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Impact of anthropogenic and climatic stressors in North Atlantic islands using lake sediment bioindicators (Diatoms and Chironomids).

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Título del Trabajo de Fin de Grado: Impact of anthropogenic and climatic stressors in North Atlantic islands using lake sediment bioindicators (Diatom and Chironomid)

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Abstract

The oceanic islands are considered fragile ecosystems. These delicate places were controlled by climate changes in the past, however with the arrival of humans, the anthropogenic pressure in this kind of habitat became undeniable. So, to assess the human impact and climatic pressure, two bioindicators (Diatom and Chironomid) located in the lakes of the Azores Archipelago, Faroe Islands, Greenland and Iceland were used. Several corers (Russian type-corer and UWITEC gravity corer) were used to take sediment samples in the lakes and then using the right resources the identification of the different species of the bioindicators began. The chironomids result indicated the initial impact of humans was not very severe and the principal changes were attributed to climatic change. However some activities like fish introduction could greatly affect these organisms. The diatoms showed a domination of benthic species before the anthropogenic presence, but with the arrival of humans there was a shift to planktonic dominance in the lakes. Since the colonization of the islands, notable changes occurred in the landscapes, activities like deforestation or animal introduction led to a visible transformation in the surroundings of the lakes. However, some lakes did not show many changes during the initial presence of humans. These changes were more attributed to climatic consequences. The period of the MWP (Medieval Warm Period) and the LIA (Little Ice Age) for instance, greatly affected the ecosystems of these kinds of places and several changes were observed. So, the utilization of these bioindicators can be useful to observe the changes that were produced by the climate and furthermore, the anthropogenic impact.

Introduction

Most contemporary terrestrial ecosystems worldwide are considerably influenced by cultural activity. The timescales in which this activity has operated vary greatly. So, there is a special interest to work in areas where the human impact is relatively recent, for example, in oceanic islands, where they are considered to be very fragile ecosystems and easily modified through natural and human disturbances (Sax & Gaines, 2008).

It is fair to say that oceanic islands are mainly controlled by climate changes and volcanism, but recently these changes in ecosystems were attributed also to the anthropogenic impacts. For example in the Faroe Islands before human settlement there was a stable shrub-woodland cover however, after the arrival of humans these islands suffered a transition from shrub-covered to open landscapes that were used for agricultural activities such as, production of livestock (Hannon et al., 2001; Jóhansen, 1985). Another example of the human disturbance can be the introduction of non-native species into the environment. This introduction is one of the main threats to autochthonous biodiversity globally and one of the major reasons for the decline of worldwide diversity (Mooney and Cleland, 2001; Vitousek et al., 1996). In the Azores Archipelago for instance, the introduction of fish in the fishless lakes caused an immense impact in the aquatic environment (Raposeiro et al., 2017).

As mentioned earlier, apart from the anthropogenic impacts, oceanic islands are mainly controlled by climate changes and volcanism. These climate changes are the principal factor in the ecology of oceanic islands, especially islands located in the North Atlantic like, the Faroe Islands, Iceland and Greenland. Moreover, if we look back in the past, the North Atlantic Region in the first millennium suffered a rapid environmental change (Andersson et al., 2003; Dolven et al., 2002). This rapid change increased the number of stressors affecting the different ecosystems of the world, including the Arctic ecosystems. Besides, nowadays the effects of climate change are becoming increasingly evident and mark biological shifts in both aquatic and terrestrial ecosystems (Post et al., 2009; Smol et al., 2005).

So, to fully understand these ecosystems processes and the different stressors like human impact or climate change, it must be assessed over a range of timescales. Even if long-term climate change is a major driver of natural ecosystem variability, identifying evidence of past climatic change can be helpful to better visualise human-induced impacts because often it is confounded.

As a result, lakes located in the oceanic islands of the Azores Archipelago, Faroe Islands, Greenland and Iceland have been studied to assess the influence of both climatic change and anthropogenic pressure in the lakes ecology using aquatic organisms as bioindicators. We are focusing on the works of Vázquez-Loureiro et al., (2019), Raposeiro et al., (2017), Hannon et al., (2005a), Gathorne-Hardy et al., (2007), Perren et al., (2012), Millet et al., (2014) and Gathorne-Hardy et al., (2009).

Studied Islands

The Azores Archipelago lies in the middle of the North Atlantic Ocean. It is a group of nine volcanic islands, roughly 1500 km from Europe and 1900 km from America. A temperate oceanic climate is characteristic of the archipelago, with mild temperatures and a rainfall regime with a strong seasonal cycle and high relative air humidity (Hernández et al., 2016) (Fig.1).

On the other hand, the Faroe Islands are a small archipelago of 18 inhabited islands and numerous islets in the North Atlantic. It is about 300 km northwest of the Shetland islands and 675 km west of Norway (Fig.1). This archipelago has a strong maritime climate and the terrestrial landscape is sensitive to temperature changes as the islands are narrow, with an average distance of 5 km to the sea. The weather is windy, humid and changeable (Sogaard, 1996)

Furthermore, Greenland is the world's largest island and an autonomous Danish dependent territory. It lies in the North Atlantic Ocean, with two-thirds of the island in the Arctic Circle. It is 800 km away from the North Pole and separated from Canada's Ellesmere Island by only 26 km. The nearest European country is Iceland, lying about 320 km to the east (Fig.1). The climate of Greenland is Arctic with rapid weather changes and cold temperatures (Rasmussen, 2019).

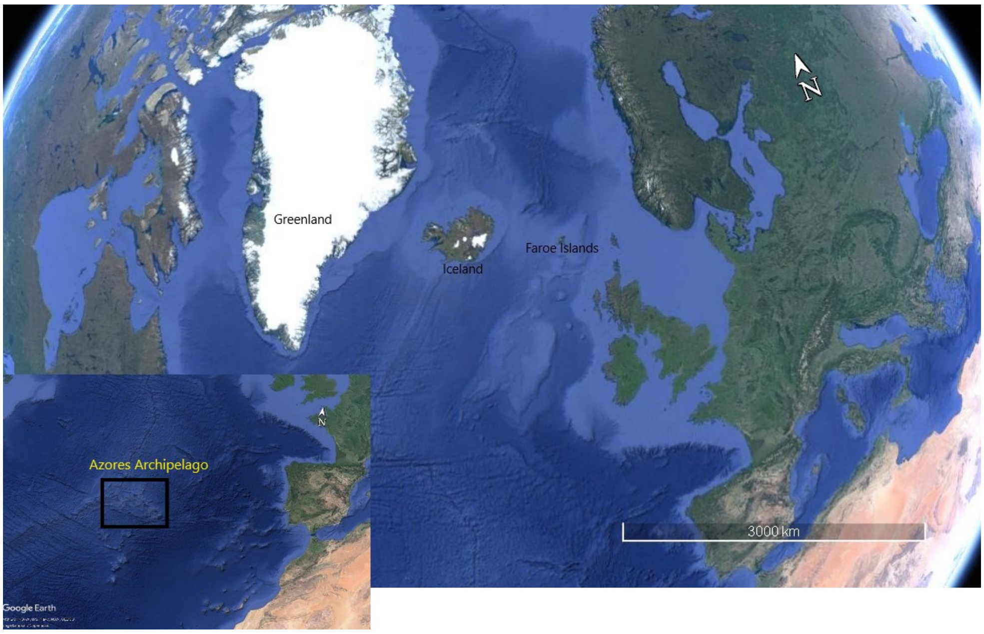

Figure 1. Locations of the studied islands by Google Earth Pro

Finally, Iceland is an island in the North Atlantic, lying on the constantly active geologic border between North America and Europe. It is 320 km from Greenland (Fig.1). Its climate is maritime subarctic influenced by changes in both atmospheric and oceanic circulation patterns (Andrews and Giraudeau, 2003). Temperatures do not vary much throughout the country.

Islands environmental settings and human settlement

The Azores Archipelago is geologically young (8.12 Ma- Santa Maria Island) (França et al, 2003) but at the same time the geology of the region is complex because of the volcanic nature of the islands and the existence of complex tectonic plate movements. The geology of Sao Miguel Island for instance is dominated by three active composite volcanoes (Sete Cidades, Fogo and Furnas) and since settlement in the 15th century, 26 eruptions have taken place in the Azores (Weston, 1964; França et al, 2003).

It was officially colonized by the Portuguese in 1432 AD. Since the precolonization times to present, notable changes in the landscape have occurred (Dias, 1996). Biodiversity impairment is a well-recognized consequence of deforestation and exploration of natural resources with the later biological invasion from man-mediated introductions of species. According to Kottelat & Freyhof (2007), the goldfish may have arrived from the Portugal mainland in 1611 AD and the fish stocking in lakes started in 1879 AD. Also, water quality deterioration due to cultural eutrophication has been reported in the Azores lakes since the 1980s, which has been related to agricultural and farming activities (Gonçalves, 2008; Cruz et al., 2015).

On the other hand, the Faroe Platform was formed during the period of Paleocene (62-52 Ma), when the huge volcanic activity of the region led to a continental break-up between Greenland and Eurasia. The Faroe islands are considered volcanic in origin however, nowadays it is not an active volcanic region due to the evolution of tectonic plates (Jolley and Bell, 2002; Ritchie et al., 1999; Saunders et al., 1997).

These volcanic islands remained uninhabited until the late first millennium AD, when the Norse (Nordic people) colonized the archipelago (Arge, 1993), but there may have been limited earlier settlement by Irish hermits in the sixth to eight centuries AD (Hannon et al., 2005; Hannon & Bradshaw, 2000; Jóhansen, 1985; Jóhansen, 1979). These human settlers brought many plants and animals with them, including sheep, cattle, goats and pigs (Church et al., 2005) changing the natural environment through grazing. Furthermore, there is a debate between the trees of the Faroes being of natural origin or planted at the time of settlement (Hannon & Bradshaw, 2000). Maybe the assumption of Faroes being unwooded must be reconsidered, However, these islands have supported limited natural tree growth in the past, from BC 2500 until AD 770 (Hannon and Bradshaw, 2008).

The geological development of Greenland spans almost four billion years. The central basement came into existence during mountain-building episodes (38000-1600 Ma). Then two coast-parallel younger mountain chains formed in North-East and North Greenland (430-450 Ma) and with the plate-tectonic opening of the North Atlantic Ocean (55 Ma) major volcanic successions occurred in East and West Greenland (Henriksen, 2008). However, nowadays Greenland is not known for having volcanic activity but evidence of past volcanic activity can be seen in sediments carried by Greenland's glaciers.

Referring to the human settlements in Greenland, South Greenland is a very interesting place due to its unique history of human-environmental relationships. At the end of the 10th century, the Norse colonized the areas in the Eastern Settlement and later the Western Settlement (Gad, 1970). However, in the 15th century the Norse failed to cope because of the environmental changes during the LIA (Little Ice age) between 1400 and 1900 AD, provoking cooler temperatures. This led to abandonment of the region (Dugmore et al., 2012; Massa et al., 2012). Five hundred years later, the Denmark governments resumed agriculture in South Greenland in the beginning of the 20th century. When the Norse were still on the island, they used the catchment of the lakes for grazing livestock as well as hay production (Nørlund, 1936). Furthermore, when agricultural practices resumed in the 1920s, they started using new agricultural techniques.

In contrast to Greenland, Iceland is a relatively young island (18-25 Ma). The formation of this island also started with the plate-tectonic opening of the North Atlantic Ocean (55 Ma). It is one of the regions with the most volcanic activity in the world, having 130 volcanoes and 30 of them still being active.

Humans arrived in Iceland approximately in 874 AD, but Dicuil´s *De mensura orbis terrae* supported the idea of the Irish monks occupying the country before the Norse settlers (Buckland et al., 1995; Sveinbjarnardóttir, 2002). This Norse colonization caused major impacts on the natural environment. The land-use practices and introductions of grazing animals, particularly sheep, precipitated catastrophic environmental change (Buckland et al., 1990.; Edwards et al., 2005), including irreversible erosion (Ólafsdóttir and Guomundsson, 2002).

Diatom and Chironomid as paleoenvironmental indicators

For the paleoenvironmental reconstructions, several bioindicators have been used. These bioindicators are used to assess the quality of the environment and how it changes over time (Holt and Miller, 2010). Changes in the environment are attributed to anthropogenic disturbances as well as natural stressors (Holt and Miller, 2010). Here we focused on some of the bioindicators located in the sediments of the lakes.

On one hand we have the Chironomids, holometabolous insects. In lakes, these insect´s larvae are benthic organisms that produce chitinous remains (head capsules, HC) during their development. These remains (HC) can be extracted and identified, allowing the possibility to reconstruct changes in the environment (Raposeiro et al., 2017) (Fig. 2A).

The chironomids are good indicators of temperature changes and also they can show disturbances by the introduction of non-native species in the lakes, like fish (Armitage et al., 2012). So, they are widely considered to be valuable climate proxy in the sediment record (Walker and Cwynar, 2006).

On the other hand, we have Diatoms, which are single-celled algae and primary producers. They are organisms with cell walls composed of silica. These silica walls are key for the identification because the characteristics of the frustules are the principal taxonomic criterion (Vázquez-Loureiro et al., 2019) (Fig. 2B).

These organisms have distinct ranges of pH and salinity where they will grow and also tolerances for other environmental variables. These distinct ranges and tolerances have been used successfully to trace the nature of human impacts (Fritz, 1989; Bradshaw, 2005) and also for disentangling the impacts of early human settlement (Anderson et al., 1995; Ekdahl et al., 2004).

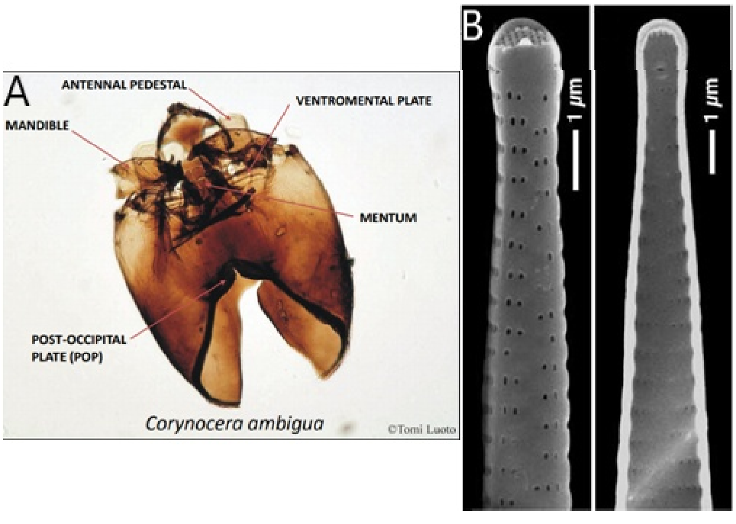

Figure 2. Examples of a Chironomid Head Capsule (A) and a Diatom (*Fragilaria tenera*) (B) by Tomi Luoto and Perren et al., (2012)

METHODOLOGICAL APPROACHES

Studied lakes and sampling

In the Azores, Lake Azul was sampled, located in Sao Miguel Island. The lake is situated in the westernmost part of Sao Miguel, in a caldera called Sete Cidades (Figure. 3). It is 260 m above sea level (Pereira et al., 2014) with an area of 435 ha and maximum depth of 27 m. In September 2011, were taken a total of 15 cores (AZ11) using a 60 mm diameter UWITEC gravity corer from UWITEC floating platform (Fig.3 D).

In the Faroe Islands, Gróthúsvatn and Heimavatn were sampled by Gathorne-Hardy et al., (2007) and Hannon et al., (2005b). The first one is located on the island of Sandoy, about 1,5 km from the settlement of Sandur (Fig. 4). It is 1 m above sea level with an area of 20 ha and maximum depth of 2 m. A core was taken from the middle of the lake using a large Russian-type corer (depth of 2 m). The second lake is located on the northern island of Eysturoy, and is situated beside the village of Eioi. Cores of 1m were taken in the basin closest to the village by the same type of corer.

In Southern Greenland a lake called Igaliku was sampled in 2007 (Fig. 5 right), using a UWITEC gravity corer and piston corers in the deepest part of the lake. This lake occupies a low valley between the head of Igaliku fjord and Erik’s fjord and lies in the location of a medieval settlement. It has a surface of 34 ha and a maximum depth of 26 m. The catchment of the lake was mostly used as extensively grazed grassland (Gauthier et al., 2010).

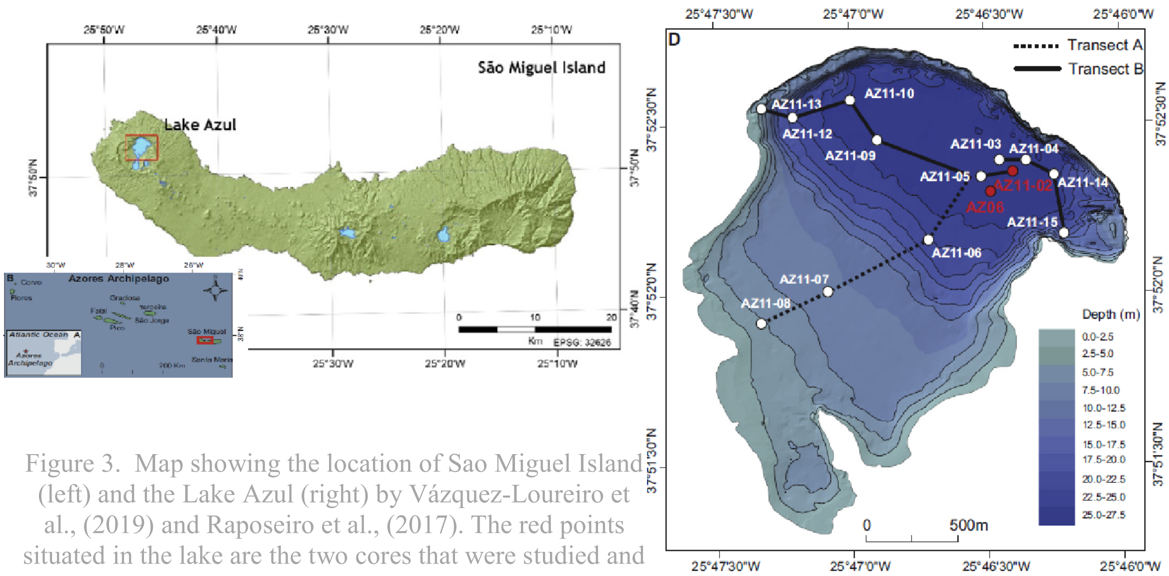

Figure 3. Map showing the location of Sao Miguel Island (left) and the Lake Azul (right) by Vázquez-Loureiro et al., (2019) and Raposeiro et al., (2017). The red points situated in the lake are the two cores that were studied and analyzed.

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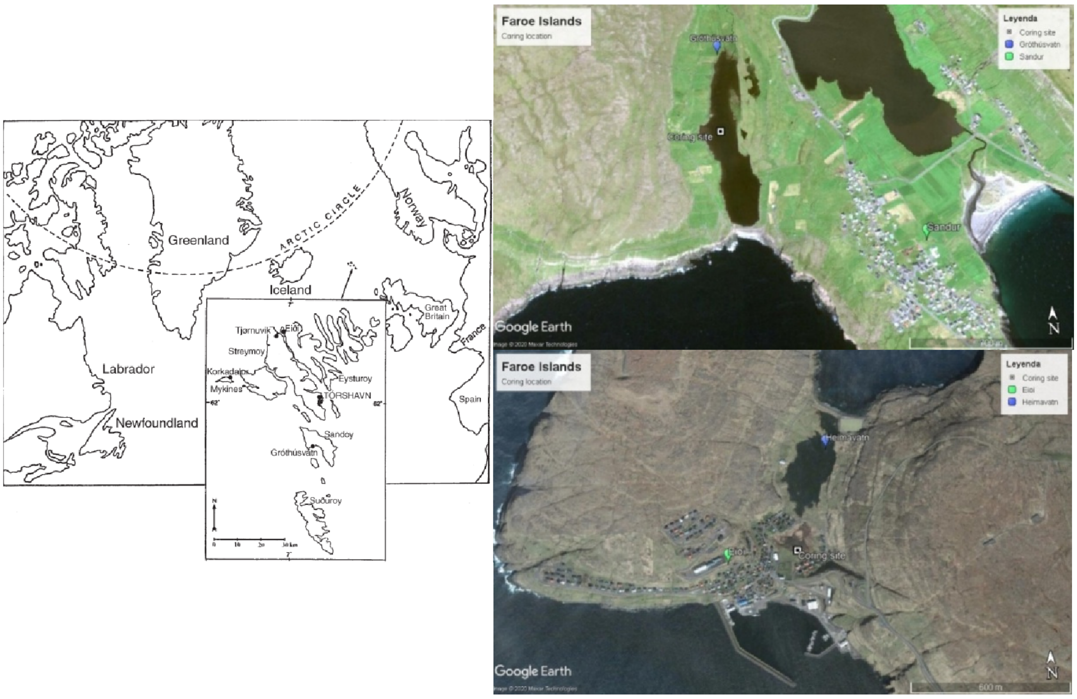

Figure 4. Map showing the locations of Faroe Islands (Left) by Hannon et al., (2005b) and the studied lakes Gróthúsvatn and Heimavatn (Right) by Google Earth Pro.

Three overlapping cores were taken from a boat near the middle of the lake Breioavatn (Iceland) (Fig. 5 left) using a Russian-type corer (Jowsey, 1966) in a depth of 80 cm. This small oval lake is located 2 km northeast of the hamlet of Reypkholt and is 100 m above sea level. It has a surface of 3.5 ha with a maximum depth of 80 cm.

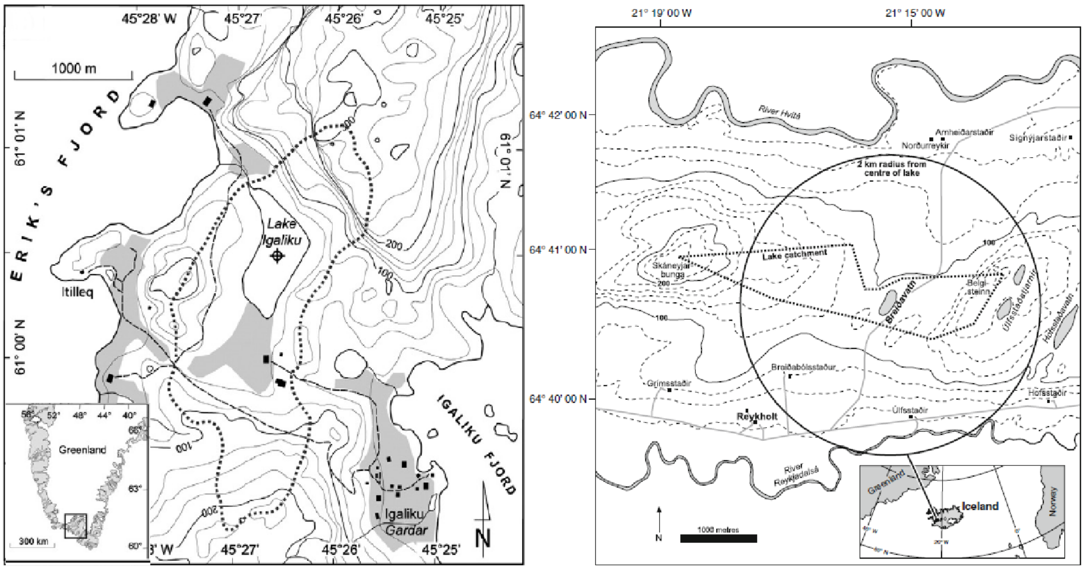

Figure 5. Map showing the location of Lake Igaliku (Right) by Millet et al., (2014) and Lake Breioavatn (Left) by Gathorne-Hardy et al., (2009)

Laboratory analysis

Diatom analysis was performed following the standard procedures (Renberg, 1990). At least 350-400 raw valves were counted for each sample and different kind of microscopes were used for the identification (Hannon et al., 2005a; Perren et al., 2012; Vázquez-Loureiro et al., 2019). For the identification, several sources were used; the literature from Greenland (Foged, 1972, 1977) and Labrador (Fallu et al., 2000) and also standard sources like (e.g., Krammer and Lange-Bertalot, 1986-1991; Lange-Bertalot, 2000-2013) . The raw valve counts were converted to percentage abundances data using different models.

Chironomids for instance, were extracted from the sediment at 2-8 cm intervals with 1-5 cm3 of sediment per sample. This extraction followed the standard procedures using the methods of Brooks et al., (2007) and Lang et al., (2003) (Gathorne-Hardy et al., 2007; Gathorne-Hardy et al., 2009; Millet et al., 2014; Raposeiro et al., 2017). The identification was made by microscope and using different sources, such as, Hofmann (1971), Cranston (1982), Wiederholm (1983),Rieradevall and Brooks (2001), and Brooks et al., (2007). 50 HC at least were counted and the relative abundance of each taxon was presented as a percentage of the total abundance.

Data analysis

PCA (Principal component analysis) was used by these studies to get a better view of the variations and patterns of the samples. PCA is essentially a coordinate transformation where the X and Y axis are rotated into a new axis X' that lies along the direction of the maximum variation in the data. Millet et al., (2014) used the Vegan packages for R (Oksanen et al, 2011) to perform the PCA. A covariance matrix of diatom taxa with relative frequencies >1% was used by Perren et al., (2012) for the analysis. On the other hand, Vázquez-Loureiro et al., (2019) used software called CANOCO 4.5 to perform the PCA.

The DAZs (Diatom Assemblage Zones) was performed by Vázquez-Loureiro et al., (2019) using stratigraphically constrained cluster analysis based on squared Euclidean dissimilarity (CONISS, Grimm, 1987). Zonations with variances that exceeded the values generated by a broken-stick model of the distribution of variance were considered significant (Bennett, 1996).

To identify chironomid assemblages, Cluster analysis was used by Raposeiro et al., (2017). Also, ANOSIM was used to test for significant differences between, before and after fish introduction. The groups were defined according to the timing of introduction of fish species or fish groups. ANOSIM is a non-parametric analysis which tests for differences among samples within pre-defined groups.

Millet et al., (2014) also used stratigraphically constrained cluster analysis by Coniss (Grim, 2004) to define the zones of the chironomid assemblage. The number of statistically different biozones was assessed using the broken stick model.

In order to investigate the relationships between the chironomid data and temperature, Gathorne-Hardy et al., (2009) used detrended correspondence analysis (DCA) using CANOCO program version 4.51 (ter Braak and Smilauer, 2002) with rare species down weighted.

RESULTS

Paleoenvironmental reconstruction

Azores Archipelago

Micropsectra contracta-type (84%), *Psectrocladius sordidellus* type (67%) and *Micropsectra type A* (64%) were the dominant taxa in the chironomid assemblage.

ANOSIM analysis showed that the chironomid assemblages were statistically different before and after predator introduction. Also this analysis showed that the first fish introduction around 1790 resulted in highly significant differences in chironomid assemblages. After the introduction of goldfish and also of carp, *Micropsectra type A* and *Macropelopia* type decrease. The dominant taxa, *Micropsectra-type* A, *Micropsectra contracta*-type and *Macropelopia* are considered indicators of good quality including oxygen-rich conditions (Mousavi et al., 2002; Oliver, 1971). Some *Micropsectra* species dominate deep ultraoligotrophic alpines lakes (Frossard et al., 2014; Frossard et al., 2013), while *Macropelopia* is characteristic of acidic lakes (Brooks et al., 2007; Brundin, 1956).

Fish stocking in Azorean lakes started in AD 1879. There was a decrease in abundance of cold and oligotrophic taxa, such as *Micropsectra*-type A and *Micropsectra contracta*-type (Brooks et al., 2007; Heiri et al., 2011), and an increase in abundance of warmer and meso/eutrophic taxa *Chironomus plumosus*-type and *Glyptotendipes pallens*-type (Brooks et al., 2007; Osborne et al., 2000). This suggests that the introduced fish species had a large effect on chironomid assemblages (Fig. 6).

Apart from fish introduction, climate oscillations and volcanic eruptions could have played a role in shaping the chironomid assemblage. In Lake Azul, *Chironomus plumosus*-type was present during the period of AD 1280-1440, the latest stages of the warm and arid Medieval Climate Anomaly, and absent during the Little Ice Age (AD 1450-1700). This suggests that this specie seem to be controlled by climate factors (Heiri et al., 2011; Brooks, 2000).

Cluster Analysis made by Raposeiro et al., (2017) show two different zones in the chironomid assemblages. This zone separation can be used to observe the species present in fishless situation and in a fish introduced situation.

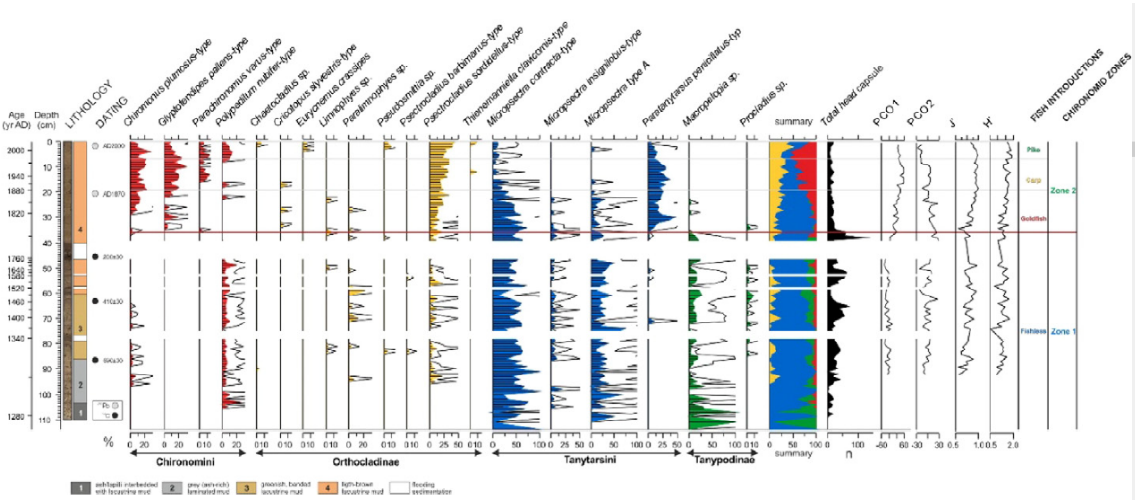

Figure 6. Paleolimnological data from Lake Azul by Raposeiro et al., (2017). Chironomid remains are indicated as percentages of head capsules are concentration per gram. The colours are the different chironomid families/subfamilies (red- Chironomini; yellow- Orthocladinae; blue- Tanytarsini; green- Tanypodinae. Horizontal white bands represent flood events.

Zone 1: AD 1290-1780

This zone is characterized by the dominance of oligotrophic-mesotrophic, oxyphilous and detritivore species, such as *Micropsectra contracta*-type and *Micropsectra type A*. There also is a dominance of few taxa. All samples from this zone were deposited during the period that fish communities were absent.

Zone 2: AD 1780-2011

There is a decrease of detritivorous taxa, like *Micropsectra contracta*-type and *Micropsectra type A*. Furthermore, an increase of the detritivore/grazers, hypoxia-tolerant, eutrophic species like *Chiromonus plumosus*-type and *Glypotendipes pallens*-type was observed. All samples from this zone were deposited in the period where the fish communities were present.

On the other hand, in the diatom assemblages, between AD 1290 and 1940, the benthic diatoms were the dominant species. But after 1940 AD, planktonic diatoms such as *Aulacoseira spp*, *Asterionella formosa* and *Fragilaria crotonensis* began their dominance.

The recent history of Lake Azul starts with a volcanic event. This event corresponds to the Caldeira Seca volcano eruption (P17) in AD 1290, which accumulated tephra deposits in Sete Cidades caldera (Cole et al., 2008). High abundances of euplanktonic and eutrophic *Aulacoseira.granulata* were found (Fig.7). Diatoms of the genus *Aulacoseira* are characteristic of well-mixed waters necessary to maintain their buoyancy and high nutrient condition (Hall and Smol, 2010). Also *Nitzschia* *valdestriata* was present. The diatom assemblage found in this phase indicate a moderately deep, well mixed, and meso to eutrophic lake.

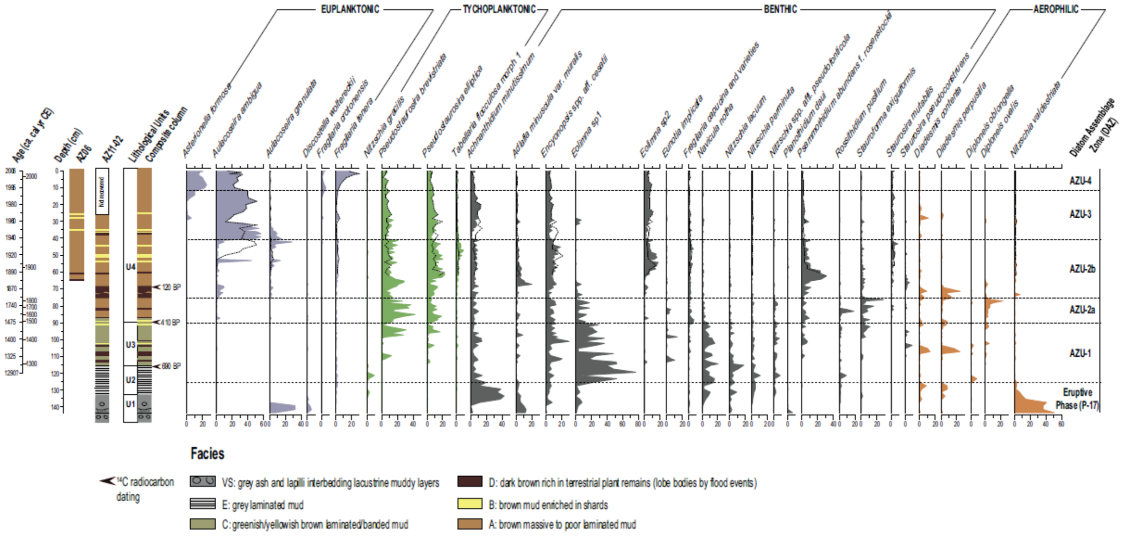

Figure 7. Diatom percentage diagram for selected taxa of Lake Azul cores: AZ11-02 (filled curves) and AZ06 (discontinued lines) (Vázquez-Loureiro et al., 2019). Diatom Assemblage Zones generated by broken-stick model of the distribution of variance (Bennett, 1996) are represented by discontinued lines.

Between AD 1290 and 1480 high abundances of *Eolimna* sp1, *Navicula* sp-1 and *Nitzschia* spp were found. These epipelic species are typical of both shallow and mid-depth zones of lakes where light can reach the bottom (Wang et al., 2012). These characteristics would indicate a moderately shallow water environment (Wolin & Stone, 2010).

In the period of AD 1480 and 1870, water level increased, which allowed a relatively large increase in littoral vs. pelagic environments. Fragilarioid taxa (mainly *Pseudostaurosira brevistriata* and *Pseudostaurosira elliptica*) became dominant. These taxa are characteristic of the shallow-water littoral zone of a wide variety of water bodies under conditions of environmental instability (Reed et al., 1999).

The facies D that we can observe in Fig.7 with black color indicates flood events, where massive terrestrial sediment was deposited. In this level a relatively high abundance of aerophilic diatoms can be found, such as *Diadesmis* and *Diploneis*.

In AD 1870-1940, there was a big landscape change that led to an increase in lake productivity with the regular presence of the euplanktonic and meso- to eutrophic diatoms of genus *Aulacoseira*.

A broken-stick model of the distribution of variance allowed identification of four significant Diatom Assemblages Zones (AZU-1 to AZU-4). PCA was also performed to interpret the underlying environmental variables explaining the composition of the diatoms assemblages.

Faroe Islands

Chironomid assemblages in the analyzed sediment record of Gróthúsvatn were dominated by *Tanytarsus lugens* type. *Ablabesmyia, Procladius*, *Psectrocladius sordidellus* type, *Dicrotendipes* and *Chironomus* were also abundant. Following landnám (Norse colonization) (dotted line in Fig. 8) there are no large-scale changes in the core. After landnám, *Dicrotendipes* increase a bit and also there is a small rise in the apparent TP (Total Phosphorus) (Gathorne-Hardy et al., 2007). *Eukiefferellia, Thienemanniella* and *Synorthocladius* decrease in relative abundance approaching the top of the core.

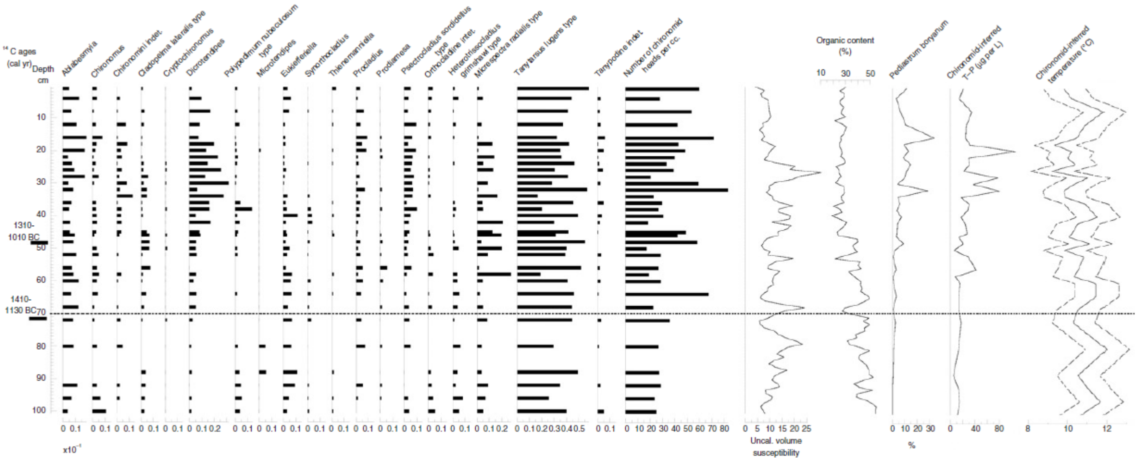

Figure 8. Selected chironomids found in the core of Gróthúsvatn by Gathorne-Hardy et al., (2007). Pediastrum boryanum (expressed as percentage of the total land pollen) is shown. Chironomid-inferrred temperature (solid line, errors are dotted lines) and TP are shown in the right of the figure. The dotted line at 70cm represents human arrival.

According to the TP changes, the relative abundance of *Dicrotendipes* may be the major driver. These changes may indicate some levels of eutrophication followed settlement but it is unlikely that the lake ever became anoxic. A study in the Swiss Alps has shown that oxygen deficiency can cause *T.lugens* type to disappear (Heiri & Lotter, 2003) but in the study of the lake Gróthúsvatn *T.lugens* type is continuously present at high frequency. Besides, the proportion of rheophilous taxa does not increase because if the lake was at some point anoxic, limnophilous species of chironomid would have been become rare and the rheophilous species more abundant (Gathorne-Hardy et al., 2007).

The little changes that *Chironomus* spp. and *Procladius* sp. shown indicates that the increase of the trophic status in Gróthúsvatn following landnám was not very severe. These two species tend to increase in relative abundance with higher TP and eutrophic conditions (Brooks et al., 2001; Wiederholm, 1983).

On the other hand, diatom assemblages in the analyzed sediment record of Heimavatn were dominated by benthic and littoral forms. In general good preservation of diatoms was recorded in the entire core. The main change occurred between AD 530 and 570 with increases in the percentage abundance of *Achnanthes linearis*, *Fragilaria vaucheriae v. vaucheriae* and small increases in the planktonic forms (Fig.9). These changes suggest disturbance on the lake and an increased supply of nutrients to the lake. However, the first indication of human impact was given by the macrocharcoal fragments at AD 570.

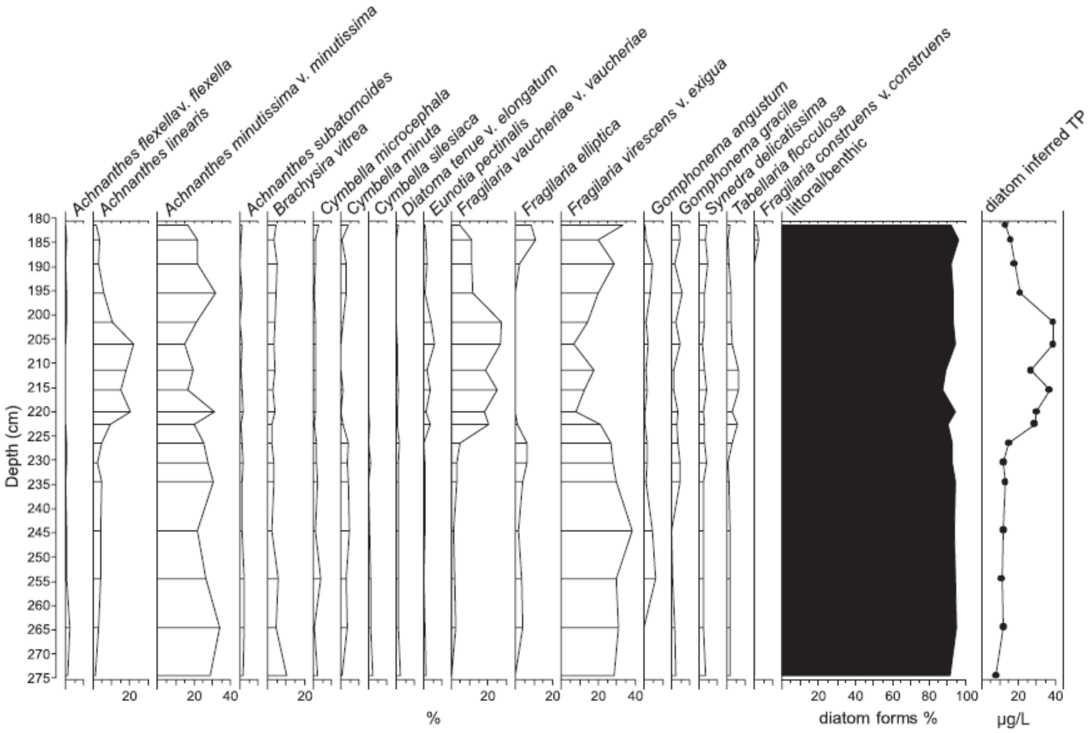

Figure 9. Summary diatom diagram for Heimavatn, showing species found and diatom habitat preferences and diatom-inferred total phosphorus (TP) concentration by Hannon et al., (2005b).

Greenland

Throughout the entire record of Lake Igaliku the chironomid assemblage was dominated by *Heterotrissocladius subpilosus*-type and *Micropsectra insignilobus*-type (Figure. 10).

Two significant biozones were recognized (IGA-1 and IGA2) after the cluster analysis. IGA-1 spans between AD 1988 and 2007. IGA-2 instead, covers the AD 540-1988 time window. The chironomid diagram shows that during IGA-2, major changes occurred.

IGA-1 consisted of high relative abundance of *M.insignilobus*-type and *C.arctica*-type, while IGA-2 samples are characterized by high relative abundance of *H.subpilosus*.

H.subpilosus-group includes strongly cold and ultraoligotrophic species (Saether, 1975), and features both low trophic (Total Nitrogen) and surface water temperature optima (Brodersen & Anderson, 2002). The modern distribution data and ecology of the taxa suggest that climate and in-lake processes are possible interacting forcing factors of the primary shift that occurred in the chironomid community.

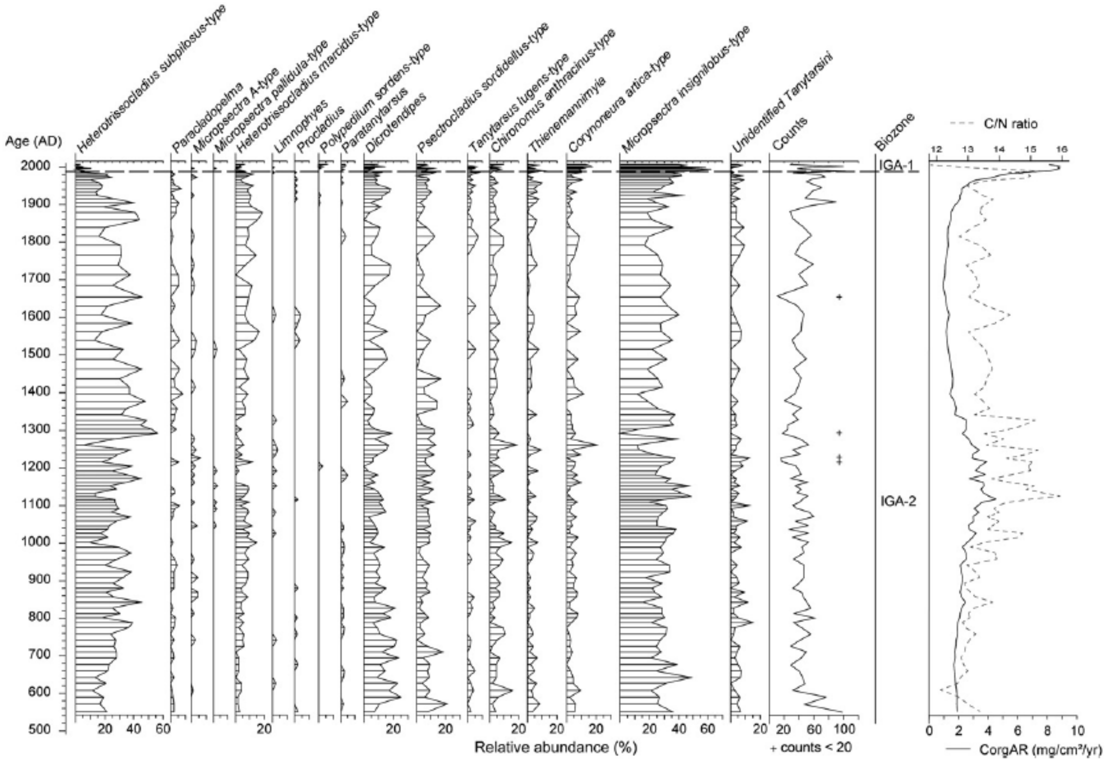

Figure 10. Percentage diagram of the most common chironomid taxa and changes in the carbón accumulation rate (CorgAR) and in the carbon:nitrogen ratio (C/N). The dotted lines indicates the limits of the chironomid biozones from the cluster analysis (Millet et al., 2014)

In the diatom analysis instead, the planktonic component was dominated by *Cyclotella stelligera*, *C rossi, C. comensis*, *C. tripartite* and *C.ocellata*. The benthic taxa were dominated by *Brachysira vitrea*, *Achnanthes* and *Achnanthidium* and *Fragilaria sensulato*.

With the arrival of the Norse period, the sediments registered slightly higher relative frequencies of the diatom taxon *Cyclotella stelligera* (Fig.11). However, Norse farming did not leave a significant impact on these environmental proxies.

In general, diatom assemblages have been stable over the last 1450 years, but in the last 30 years *Cycotella stelligera* and *Fragilaria tenera* have increased dramatically. The highest value of *C.stelligera* occurs in the period following AD 1980. The increase of *F. tenera* may mark a nutrient enrichment within the last 30 years.

In addition, PCA analysis showed that the degree of recent changes in Lake Igaliku was unprecedented. Samples since AD 1976 marked a shift reflecting changes in the biological and geochemical proxies. After 1976, there was a rise in planktonic diatoms (*C. stelligera*, *F. tenera*), reflecting increased nutrient additions and the beginnings of industrialized agriculture.

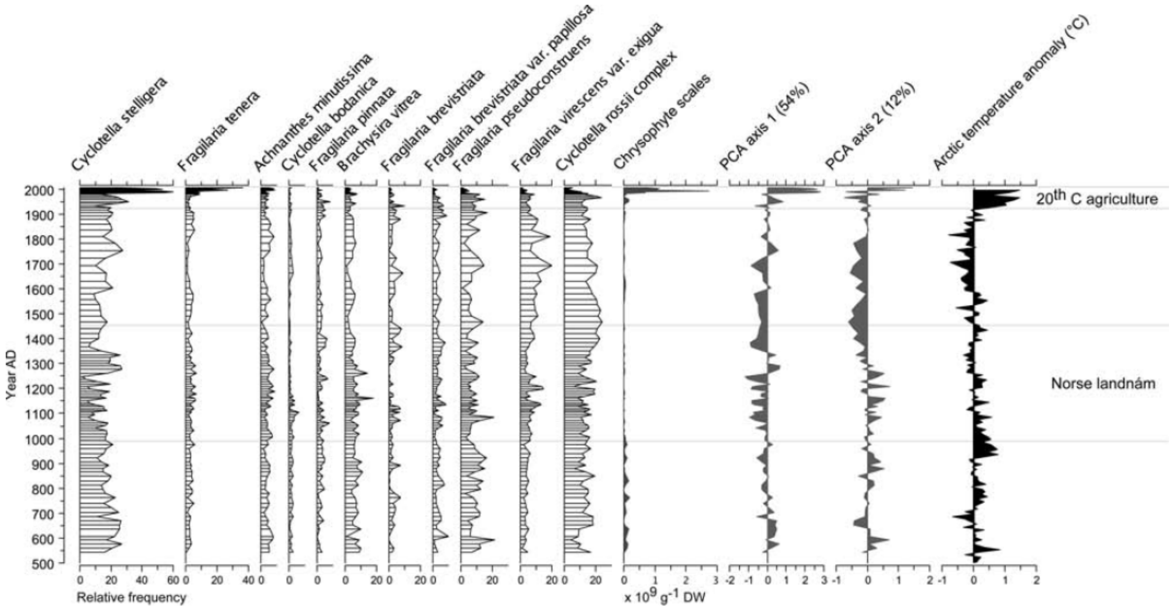

Figure 11. Stratigraphic diagram showing the relative frequency of important diatom taxa of Lake Igaliku. The periods of Norse and 20th century agriculture are shown (Perren et al., 2012).

Iceland

The chironomid assemblages in the analyzed core of Breioavatn were dominated by *Psectrocladius sordidellus* type, *Chironomus, Dicrodentipes* and *Tanytarsus lugens* type. There are peaks in *Dicrotendipes* and *Ablabesmyia* from (AD 1100-1300). From AD 1500, *Dicrodentipes* and *Psectrocladius sordidellus* fall (Fig.12).

The increase in the thermophilous *Dicrotendipes* after the arrival of humans suggests that the chironomid fauna was not affected directly by the initial impacts of settlement. However, there was an increase in relative abundance of *Pediastrum*, a green alga used as an indicator of nutrient levels (Lawson et al., 2005, 2007; Woodward & Shulmeister, 2005) just after landnám. The chironomid assemblage from Breioavatn shows no sign of any changes associated with increased nutrient levels, such as *Dicrotendipes*, *Ablabesmyia* and *Cricotopus*, that were reduced throughout this phase.

DCA analysis and chironomid-inferred temperature reconstruction made by Gathorne-Hardy et al., (2009) indicate that the temperature was the most dominant environmental variable affecting chironomid assemblages. There is an increase in relatively thermophilous taxa between AD 1100 and 1300, which correspond with a rise in temperature.

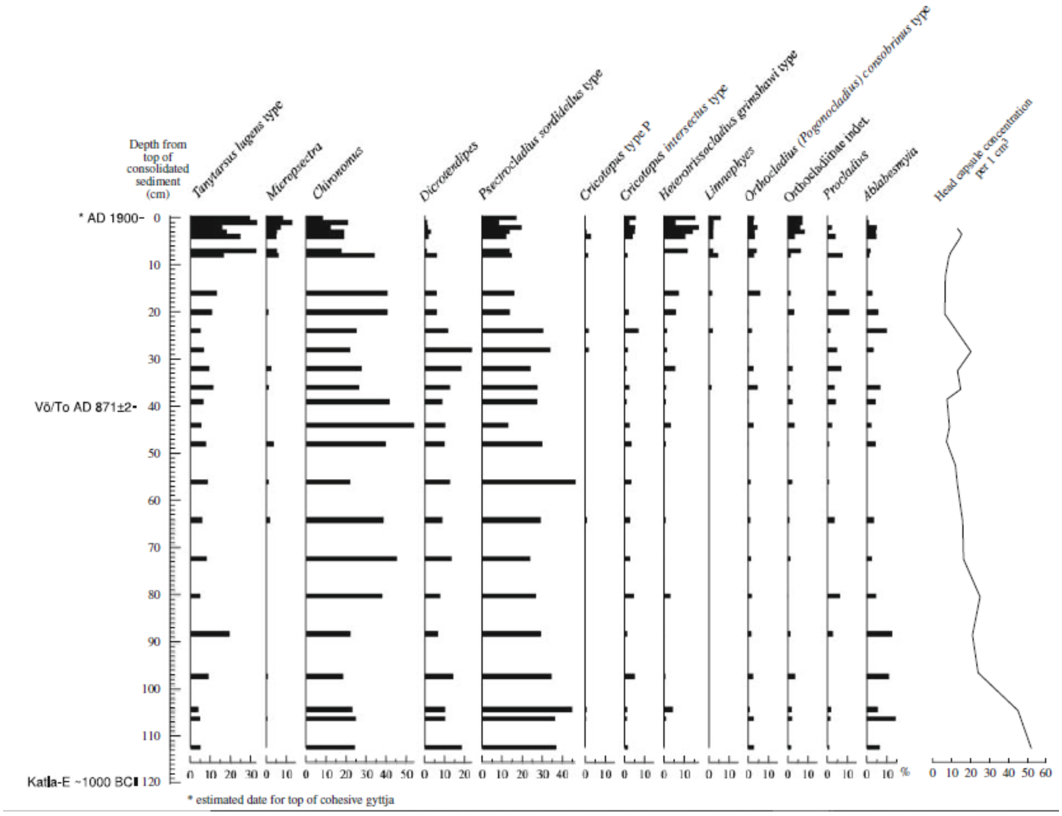

Figure 12. Selected percentages of fossil chironomids found in Breioavatn by Gathorne-Hardy et al., (2009).

The Breioavatn sequence is one of the few chironomid-inferred reconstructions that show an unambiguous LIA record (Brooks & Birks, 2004; Velle et al., 2005). This means that there was no significant change in productivity after landnám.

HUMAN DISTURBANCES AND CLIMATE EFFECT

Azores Archipelago

After the colonization of the Azores (AD 1490), human activities began with land clearance and deforestation (Rull et al., 2017). These activities brought high nutrient concentration to the lake. Until AD 1790, Lake Azul was considered oligotrophic and the chironomid concentration was high.

Nevertheless, after AD 1790, distinct changes in the aquatic environment occurred. There were two main reasons for these changes. Firstly, the introduction of *Carassius auratus,* a Goldfish. This predator had a strong effect on chironomid assemblages among other species, exploiting the initial high densities of these invertebrates. Secondly, the anthropogenic activities in the catchment, such as cutting native vegetation and land clearing for agriculture and livestock production (Moreira, 1987; Rull et al.,2017). So, the feeding strategy of the goldfish and the human activity in the catchment amplified the nutrient load to the lake increasing the percentage of carbon and nitrogen.

Furthermore, in AD 1879 fish stocking started changing the ecology of the lakes, and also the landscapes were suffering changes with the introduction of new tree species, *Cryptomeria japonica* and *Pinus spp* (Rull et al., 2017). One of the newly introduced fish was the Carp, which changed the oxygen conditions of the lakes due to the carp's tendency to lead to higher turbidity (Miller & Rowl, 2006; Richardson et al., 1995), reducing the light availability and algal production. These activities led to an eutrophication of the lakes, for instance in Lake Azul.

On the other hand, the climate effect cannot be underestimated. Between AD 1280 and 1440, there was a period of warm and arid weather called the Medieval Climate Anomaly (MCA). During this period the appearance of some warm chironomid taxa in the lakes occured.

Following the MCA, between AD 1450 and 1700 this region suffered a decrease in temperatures. This period was called the Little Ice Age (LIA). During LIA, several flooding events happened in Lake Azul. These events led to an increase of benthic vs planktonic habitats.

Faroe Islands

After colonization of the Faroes (8-10th century), records from Gróthúsvatn indicated a gradual change in the landscapes. These changes were attributed to the introduction of sheep. Grazing produced the replacement of some plants to more grazing-resistant ones like *Poaceae*. Also there was a decrease in trees called *Juniperus* due to overexploitation.

The TP (Total phosphorus) increases also may indicate that some level of eutrophication occurred following settlement between the 6th and 10th century, but it was improbable that the lake became anoxic. Also, the green alga Pediastrum indicates that after human arrival the productivity of the lake Gróthúsvatn increased.

The erosion that Lake Gróthúsvatn suffered from may have been mainly natural, because the erosion was more or less continuous and unchanging even before the arrival of humans. The catchment was already eroding.

On the other hand, climate change had a great impact on the Faroe Islands. In the period of the LIA, the largest increases in TP occurred in Gróthúsvatn. There is a possibility that the temperature decline increased the production of the lake. The cooler temperatures can reduce the growth rate of plants, so they reduce their ability to recover from grazing allowing them to become more open and the nutrients to be washed into the lake.

Furthermore, in Heimavatn prior to the settlement in the sixth century (AD 570), the data sediments indicate vegetational and environmental changes. There were disturbances detected between AD 530 to 570, before the appearance of macrocharcoal and cereal remains (Hannon et al., 2005a). These changes were most likely driven by climatic change, expressed as reduced sea surface temperature and increased storminess with extreme wind and precipitation. Also, studies indicate that the heathland development observed in the Faroes can be caused by climate change (Humlum and Christiansen, 1998; Bianchi and McCave, 1999).

Greenland

In the period of colonization of Greenland (around the 10th century), the subsistence of these settlements was based on a balanced combination of pastoral farming, hunting and gathering of wild species (Dugmore et al., 2012). However, in the 13th century a strong change in the balance between terrestrial and marine food occurred. Norse people changed from 20% marine food around AD 1200 to 80% marine food at the end of the settlement around AD 1450 (Arneborg et al., 2002; Arneborg et al., 1999).

With farming activity returned in the 20th century, between AD 1920 and 1980, the lake catchment was used for sheep grazing, this kind of farming was considered analogous to Norse-practices, having a small impact on the lake's ecology. However in the beginning of AD 1976, the agricultural methods shifted towards fodder production and the utilization of fertilizers. The massive use of fertilizers led to an unprecedented increase in nutrient availability in the lake water (Massa et al., 2012; Perren et al., 2012).

The sediment sequence does not show a shift in the decades following the 1920s, but in AD 1980, with the changes in farming activities, indicate that agriculture is the principal driver of ecological changes in the lake. The unclear concordance between chironomid assemblages and temperature show the drastic impact of the new agricultural techniques, including a higher value of Organic Carbon Accumulation Rate (CorgAR) and the decrease in the C/N ratio in the lake.

On the other hand, the colonization of islands like Greenland started in a warm period called the Medieval Warm Period (MWP) between AD 885 and 1235. Then, the MWP was followed by a cooling trend in temperatures that corresponds to the LIA.

Between the periods of the LIA, there was high climate variability. Periods like AD 1280-1460, AD 1640-1780 and AD 1840-1920 also suffered a cooling trend. Because of these cold periods, scientists believe that the LIA may be one of the reasons why the Norse abandoned the settlement. The shift towards the dominance of marine sources seem strongly linked to the cooling of the local climate, mainly because the cold climate reduced the livestock survival rate (Dugmore et al., 2012) and because the core sediment indicates that in AD 1335 there was a decrease in farming activities.

With the post-LIA warming or industrialization beginning in the 1920s, strong warming occurred in the region. There were some fluctuations in the temperature but from the 1980s, the temperature increased.

Iceland

Since the arrival of humans between the 7-9th centuries, the landscape of Lake Breioavatn has been subjected to human impact. There was an increase in the erosion, animals were introduced (sheep) and the woodland was cleared. These kinds of activities led to an environmental change in the lake. Because of the harsh environment by the 11-12th century, the farming strategies changed to cattle and sheep.

On the other hand, the climate may be one of the reasons why in the mid-tenth- century, many farms were apparently struggling to maintain the farming patterns of the ancestral homelands economy and they had to change the farming strategies.

There was a rise in temperatures between AD 1100 and 1300, which may be associated with the MWP. However, after AD 1500 the effects of the LIA were noted in the climate an there was a significant decline in mean summer temperature. Other records (Mckinzey et al., 2005) indicates a LIA amelioration around the first half of the 19th century and a temperature decline in the second half.

The sediment analysis suggests more unstable climate in the last millennium compared with the previous two millennia.

DISCUSSION

Climate variability on the islands/lakes

As we mentioned earlier, the effects of the climate variability impact greatly on the ecosystems of these oceanic islands. Moreover, the islands located in the North Atlantic may be more exposed to the drastic impact of these climatic changes. These climate variations brought three main climate periods in the last millennium, also mentioned earlier. The Medieval Warm Period (MWP), followed by the Little Ice Age (LIA) and the Industrial era or Post-LIA warming. There is a general consensus defining the MWP and Industrial era as warm periods and the LIA as a cooler period (Mann et al., 2009).

With the Medieval Warm Period (between AD 900 and 1100), Norse settlers expansion took place in the North Atlantic region. This climate period was ideal for human settlements, so after the colonization of the Faroe Islands and Iceland (around the first millennium), the first farmers arrived in Greenland by the end of the 10th century, with the peak of their farming activities in the 12-13th century. These human arrivals changed the surrounding landscape with agricultural activities. The Azores Archipelago instead, remains supposedly human-free until the 15th century and the most characteristic change in the period of MWP was the occurrence of some warmer chironomid taxa in the lakes (*Chironomus plumosus*-type) (Raposeiro et al., 2017). However, Rull et al., (2017) pollen record of the Sao Miguel Island suggested that the caldera of Sete Cidades was settled by humans by the end of the 13th century, almost immediately after the cessation of the latest volcanic event (P17) in AD 1290.

Following the MWP there was a transition to cooler temperatures (LIA). The main mechanism driving climate cooling during the LIA has been linked to two major external forcing factors; solar activity, with a decrease in the incident solar radiation (Shindell et al, 2001; Solanki et al., 2004; Vaquero & Trigo, 2015) and strong volcanic activity (Bradley & Jones, 1992; Fischer et al., 2007). During this stage, Rull et al., (2017) identified human disturbances such as local forest burning, cereal cultivation and animal husbandry within the caldera of Sete Cidades, however the effects of human activities were not severe enough to be noticed in this epoch. However, in the Faroe Islands the LIA greatly affected the lake with an increase in TP and in the productivity of the lake. Greenland is a special case because the LIA may be one of the main reasons for the disappearance of the Norse settlement in the 15th century due to the extreme climatic conditions and with the failure of farming. Nevertheless, one of the greatest effects of the LIA in Iceland was the erosion of the land. The climate conditions in this period led to the negative effect of soil loss due to erosion on the agricultural economy and overgrazing due to the abandonment of the agricultural activities caused an increased erosion of the land.

With the Industrial era or Post-LIA warming there was a shift in agricultural activities. These changes led to new modern agricultural techniques such as the massive use of fertilizers that impacted the biological dynamic of the lakes, allowing eutrophication. In Greenland for instance, until AD 1980 the magnitude of both climatic (LIA and MWP) and anthropogenic stressors (Norse) were not sufficient to change the ecology of Lake Igaliku. Furthermore, in AD 1940 the oligotrophic inertia of Lake Azul was interrupted due to human activity.

Anthropogenic or environmental stressors in the lakes

The changes in the ecology of the lakes in the last centuries can be attributed to human activities. Agriculture had a great impact on the aquatic environment of the lakes. Activities like deforestation, introduction of animals and different farming techniques. However, the effect of the climate cannot be underestimated as we observed earlier. Before the arrival of humans, the environments of these islands were driven by climatic changes. Nevertheless, other environmental factor also had to be considered, such as volcanism.

One of the principal environmental drivers in the history of Lake Azul was volcanism. The last eruption occurred in AD 1290 (P17) in Caldera Seca. These eruptions carried a dramatic change to the lake ecosystems. The lake condition changed from meso-eutrophic to oligotrophic and the new pioneering biological communities restarted ecological succession.

Although volcanism can be a key factor in the Faroe Islands the principal driver of the ecology of the lake was the climate. The position of the islands in the North Atlantic makes them particularly sensitive to the effects of temperature changes on the surrounding water (Hansen, 1996). Development of heathland, shift of the flora and increased soil erosion can be some of the effects of climate change on the lake. In addition, in Lake Igaliku the climate was the primary controlling factor of the ecology of the lake between AD 1870 and 1988 and also the key driver of the Norse subsistence since their arrival in the 10th century. In the Lake Breioavatn also, the chironomid assemblages were influenced primarily by climate and seem to have been unaffected by human-induced environmental changes.

On the other hand, exotic species introduction (Sax & Gaines, 2008), livestock production, local species extinctions (Wood et al., 2017) and the forest clearance (Cañellas-Boltá et al., 2013) are the most prominent impacts exerted by human colonization on the these islands. For instance, in the catchment of the lakes like Breioavatn and Heimavatn the principal change observed was the woodland clearance for pasture. In Breioavatn farm prosperity was maintained by extensive and diverse utilization of natural resources for the use of mixed livestock and numerous shielings. In Heimavatn, humans may be the principal reason for the transition from shrub-covered to open landscape (Hannon et al., 2001; Jóhansen, 1985) however, it was unclear whether the treeless heathlands that characterize the Faroe Islands (sensu Fosaa, 2003) were a cultural product or developed by climatic change (Bennett et al., 1992). Furthermore, the best examples of the damage caused by the anthropogenic impact on the lakes are presented in Lake Igaliku and Azul. In both of the lakes between AD 1940 and 1988 there was a shift in agricultural techniques, becoming more modern and mechanized agriculture.

These activities were characterized by the use of fertilizers and intensive livestock production. The chironomid and diatoms data suggest that after the modernization of agriculture, these lakes suffered an unprecedented change referencing the eutrophication.

Bioindicators for the detection of environmental disturbances

For the lake’s environmental changes and historical background, these bioindicators have shown the important role that they play in understanding the ecological evolution that the lake suffered within the climatic or anthropogenic changes.

Firstly, it is well known that the most important environmental variable affecting chironomid composition is temperature (Brooks and Birks, 2001). As we saw in the analyzed lakes, the chironomid data can reconstruct a good quality temperature reconstruction. This chironomid-inferred temperature reconstruction has helped many scientist to a better understanding of the effects of the climate on the lakes and with the identification of the different chironomid taxa, it was possible to determine the condition of the lake in that period of time. However, in times of low-amplitude temperature changes, the influence of temperature may be outmatched by the influence of other environmental factors on the chironomid response. The most recognized influenced factors are trophic status (Brooks et al., 2001), oxygen conditions (Quinlan & Smol, 2001), organic matter in the sediment (Verneaux and Aleya, 1998), and salinity (Eggermont et al., 2006). Furthermore, anthropogenic impact has led to changes in the trophic status, the introduction of fish, grazing animals, deforestation and farming activities altered the condition of the lakes and the chironomids suffered pronounced changes that have been presented in the sediments of the lakes.

Secondly, the diatom assemblages were used to reconstruct within-lake changes in biological communities and lake nutrient status. The diatoms are a very good representative of the condition of the lake because they are particularly sensitive to changes in the lake catchment. The abundance of some types of species gives us a clue about the oligotrophy of the lake and also we can use the diatoms data to reconstruct the total phosphorus of the specific period of time. The increase of nutrient supply by the environment or by anthropogenic impact is well presented in the sediments by the diatoms. The environmental factors like volcanism or human activities such as fertilization, fish stocking and livestock can be some of the most important elements to be considered in the changes in the diatom assemblages.

These indicators are affected differently in terms of environmental factors. For example, diatoms can be a very good representative of the eruptions because with species changes it is possible to identify the condition of the lake however, the chironomids were almost absent in the period of eruption, making it difficult to identify the changes in this species and in the environment. Nevertheless, the chironomid can be better indicators of climate changes as we can observe how the chironomid fluctuated with the temperature changes.

CONCLUSION

Lakes can be one of the best representations of the environmental evolution caused by climate change and human-induced practices. Furthermore, lakes sediment data located in oceanic islands can be a significant tool to assess the importance of the historical observation on the ecosystems, as the oceanic islands are considered fragile ecosystems and highly vulnerable to biological invasion (Sax & Gaines, 2008). However, any eutrophication effect on a collection of different lake systems, natural or human-induced, must take into account that each lake has its own characteristics which make it unique regarding resistance, resilience and trajectory (Le Moal et al., 2019; Thornton et al., 2013).

Adaptation to current and future climate change requires understanding not only of the range of natural climate variability and scenarios for the future, but also the response of ecosystems and civilizations to multiple stressors (Perren et al., 2012). Besides human direct actions on freshwater ecosystems, it is also necessary to assess the relative importance of natural processes which can also induce increases in productivity, as climate-related or volcanic factors (Vázquez-Loureiro et al., 2019). However, in the last decades, human activities have been dramatic and have striking effects on these types of ecosystems, due to their isolated location and small sizes (Vázquez-Loureiro et al., 2019). Habitats that were once rare became common, and more natural environments were largely destroyed.

Although the anthropogenic impact did exacerbate the ongoing degradation of vegetation, it was not the primary agent in some places. In Iceland for example, the forest cover began to diminish from 3000 BP, probably through climate change, and the overgrazing produced by humans contributed to a problem caused essentially by climate change. However, with the new agricultural techniques and industrialization in the 20th century, these fragile ecosystems were dramatically impacted due to massive use of fertilizers (among other things) and causing eutrophication in some of these lakes. Observing that this kind of eutrophication was not seen in the past, we can assume the magnitude of human activities and their drastic impact on the environments.

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