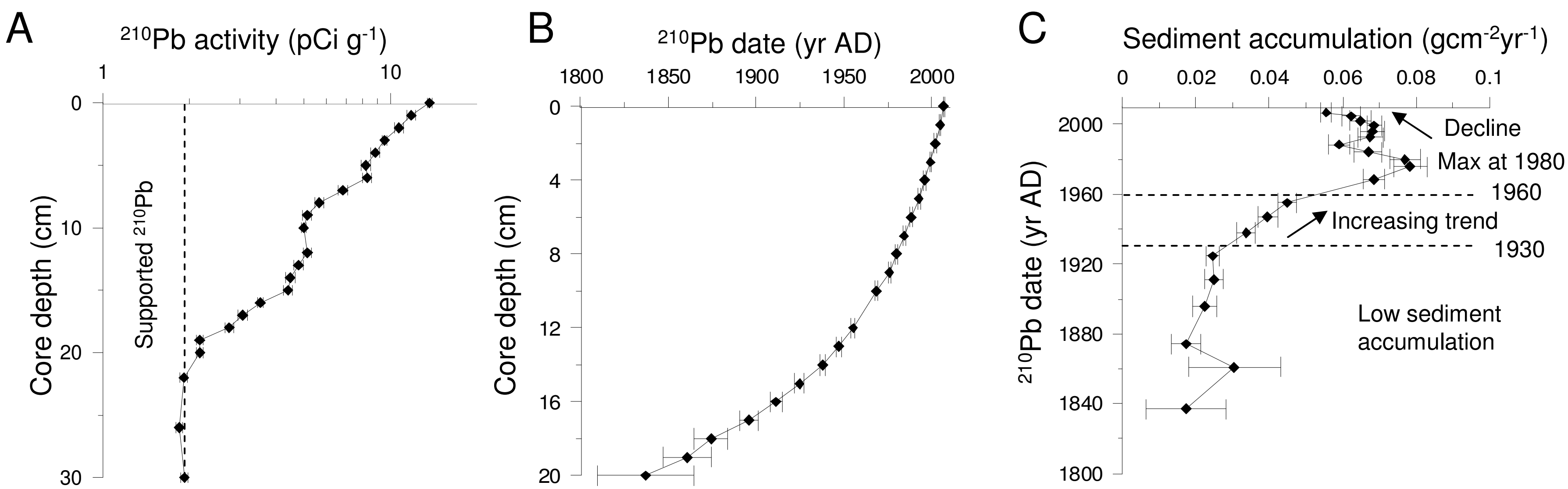
Fig. 5 Pollen diagram of selected taxa from core ENO07-1C-1M plotted against depth and age in yr AD. Pollen zones and sedimentological units are indicated on the right. “Other mesophytes” is the sum of *Fraxinus*, *Salix*, *Tilia* and *Ulmus*. “Other *Pinus*“ is other *Pinus* pollen types different from *Pinus sylvestris* type. Ericaceae includes *Erica* type and *Calluna vulgaris*. Compositae is the sum of *Aster* type, Cardueae and Cichorioideae. *Plantago* sp. includes *P. coronopus* type, *P. lanceolata* type and *P. major/media* type. Filicales is the sum of F. trilete and F. monolete. Shaded curves represent x10 exaggeration of base curves.

Fig. 6 Composite diagram plots against age showing the regional climate reconstruction for Central Cantabrian region developed in this study. Annually averaged regional anomaly temperature and precipitation series are represented by the thin lines and the 5-years averaged anomaly are depicted by the thick lines. Selected information about climate and anthropogenic changes inferred throughout the proxy data from Lago Enol sediments together with Sedimentological Units, Pollen and Diatom Zones are also included.

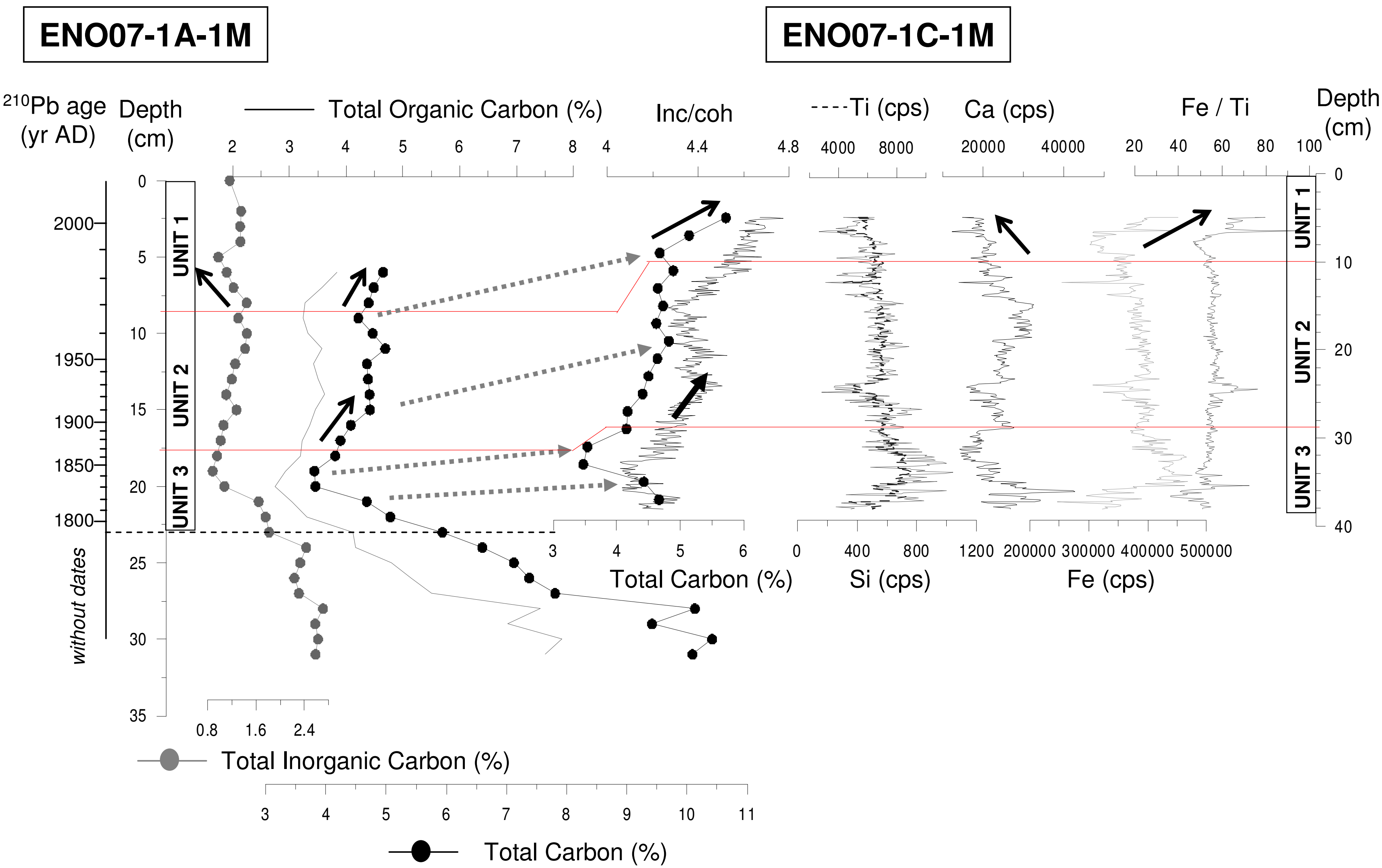
Table 1 Factor loadings for significant diatoms found in Lago Enol included, those with an abundance >1% in at least one sample, in the Principal Components Analysis.

Taxa	PC1	PC2
Achnanthes conspicua	0.0	-0.2
Achnanthidium minutissimum	0.8	0.0
Amphora inaeriensis	0.4	0.0
Amphora pediculus	0.3	0.4
Amphora thumensis	-0.3	0.4
Cavinula scutelloides	-0.7	1.1
Cyclotella comensis	-0.5	-1.2
Cyclotella cyclopuncta	-0.6	-0.1
Cyclotella ocellata	1.7	-2.1
Cyclotella radiosa	-1.5	-2.7
Naviculadicta vitabunda	-1.2	0.7
Planothidium lanceolatum	-1.0	-0.4
Pseudostaurosira brevistriata	1.1	0.8
Staurosira construens var. *construens*	-2.3	0.4
Staurosira construens var. *venter*	-0.5	0.1
Staurosirella leptostauron	-0.5	-0.1
Staurosirella pinnata	0.2	1.0

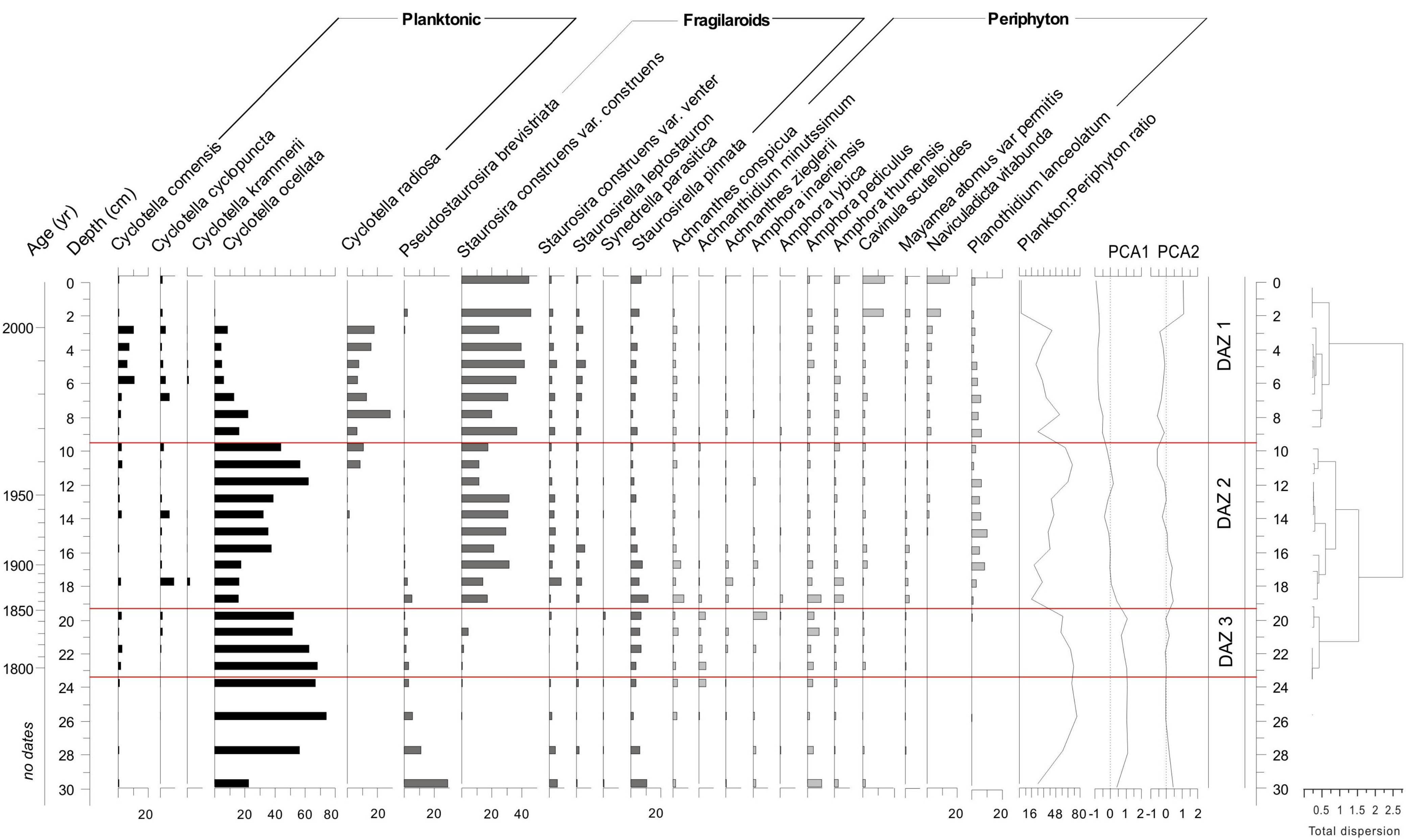

A
Comeya hollow
Lago Enol
Bufferrera
Lago Ercina
CANTABRIAN SEA
SPAIN
MEDITERRANEAN SEA
CANTABRIAN SEA
Studied area
ASTURIAS
Picos de Europa
Picos de Europa
Enol basin
0 250 500 1000 m
N
B
ENO07-1C-1M
ENO07-1A-1M
N
0 50 100 200 m
C
Precipitation Station
Temperature Station
SDATS Station



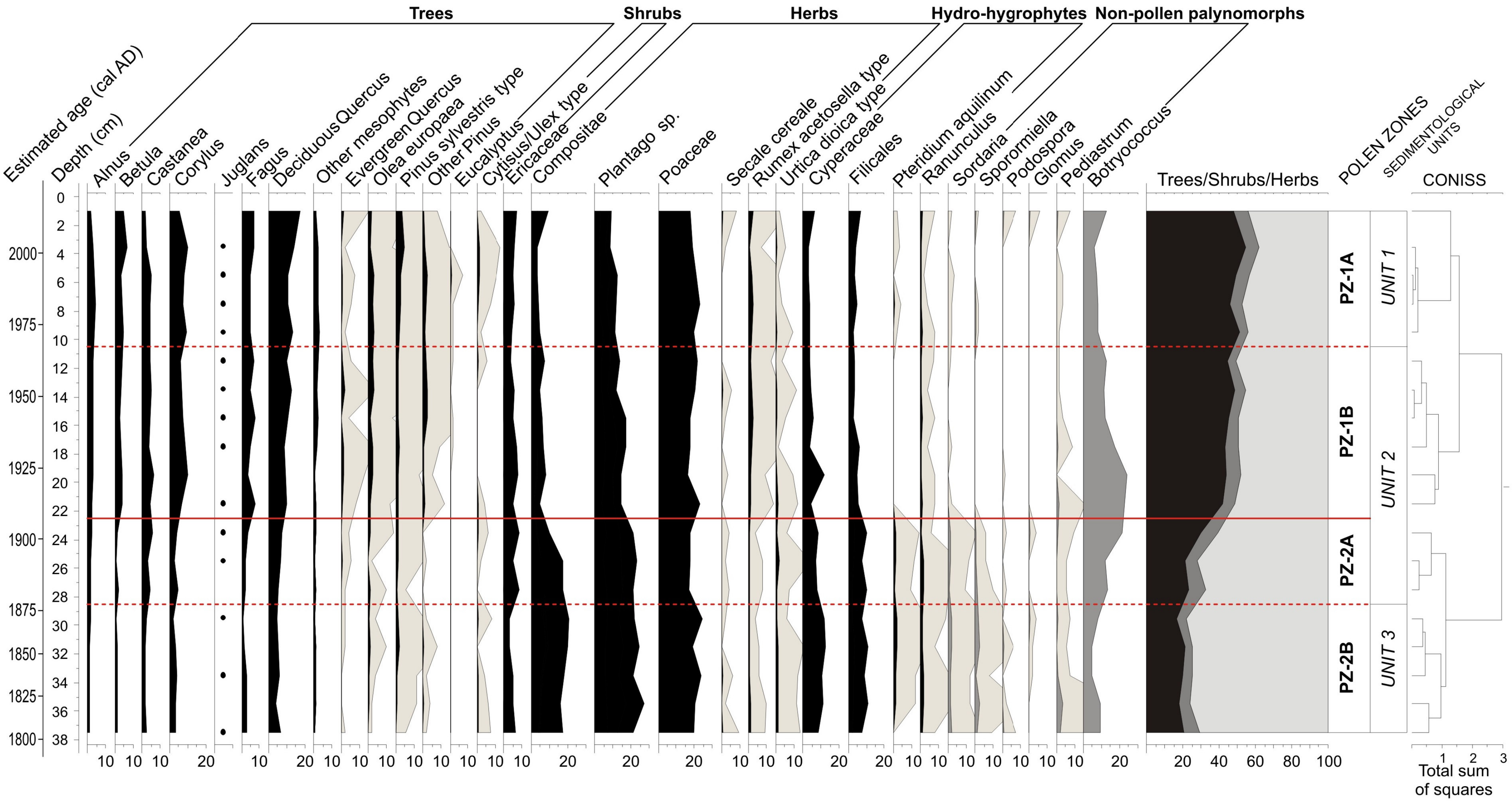
A
^{210}Pb activity (pCi g^{-1})
1
10
0
10
20
30
Core depth (cm)
Supported ^{210}Pb
B
^{210}Pb date (yr AD)
1800
1850
1900
1950
2000
0
4
8
12
16
20
Core depth (cm)
C
Sediment accumulation (gcm^{-2}yr^{-1})
0
0.02
0.04
0.06
0.08
0.1
2000
1960
1920
1880
1840
1800
^{210}Pb date (yr AD)
Decline
Max at 1980
1960
Increasing trend
1930
Low sediment
accumulation

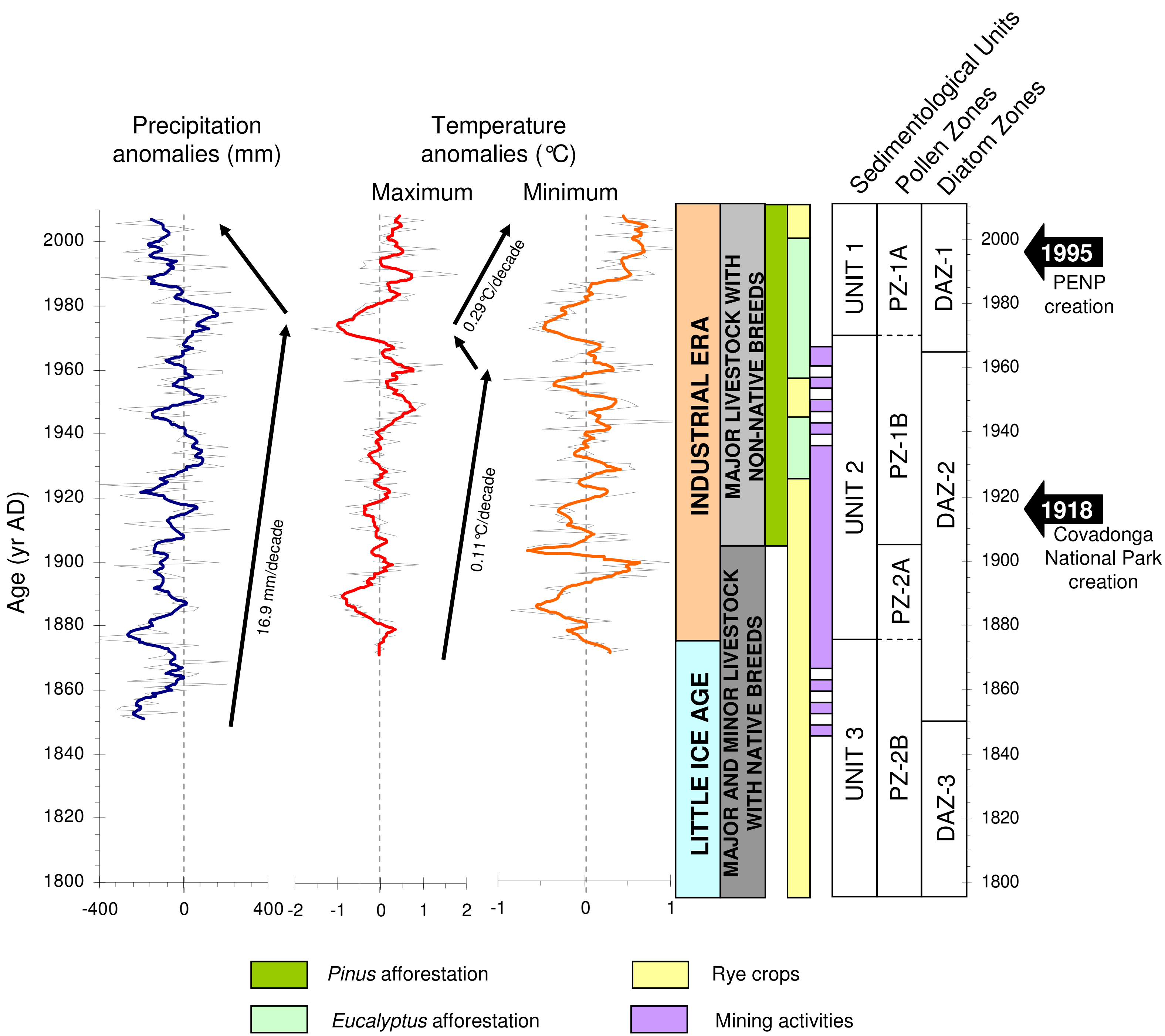


ENO07-1A-1M
ENO07-1C-1M
210Pb age (yr AD)
Depth (cm)
Total Organic Carbon (%)
Inc/coh
Ti (cps)
Ca (cps)
Fe / Ti
Depth (cm)
UNIT 1
UNIT 2
UNIT 3
without dates
Total Carbon (%)
Si (cps)
Fe (cps)
Total Inorganic Carbon (%)
Total Carbon (%)



Planktonic
Fragilaroids
Periphyton
Age (yr)
Depth (cm)
Cyclotella comensis
Cyclotella cyclopuncta
Cyclotella krammerii
Cyclotella ocellata
Cyclotella radiosa
Pseudostaurosira brevistriata
Staurosira construens var. construens
Staurosira construens var. venter
Staurosirella leptostauron
Synedrella parasitica
Staurosirella pinnata
Achnanthes conspicua
Achnanthidium minutssimum
Achnanthes zieglerii
Amphora inaeriensis
Amphora lybica
Amphora pediculus
Amphora thumensis
Cavinula scutelloides
Mayamea atomus var permitis
Naviculadicta vitabunda
Planothidium lanceolatum
Plankton:Periphyton ratio
PCA1
PCA2
DAZ 1
DAZ 2
DAZ 3
no dates
Total dispersion


Trees
Shrubs
Herbs
Hydro-hygrophytes
Non-pollen palynomorphs
Estimated age (cal AD)
Depth (cm)
Alnus
Betula
Castanea
Corylus
Juglans
Fagus
Deciduous Quercus
Other mesophytes
Evergreen Quercus
Olea europaea
Pinus sylvestris type
Other Pinus
Eucalyptus
Cytisus/Ulex type
Ericaceae
Compositae
Plantago sp.
Poaceae
Secale cereale
Rumex acetosella type
Urtica dioica type
Cyperaceae
Filicales
Pteridium aquilinum
Ranunculus
Sordaria
Sporormiella
Podospora
Glomus
Pediastrum
Botryococcus
Trees/Shrubs/Herbs
POLEN ZONES
SEDIMENTOLOGICAL UNITS
CONISS
PZ-1A
PZ-1B
PZ-2A
PZ-2B
UNIT 1
UNIT 2
UNIT 3
Total sum of squares



Precipitation anomalies (mm)
Temperature anomalies (℃)
Maximum
Minimum
Age (yr AD)
16.9 mm/decade
0.11 ℃/decade
0.29 ℃/decade
INDUSTRIAL ERA
LITTLE ICE AGE
MAJOR LIVESTOCK WITH NON-NATIVE BREEDS
MAJOR AND MINOR LIVESTOCK WITH NATIVE BREEDS
Sedimentological Units
Pollen Zones
Diatom Zones
UNIT 1
UNIT 2
UNIT 3
PZ-1A
PZ-1B
PZ-2A
PZ-2B
DAZ-1
DAZ-2
DAZ-3
1995
PENP creation
1918
Covadonga National Park creation
Pinus afforestation
Eucalyptus afforestation
Rye crops
Mining activities