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The lake record of the Anthropocene in mediterranean regions: Iberian and Chilean examples

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Abstract

Recent global warming and accelerating human activities have greatly impacted surface processes, ecosystems dynamics and biogeochemical cycles. Paleo records provide robust reconstructions of past global changes to define the onset, timing and intensity of the human imprint on the Planet during this new epoch, referred as *Anthropocene*. Selected lake sequences from the Iberian Peninsula and central Chile illustrate the dynamics and structure of the large impact of human activities in sediment fluxes, heavy metals and carbon accumulation during the last two millennia and particularly since mid 20th century. The strongest impact on sediment delivery occurred during the early Medieval times and late 19th century in Iberian lakes, and during the Colonial period and early 20th century in central Chile, reflecting in both cases the acceleration of agricultural and cattle farming. Heavy metal concentrations demonstrate the global reach of the Roman Empire mining activities, the large environmental impact of the Industrial Revolution and the Great Acceleration and the decreasing impact after the implementation of conservation policies in the late 20^{th} century. The increasing carbon accumulation rates in most lakes during the last decades stands out as a unique signature of the Anthropocene in lake dynamics.

The survey of selected sites in Chile and Spain demonstrate the long reach of human impact in the Mediterranean lakes and watersheds during the last two millennia, the intensification during Medieval times in Spain and Colonial period in Chile and the acceleration during the last decades. Past periods of high human impact in Mediterranean lakes and watersheds serve to better understand, model, and predict the effects of the current environmental and climate crises.

1 INTRODUCTION

The global impact of human activities in the Planet and their synergetic interactions with the biological and geological cycles –known as Global Change (Duarte, 2009)– have led to the controversial proposal of a new epoch in the geological time scale: the *Anthropocene* (Crutzen, 2002). Beyond the discussion of the need and usefulness of a new division in the Stratigraphic Geological Chart, the proposal has served to articulate the dangerous impacts of our civilization in the Planet and to illuminate the ways forward out of the environmental and climate crises. Human impact in the landscapes and ecosystems is as old as our species, and we have been responsible for some of the largest extinctions in all continents and ecosystem transformations following *Homo sapiens* migrations from Africa during the "*PaleoAntrophocene*" (Sandom *et al.*, 2014). However, the establishment of the agriculture and the Neolithic Revolution increased our footprint in the Planet and could have caused the anomalous rise in atmospheric CO_2 that began near 7000 years ago and in methane (CH_4) near 5000 years ago (Ruddiman, 2003; Ruddiman *et al.*, 2020). The comprehensive synthesis of global land use by Stephen *et al.* (2019) shows that cropland agriculture and pastoralism had already become extensive by 6000 years ago and had 'largely transformed the planet' by 3000 years ago. In any case, the intensity of landscape transformation jumped after the Industrial Revolution and exponentially since the mid 20^{th}

century, a period known as The Great Acceleration (Steffen *et al.*, 2015).

The Anthropocene poses particular challenges in regions with Mediterranean climates as they are characterized by strong seasonality an annual water deficit and a long history of human occupation of the territories (Carrión *et al.*, 2010; Lionello, 2012). But our knowledge of the human impact on Mediterranean Watershed-Lake Systems dynamics is hindered by the absence of integrated studies, including all the variety of geographic contexts (most studies deal with a particular area) and a larger than a few decades time-span (García-Ruiz *et al.*, 2013, 2015).

Lakes provide the needed archives of past human impact in the Planet. Sediment in lakes reflect the environmental – climate – anthropic interactions along three main processes: i) Endogenic, related to the features of the depositional systems (relief, sediment availability, limnological and geomorphic processes and so on); ii) Climatic, controlling vegetation, frequency and intensity of rainfall, wind and temperature and iii) Anthropic, mainly through changes in the land uses, natural resources exploitation, infrastructure and industrialization (Valero and Moreno, 2011). A recent review (Dubois *et al.*, 2017) has shown that first human impacts on aquatic systems and their watersheds are highly variable in time and space. For millions of years, environmental, biogeochemical and surface (depositional, hydrological) processes have been co-varying in parallel with climate, but the multicomponent nature of the current global change, directly disturbing element cycles (C, N, P), and altering land uses and geomorphic processes creates new combinations that may have no past analogues (Catalán *et al.*, 2013). My research during the last decade has been focused on trying to understand the climate and human interactions in surface processes and ecosystem dynamics using lake sediments as archives of these past changes. In our research group we try to identify the signatures of the Anthropocene in watersheds and lakes, the timing and varied intensity of the processes and how current rates compare with past periods of rapid global change. In this contribution, I summarize our findings of Anthropocene signals in Mediterranean regions from the Iberian Peninsula and central Chile during the last 2000 years in three main areas: i) sediment fluxes (soil erosion, sediment mobilization), ii) biogeochemical cycles (carbon accumulation) and iii) heavy metal deposition.

2 METHODOLOGY AND SELECTED SITES

High-resolution records spanning the last two millennia studied by our research group during the last decade include almost pristine lakes (high altitude Pyrenean and Andean lakes) and highly altered ones (intermediate altitude and coastal lakes) (Figure 1). We study those records following standard protocols for sedimentological, geochemical and biological proxies (see for example, Morellón *et al.*, 2011; Galofre, 2019; Vicente de Vera, 2020; Corella *et al.*, 2021). Short cores were retrieved with gravity UWITEC corer, split in two halves and imaged with a Geotek Multi-Sensor Core Logger (MSCL) digital camera. Heavy metals were analyzed with ICP-OES and compositional data (C, N, S) obtained with an elemental LECO analyzer; an AVAATECH X-Ray Fluorescence II core scanner at 1 mm resolution was used for geochemical analyses. Selected element ratios have been used to describe sediment input from the watershed (Al/Ti), carbonate (Ca/Ti, Sr/Ti), organic productivity (Br/Ti), and heavy metal deposition (Pb/Ti). Organic matter was also characterized using isotopic signatures (δ^{13}C and δ^{15}N). Age models were obtained using ^{210}Pb-^{137}Cs gamma ray spectrometry and AMS ^{14}C dating. Ages are given as BP (Before Present, as present 1950) or CE (Common Era). Details of lake's watershed, climate, vegetation, hydrology and limnology and the sediment sequences, the age models and detailed methodologies can be found in the original papers (see reference list).

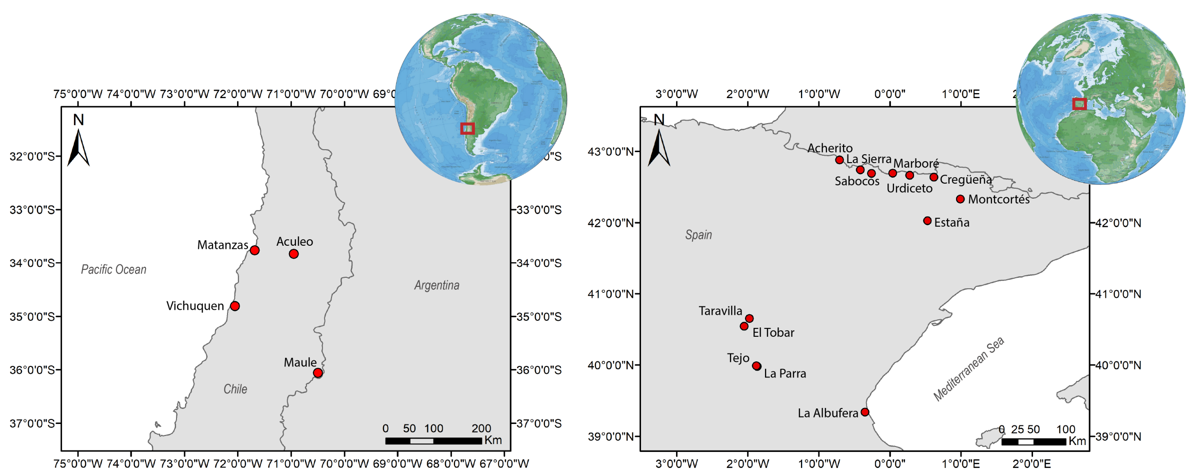

Figure 1: Location of main lakes cited in Spain and central Chile cited in the text.

3 THE ANTHROPOCENE SIGNAL

3.1 Climate Variability during the last 2000 years

Paleoclimate studies have identified several phases during the last two millennia in the Iberian Peninsula: the Iberian – Roman Humid Period (IRHP, ca. 500 BCE – 400 CE), the Late Antiquity Little Ice Age (LALIA, 536 – 660 CE), the Medieval Climate Anomaly (MCA, 900 – 1300 CE), the Little Ice Age (LIA, 1300 – 1850 CE) and the Recent Global warming in the 20^{th} century (see reviews in Morellón *et al.*, 2012 and Giralt *et al.*, 2017 and references therein). Changes in solar insolation, North Atlantic dynamics (particularly NAO phases) and even African monsoon variability controlling the westerlies and the Azores High locations and intensities have been suggested as drivers of this climate variability in the western Mediterranean (Sánchez-López *et al.*, 2016). Recent climate trends in the Iberian Peninsula show a large geographic variability, but generally include increasing temperatures and extreme events frequency and irregular precipitation patterns (Sánchez and Rodríguez-Fonseca, 2017).

In central Chile two contrasting phases during the last millennium are well identified: warmer and/or drier conditions during the MCA (Carrevedo *et al*, 2015; Frugone *et al.*, 2017; 2020; Von Gunten *et al*, 2009b), and a complex LIA, with marked colder and humid phases (Neukom *et al*, 2010a,b). Decreasing rainfall and higher temperatures have been responsible for unparalleled mega-droughts in central Chile in the last decades.

3.2 Timing and Global trends in the Anthropocene

The review of lake records from the Iberian Peninsula and central Chile reveals large changes in lake dynamics during the last 2000 years in three main aspects: sediment fluxes, heavy metal deposition and lake bioproductivity.

3.2.1 Sediment delivery

Periods of higher human pressure in the landscapes in Spain and Chile have been recorded in the lacustrine sedimentary sequences as intervals with higher magnetic susceptibility values, changes in composition (higher silicate mineral content) and in the sedimentary facies (generally coarser and/or flood-related layers). The initial phases of noticeable human impact in the Iberian landscapes occurred at a local scale during the Bronze and Iron Age, although in some areas could have started during the Neolithic revolution (see discussion in González-Sampériz *et al.*, 2017, 2019). However, the sedimentological lake record supports the hypothesis that most landscapes in Spain were created during Medieval times (García-Ruiz and Valero-Garcés, 1998; González-Sampériz *et al.*, 2019). In central Chile, Mapuche settlements and Inka agriculture may have been responsible for some increase in sediment delivery in coastal lakes prior to the 16th century, but the first large changes in the territories occurred during the Colonial Period (Frugone *et al.*, 2017; Fuentealba *et al.*, 2020).

Comparison among the Iberian Range and the Pyrenees sites underlines the major role of watershed surface area and altitude, as proxies for the timing and intensity of anthropogenic signatures. The Iberian Range sites show a greater anthropogenic role on their depositional dynamics than the high altitude Pyrenean or Andean lakes. Major periods of sediment accumulation in the Iberian Range lakes and corresponding higher denudation in the catchments occurred during cooler and wetter phases (Roman and Dark Ages, 0–800 CE and LIA 1200–1850 CE) but the most intense phases are associated to the development of the *Mesta* with deforestation for grazing (Middle Ages, 12th–13th centuries) and the period with the highest population in mountain areas during the late 19th century (Barreiro-Lostres *et al.*, 2014, 2015, 2017). Mass Accumulation Fluxes (MAF) for the last 2000 years in Iberian lakes varied within similar range values ($< 10000 \text{T/km}^2/\text{yr}$) prior to Medieval times and show a progressive increase after the late Middle Ages (ca. 15th century). El Tobar, with the largest watershed heavily modified by grazing and agriculture shows a 10-fold increase in MAF compared to smaller (Tejo and La Parra) and forested (Taravilla) watersheds. All sites show an increase in both MAF values and flooding events in the late 19th century when mountains of the now "de-populated Spain" had the highest population (Figure 2).

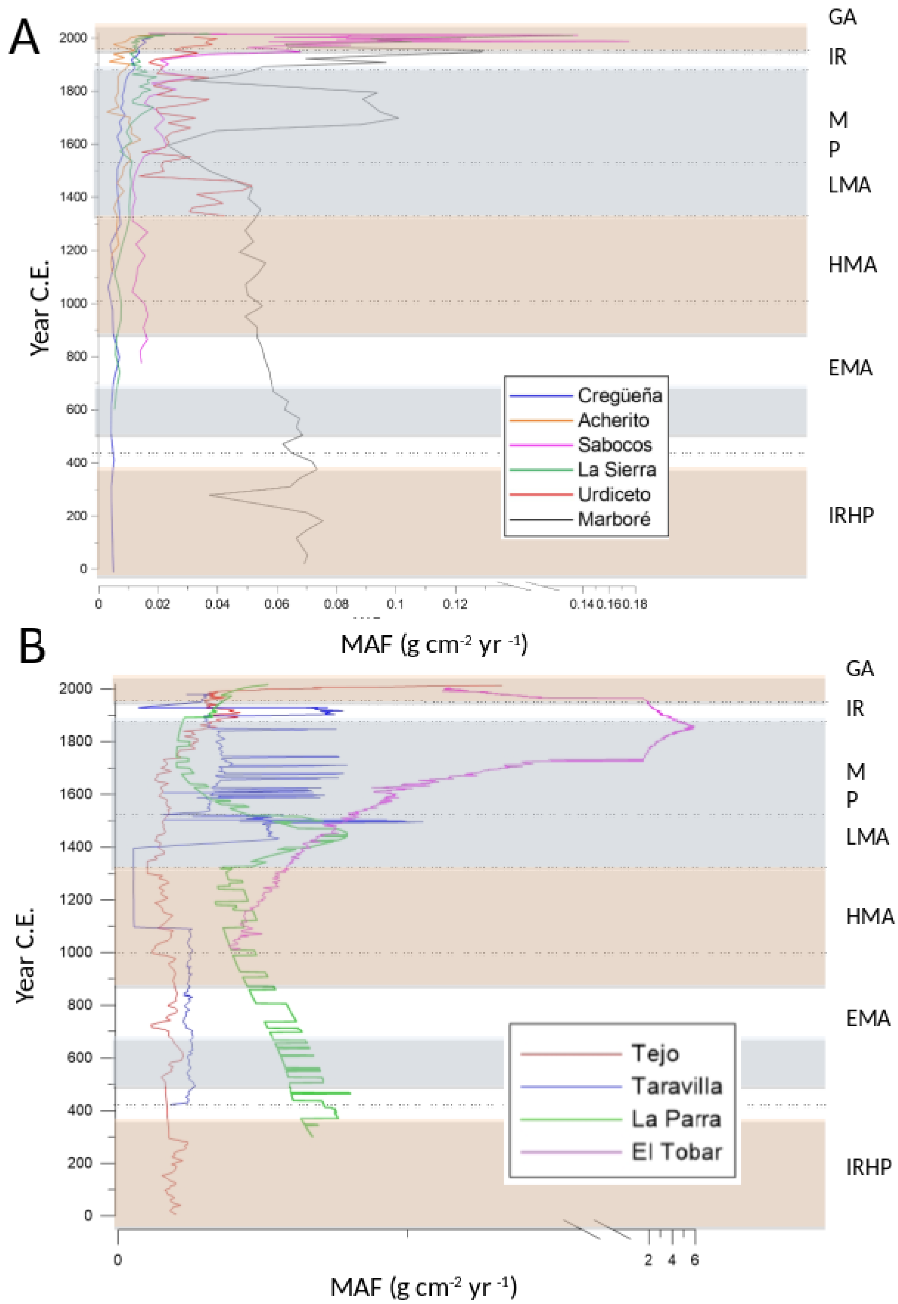

Figure 2: Mass Accumulation Fluxes (MAF) for selected Lakes (methodology based on Barreiro-Lostres et al., 2015, 2017). Main historical periods are: Roman Period (up to 476 CE), Early, High and Late Middle Ages (EMA, up to 1000 CE, HMA, 1000-1300 CE, and LMA, 1300-1500 CE), Modern/Contemporary Age (MP, up to 1850), Industrial Revolution (IR, starting around 1850 CE) and Great Acceleration (GA, starting around 1950). Warmer climate Phases as Iberian – Roman Humid Period (IRHP, ca. 500 BCE – 400 CE), the Medieval Climate Anomaly (MCA, 900 – 1300 CE) and the Recent Global warming in the 20th century are indicated in orange; colder climate phases as the Late Antiquity Little Ice Age (LALIA, 536 – 660 CE) and the Little Ice Age (LIA, 1300 – 1850 CE) in blue.

In the Pyrenees, the human impact is clear in lakes located at intermediate altitudes as **Tramacastilla** (García Ruiz and Valero-Garcés, 1998), **Basa de la Mora** (Pérez-Sanz *et al.*, 2013) and **Montmalús** (Galofre, 2019) with a long history of human impact. At lower altitude, the **Estaña** sequence contains pollen evidence of anthropogenic deforestation *ca.* 3700 yr ago (González-Sampériz *et al.*, 2017), but the first large change in sediment mobilization occurred later (9th century) (Morellón *et al.*, 2011) as the watershed was intensively transformed for agricultural use. At higher elevation, first clear evidence of intense anthropogenic impact is found ca. 700 years ago, when the intensification of both agro-pastoral and mining activities produced a generalized deforestation at the Pyrenean range scale (González-Sampériz *et al.*, 2017). Higher sediment transfer into these lakes occurred during the early to late Medieval times, when the lake levels were lower during the MCA and the watersheds were deforested for summer grazing pastures. The **Montcortés** sequence contains a unique annually and seasonally resolved archive of floods and sediment delivery during the last 3000 years (Corella *et al.*, 2019). During periods of reduced human impact in the watershed, the seasonal maxima in sediment production occurred in autumn, when rainfalls are heavier and more frequent. The two phases with the highest sediment yield occurred during the Middle Ages (1168–1239 CE) and the 19th century (1844–1866 CE) due to an interplay between increased frequencies and magnitudes of heavy rainfall and intensive agropastoral activities in the lake's watershed. Interestingly, human impact in the watershed also modified the seasonal sediment budget with peak production in winter.

High altitude Pyrenean lakes are less affected by anthropic activity in their watersheds and their sedimentation is more dependent on climate and surface hydrological processes, precipitation, and the seasonal dynamics of ice and snow. In general, more humid periods caused enhanced surface runoff, and therefore a greater transport of detrital elements to the lake of relatively coarser size, but the timing and intensity show a regional variability. Conversely, periods of greater aridity were marked by a decrease of the sediment transfer to the lake. **Marboré** (Oliva-Urcia *et al.*, 2018; Leunda *et al.* 2017), **Cregüeña** (Sociats, 2017) and **Urdiceto** (Vicente de Vera, 2017) all show more detrital facies and higher sediment input during periods of increased glacial activity (LIA and LALIA). Mass accumulation fluxes values for these high altitude lakes are much lower than the Iberian Range sites and show little variability prior to the last 2 centuries (Figure 2). All sites show a unique increase during the last centuries, although the timing of the onset is different. In

Acherito occurred between 1000–1700 CE but in La Sierra and Urdiceto happened later on (1700–1850 CE). Although all lakes have generally higher MAF values since mid 20th century, Sabocos (0.06 – 0.19 $g.cm^{-2}.yr^{-1}$) Urdiceto (0.03 to 0.045 $g.cm^{-2}.yr^{-1}$) and Marboré (0.1 to 0.24 $g.cm^{-2}.yr^{-1}$) show the largest increases. These results suggest that recent changes in the 20th century have affected lakes at all altitudes and with higher intensity that those occurred at the end of the Little Ice Age (ca. 1850 CE). The likely role of human activities in sediment dynamics even in high altitude lakes is suggested by changes during medieval times and the 20th century. Recent changes show a large regional variability as a result of the interplay of land use and climate changes. Urdiceto illustrate the changes in depositional dynamics in many lakes in the Pyrenees dammed in the 20th century: higher accumulation rates and dominance of finer facies (Vicente de Vera, 2017). Sediment delivery has maintained high levels during the last decades in watersheds as Estaña with continuous farming activities and decrease in El Tobar, as traditional farming disappears.

The impact on the landscape and the ecosystems of pre-Colombian cultures has not been evaluated in central Chile, but it seems the largest change occurred during the Spanish Conquest and the Colonial Period (16th-18th) and also during the first industrialization (19th century) (Fuentealba *et al.*, 2020). Evidence for deforestation and increased soil erosion during early Colonial, early industrialization and recent times has been found in coastal –**Matanzas** (Fuentealba *et al.*, 2020), **Vichuquén** (Frugone *et al.*, 2017, 2018)– and lowland –**Aculeo** (Jenny *et al.* 2002)– areas. Mining, agricultural activities and tree plantations have greatly changed the landscapes in central Chile in the 20th century (Frugone *et al.*, 2017; Fuentealba *et al.*, 2020).8

To sum up, the lake records suggest that although Roman activities had a considerable impact on the Iberian territories, they did not cause large-scale remobilization of sediments in the watersheds. Sedimentological evidence indicate that the largest anthropogenic impact in the low to mid altitude lake watersheds occurred during historical periods of increased human pressure, as the development of the livestock grazing and deforestation in Spain, (12th-13th centuries), the colonization period in Chile (16th–18th century), and the early industrialization (late 1800s- early 1900s) (González-Sampériz *et al.*, 2017). Since mid 20th century, warmer temperatures, irregular precipitations and changes in economic activities (rural abandonment and more tourism in Spain, tree plantation and increased irrigation in central Chile) have altered landscapes and watersheds. In Spain, rural exodus and the evolution of farming methods since mid 20th century have resulted in the loss of biological, landscape, cultural, and economic diversity. In central Chile, extensive tree plantations during early and mid 20th century represented the major landscape transformation in history.

3.2.2 Heavy metals loads

Heavy metals stratigraphies from sites all over the Iberian Peninsula clearly identify several phases of mining and smelting since the early Bronze and with peaks during Roman, Medieval and Contemporaneous times and a decrease since regulation of Pb gasoline content (García-Alix *et al.*, 2013, Martín Puertas *et al*, 2010; Hillman *et al.*, 2017). Although site-specific processes influence metals enrichments in each lacustrine system (Corella *et al.*, 2018), lead content shows similar behavior in most Pyrenean lakes, with enrichment during the Roman period, a decrease during Early Medieval times (500 - 1000 CE), a progressive increase during the High Middle Ages, more pronounced since the end of the 18th century, paralleling the industrialization process in Europe, and peaking at the mid-late 20th century (Figure 3A) (Corella *et al.*, 2017, 2018, 2021). The lake transect in the central southern Pyrenees illustrates these trends (Figures 3B). The two largest trace metal pollution phases occurred during Roman times and the Early Industrialization (ca. 1840s – 1920s CE). A third, less distinct pollution phase occurred between 1950s and 1990s, associated with the "Great Acceleration" with an increase in trace metal emissions related to road-transport, use of fertilizers in agriculture and the global boost of the chemical industry. The sharp drop in Pb in the late 20th century is related to the reduction of emissions associated with the economic recession, the closure of the local Pb mines, and the ban of leaded gasoline.

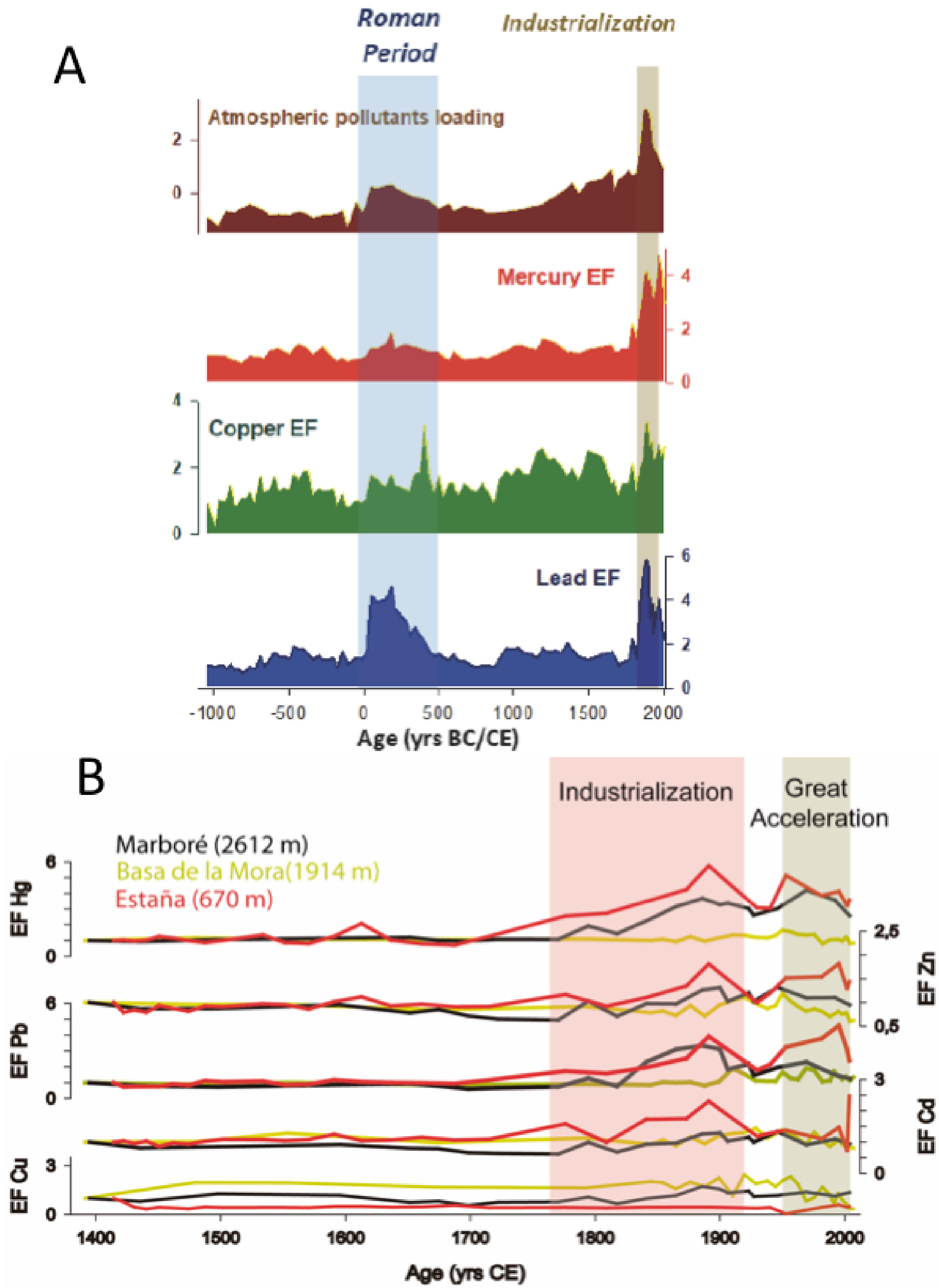

Figure 3: A. Enrichment Factors (EF) for Mercury, Copper and Lead in Marboré Lake sediments and atmospheric pollutants loadings for the last 3000 years (modified from Corella *et al.* 2021). B. Copper, cadmium, lead, zinc and mercury Enrichment Factors (EF) in Lake Estaña, Basa de la Mora and Marboré sedimentary sequences for the last 600 years (modified from Corella *et al.*, 2018)

The local source for the central Aragonese Pyrenees could be the Parzán mines, located only 16 km from Bielsa and exploited for iron, silver and lead since Medieval times, with an exploitation peak in the 16h century and a decline in the mid 20^{th} century (Mata *et al.* 2013; Corella *et al.*, 2018). No Roman exploitation and/or smelting activities have been clearly documented in the central southern Pyrenees thus far, so a regional or global origin is invoked for this period. Interestingly, global deposition of lead during Roman Period could have been higher than during recent times (Corella *et al.*, 2021).

Pre-Spanish heavy metal deposition has been documented in the northern Andes (Cooke *et al*, 2008), but not in central Chile. The main phase of heavy metal pollution in Chile occurred during the last century associated to copper and gold mining and smelting (Von Gunten *et al*, 2009a). Andean and particularly coastal lake sites all show excess copper and heavy metal deposition in the uppermost sediments, since the beginning of the 20^{th} century, when the first industrial smelters were commissioned (Frugone *et al.*, 2017, 2020; Fuentealba *et al.*, 2020).

Heavy metals signatures are clear markers of the onsets of the first globalizations: Roman times in the Northern Hemisphere, the Inka Empire in South America. They also illustrate the recent changes during the Industrial Revolution and the Great Acceleration and how global measures have contributed to decrease heavy metal pollution in the last decades.

3.2.3 Bioproductivity and Carbon fluxes

In spite of the relative small area of the Earth that they cover, lakes are a central component of the carbon cycle, both mineralizing terrestrially derived organic matter (OM) and storing substantial amounts of organic carbon (OC) in their sediments (Anderson *et al*, 2009). Paleolimnological studies have shown large OC burial rate increases during the last century (Anderson *et al*, 2013; 2020), however, the rates and controls on OC burial by lakes remain uncertain, as do the possible effects of future global change processes.

3.2.3.1 The mountain lakes

Organic accumulation in high mountain lakes is limited by the reduced vegetation and soil cover and by the low productivity that strongly depends on seasonality (ice-covered versus ice-free periods). Many sites in the Iberian Peninsula demonstrate large changes in lakes trophic states during the last millennium (Oliva *et al*, 2017; Catalán *et al*, 2009 and references therein).

Sediments accumulated in Pyrenean lakes during the last 2000 years have organic carbon values between 1 and 15% and relatively high C/N ratios suggesting a significant contribution of terrestrial carbon, even in lakes located at high altitude with watersheds almost devoid of soils, likely due to the low bioproductivity in these settings (Vicente de Vera, 2017, Sociat, 2018; Galofre, 2019). All lakes have lower values prior to 1700 CE (< 0.0013 g.cm^{-2}.yr^{-1}) (Figure 4). Most lakes show the onset of an increasing trend in TOC flux values between mid 17th – mid 19th centuries, and a more rapid increase in the mid and late 20th century. The largest increase in TOC fluxes occurred in mid 1970s in Sabocos (0.001 to 0.007 g.cm^{-2}.yr^{-1}) and Acherito (0.0005 to 0.0033 g.cm^{-2}.yr^{-1}) but later on, around 2000 CE in La Sierra (0.0008 to 0.0028 g.cm^{-2}.yr^{-1}). The 20th century increasing trend is more significant in Acherito, Sabocos and Urdiceto than in Cregüeña and La Sierra. Urdiceto reached higher values after the damming in the early 1940s (with values up to 0.002 g.cm^{-2}.yr^{-1}). Sabocos reached the highest values of the studied lakes –almost 0.008 g.cm^{-2}.yr^{-1}– in the early 1980s and has decreased after that but still with the highest values (> 0.004 g.cm^{-2}.yr^{-1}). The δ^{15}N and δ^{13}C signatures of Pyrenean lakes show a large variability likely controlled by site-specific limnological parameters but also suggest an increase in bioproductivity (Vicente de Vera *et al.*, 2020). The singularity of Sabocos, with high TOC fluxes and C flux is underlined by the highest δ^{13}C values (up to -4 per mil). Recent decreasing δ^{15}N trend could indicate a higher availability in reactive nitrogen due to human activities in the valleys. All Pyrenean lakes show evidences for an increase in carbon accumulation (TOC fluxes) and in bioproductivity (isotope signatures) during the last decades.

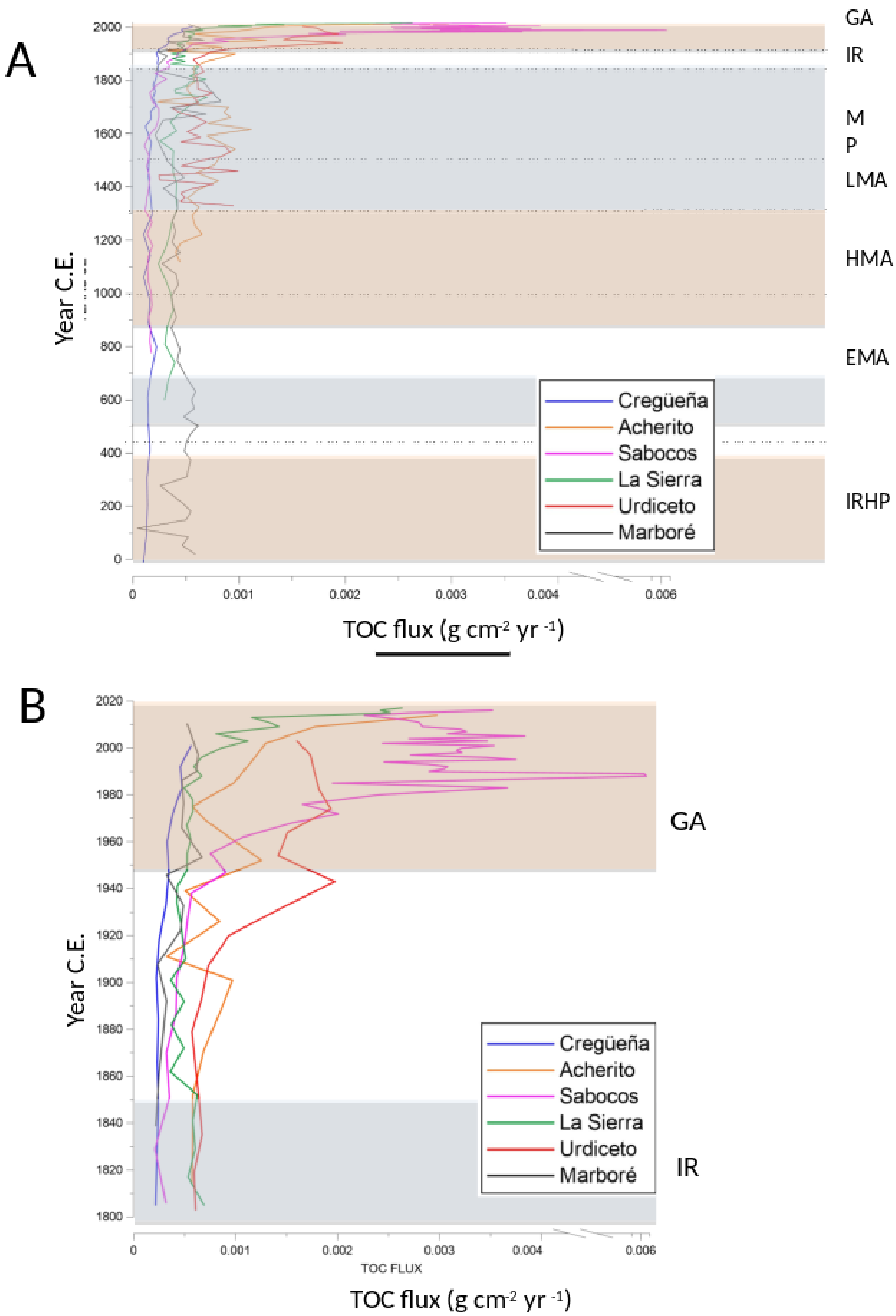

Figure 4: Organic carbon fluxes in selected Pyrenean Lakes during the last 2000 years (A) and last 150 years (B). Historical periods and climate phases as in Figure 2.

3.2.3.2 The coastal lakes

In the Spanish Mediterranean coast, the **Valencia Albufera** has been extensively studied (Marco *et al.*, 2010 and references therein). The Albufera was a saline lagoon during Medieval times and only in the last quarter of the 19^{th} century, became a freshwater system as a result of rice field expansion. The untreated sewage waters and the change of rice cultivation methods had increased the nutrient load favoring a drastic eutrophication process during the late 20^{th} century. Input from nearby industries and increasing hunting activities have also increased metal loads since the beginning of the 19^{th} century (Marco *et al.*, 2010).

The **Vichuquén** Bay in the Chilean coast was disconnected from the Pacific Ocean around 1200 yr ago and became a coastal lake (Frugone *et al.*, 2017). Interestingly, historical landscape changes - including those during the indigenous settlements, Spanish conquest and the Chilean Republic up to mid-20^{th} century - did not greatly alter sediment and nutrient fluxes to the lake. Since mid 1950s, sedimentological and geochemical evidence suggest an increase in hypolimnion anoxia, and higher bioproductivity leading to current eutrophication (Figure 5) (Frugone *et al.*, 2018). This shift is coeval with the largest transformation in the Vichuquén watershed, as native forest almost disappeared, tree plantations reached up to 60% of surface area and tourism greatly increased. In **Laguna Matanzas**, the transition from a restricted marine environment (lagoon) to a freshwater lake environment occurred around 600 yr ago. Fuentealba *et al.* (2020) showed that long-term anthropogenic use (agriculture, cattle grazing) in the Matanzas watershed since the Spanish Colonial period had little impact on nutrient and organic matter transfer to the lake. In contrast, the largest changes in organic carbon burial and C and N dynamics occurred in the mid-1970s (Figure 6), driven by the replacement of native forests and grasslands by government-subsidized tree plantations of introduced Monterrey pine (*Pinus radiata*) and eucalyptus (*Eucalyptus globulus*) and the irrigation of new agricultural fields. In both sites, recent climate trends (increasing temperatures and decreasing precipitation) may have played a role but land use changes seem the main responsible for higher transfer of nutrients from the watershed driving the observed changes in the lakes.

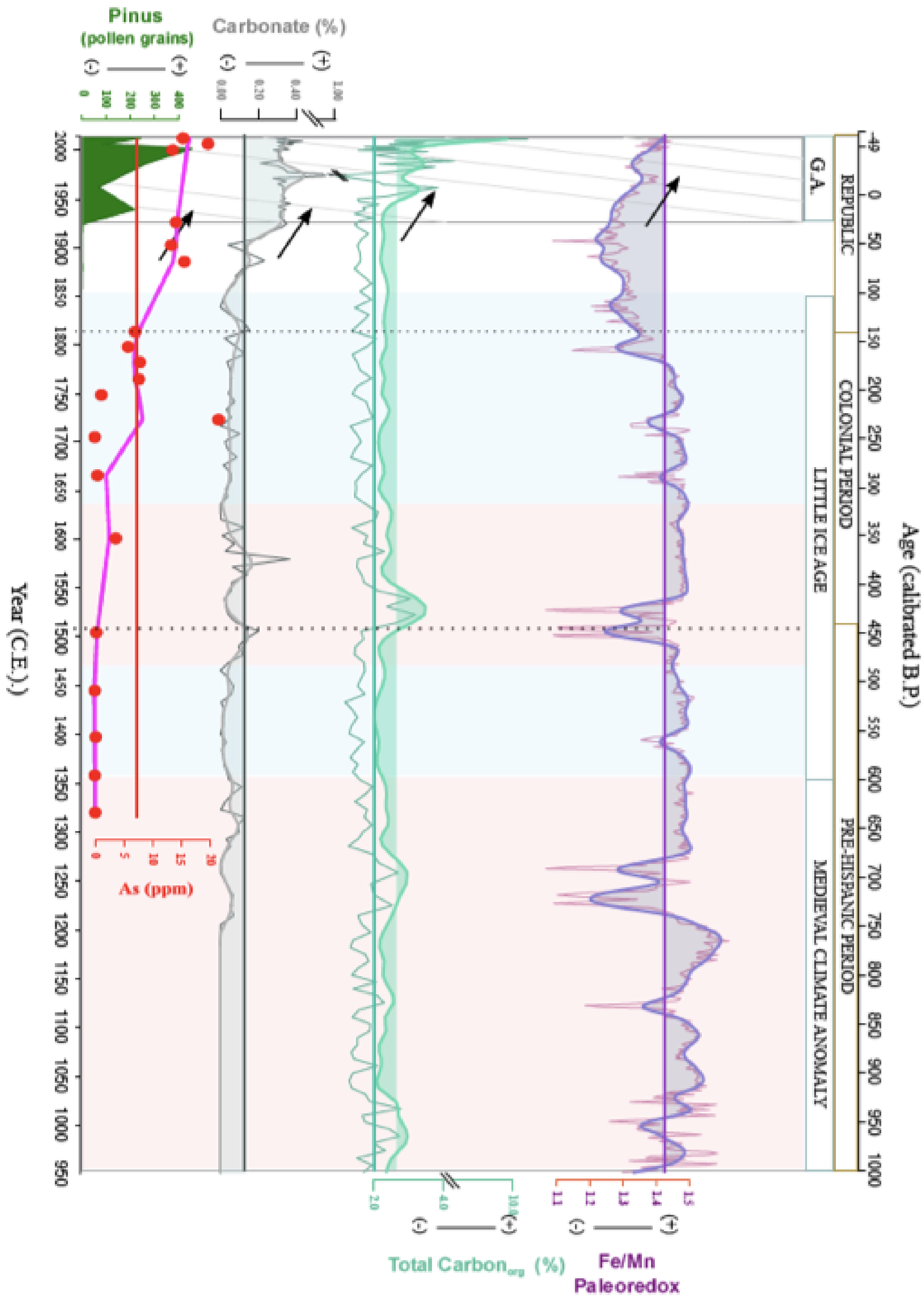

Figure 5: Geochemical proxies for the recent evolution of Lake Vichuquén (central Chile) (modified from Frugone *et al.*, 2018).

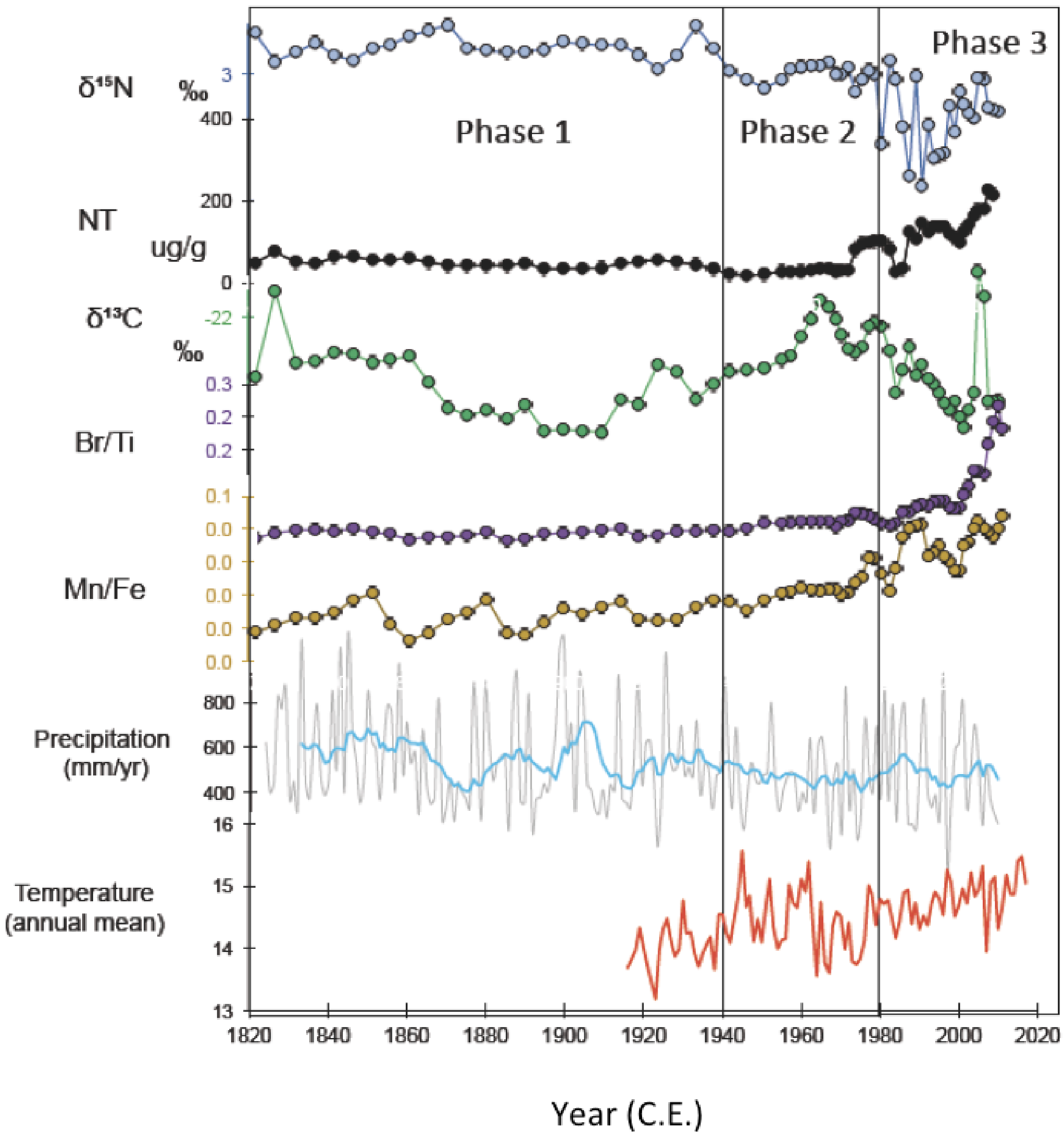

Figure 6: Geochemical proxies for the evolution of Lake Matanzas (central Chile) during the last 200 years (modified from Fuentealba *et al.*, 2020).

4 HUMAN AND CLIMATE SYNERGIES DURING THE ANTHROPOCENE

As climate and humans interactions grow even more entangled, can we identify and quantify their synergetic effects in intensified erosion, heavy metal mobilization and C fluxes in Mediterranean watersheds and lakes? Can we tell apart climate and human roles?

Sediment fluxes maximize when human and climate factors reinforce each other. Strong human disturbances in Iberian landscapes occurred during both warmer periods (MCA) and colder (LIA). The cases of the coastal lakes in Chile and the Medieval deforestation in Spain illustrate the paramount role of land use changes in lake dynamics. Our research in the Iberian Range has demonstrated that in highly human-modified landscapes, positive synergies between increasing human impact and precipitation led to peaks in sediment delivery and heavy metal remobilization (Barreiro-Lostres *et al.*, 2015). The Iberian Range sites show that during wetter phases (LIA), higher flood frequency and intensity increased sediment delivery in lake watersheds. Farmland abandonment and consequent re-vegetation since 1950s has reduced runoff, erosion and sediment yields, particularly in the larger watersheds. Since mid 20^{th} century, increase in extreme events and reforestation due to rural exodus have had opposite impacts in sediment delivery in the Iberian sites (García-Ruiz *et al.*, 2013). In the smaller watersheds, re-vegetation and changes in land use are smaller and recent changes in rainfall seasonality and increase in storminess may account for increased sediment delivery to the lakes (Barreiro-Lostres *et al.*, 2015, 2017). From a sediment delivery point of view, the Anthropocene in Iberian Mediterranean watersheds started during early Medieval times and in central Chile during the early 20^{th} century.

Heavy metal stratigraphies are a clear marker of human impact in the planet. A large heavy metal signature in the sediments deposited during the Roman Empire all over the northern Hemisphere underlines the onset of the Anthropocene during this first Globalization, although in some regions, the heavy metal pollution could have been higher during the 1900s and the Great Acceleration. Although global deposition rates have decreased in the last decades, the remobilization of the heavy metals stored in the watersheds as the hydrological cycle intensifies is a new concern (Bacardit and Camarero, 2009; Bacardit *et al*, 2012).

Changes in the global carbon cycle are a clear signature of the Anthropocene linked to recent global warming and the Great Acceleration. Although climate change has been considered the main responsible behind an increased algal productivity since the end of the 19^{th} century and during the late 20^{th} century documented in lakes in the northern (Bergstrom and Jansson, 2006; Rühland *et al.*, 2015, Catalán *et al.*, 2009) and southern hemisphere (Carrevedo *et al.*, 2015), it remains to be proven that climate is the only factor controlling these documented aquatic transitions (Catalán *et al.*, 2013). Alternative causes as nitrogen (Galloway *et al.*, 2008) and phosphorous (Camarero and Catalán, 2012) increase in high altitude lakes, and catchment mediated processes (Catalán *et al.*, 2013) could not be ruled out.

Most lakes in Mediterranean Spain and Chile show small changes in carbon dynamics during previous climate phases and a unique trend during the current Global Warming and Great Acceleration. Climate change seems to have been the main responsible of increasing carbon deposition fluxes during warmer phases of the last two millennia. However, during the last decades, higher TOC and Br/Ti, lower δ^{13}C, δ^{15}N and C/N suggest an increase in carbon accumulation in most sites, indicative of higher productivity as temperature and nutrient fluxes by atmospheric deposition increased (Galofre, 2019; Sociats, 2018; Vicente de Vera, 2020). The changes are even more intense in intermediate and low elevation lakes where the alteration of surface processes in the watersheds due to new land uses has also increased.

This regional pattern is coherent with global trends. We participated in a survey of more than 500 lakes (Anderson *et al.*, 2020) to calculate contemporary global, mean carbon sequestration rate as 19.6 g C $m^{-2}yr^{-1}$ (range: 1 to 973 g C $m^{-2}yr^{-1}$) that represents a tripling across all biomes over the last 150 years. At a planetary scale, this increase is mostly attributed to disruption of nutrient cycles and land-cover change, acting broadly synchronously across the planet. Combining biome-specific burial rates with the current global lake area estimate, the annual global C sequestration rate is 0.1 Pg yr^{-1}, off-setting annual CO_2 emissions from lakes and reservoirs by $\sim 30\%$. While there is clearly a temperature effect on global terrestrial and aquatic primary production, the increase in burial rates from pre-1900 to post-1970 is substantially greater than that attributable to global or regional temperature increases.

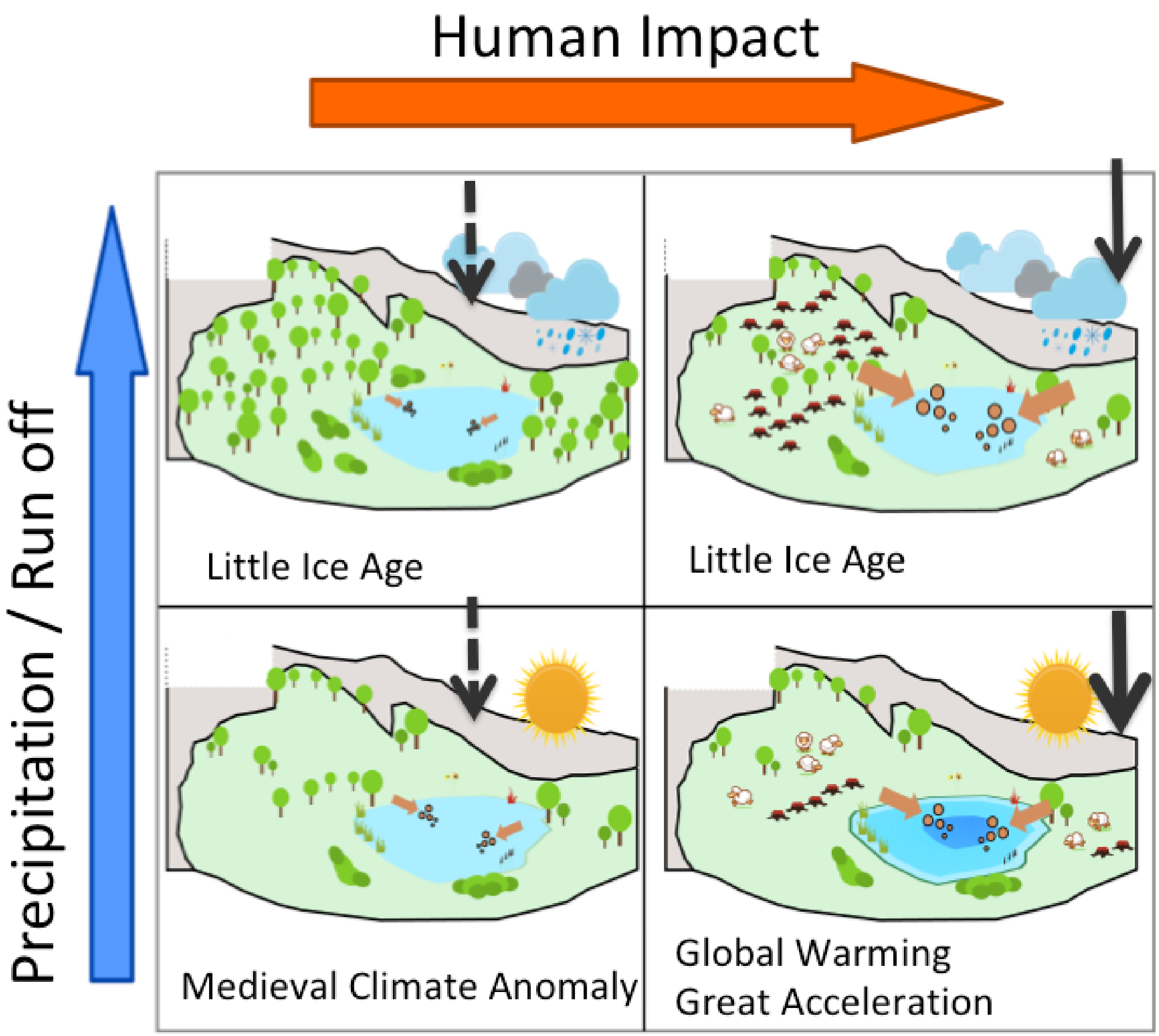

Figure 7: A sketch of human and climate synergies in Mediterranean watersheds during the last millennium (based on Barreiro-Lostres *et al*, 2017). During historical times, phases of higher precipitation and increased human impact (e.g., LIA) caused increased sediment delivery and warmer phases (e.g., MCA), an increase in lake bioproductivity. During the current Global Warming and Great Acceleration both sediment and carbon fluxes in lakes have increased. Heavy metal pollution (black arrows) was higher during periods of higher mining and smelting activities and after the Industrial Revolution.

Figure 7 summarizes the compounding effects of climate (temperature and water balance) and human activities in lakes. Historically, in most cases, wetter episodes during phases of more intense land uses in the watersheds (Little Ice Age for example) lead to higher sediment delivery and warmer phases (Medieval Climate Anomaly, as an example) to higher productivity in the lakes. Heavy metal pollution is controlled by anthropogenic emissions, although climate patterns may influence deposition too. The onset of the "Anthropocene signal" in the lake record varies according with the selected indicator: sediment, carbon or metal fluxes. Past historical periods are not perfect analogues for the current times, but all indicators underline the uniqueness of the impact on lake ecosystems during the Great Acceleration and Global Warming.

5 CONCLUSIONS

Sediment fluxes, heavy metals and carbon accumulation values in lake sediments clearly marked the main phases of human impact during the Anthropocene in Iberian and Chilean lakes. All lakes surveyed show changes associated to sediment delivery and bioproductivity during the last two millennia cold/warm climatic phases and also during the recent Global Warming/Great Acceleration. Changes during warmer periods (as the MCA and the IRHP) are not so prevalent in the high altitude Pyrenean sites. The different timing and intensity of the reconstructed changes may reflect the regional variability caused by local responses of the watersheds and lakes to climate parameters and human disturbances.

The synergic effects between climate and humans were particularly intense at the onset and the second part of the LIA and since the 18^{th} century: the climatic impact was amplified by human disturbance resulting in higher sedimentary rates and denudation rates in the catchments.

Heavy metal stratigraphies show the global reach of the Roman Empire mining activities, the large environmental impact during the industrial revolution and the great Acceleration and the decreasing values after conservation measurements in the late 20^{th} century.

Most lakes suggest higher carbon accumulation in the sediments during warmer phases. However, the last decades stand out with unique increasing trends in carbon accumulation in most sites. Climate change seems to have been the main responsible of increasing carbon deposition fluxes during the last two millennia prior to Medieval times. However, recent trends in carbon accumulation could also have been favored by higher productivity as fluxes from anthropically-derived (reactive nitrogen) nutrient have increased even in high altitude settings.

The survey of selected sites in Chile and Spain demonstrate the long reach of human impact in the Mediterranean lakes and watersheds during the last two millennia, the intensification during Medieval times in Spain and Colonial period in Chile and the acceleration during the last decades. Past periods of high human impact in Mediterranean lakes and watersheds serve to better understand, model, and predict the effects of the current period of environmental and climate crises.

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