Investigating the impact of anthropogenic land use on a hemiboreal lake ecosystem using carbon/nitrogen ratios and coupled-optical emission spectroscopy

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ABSTRACT

Anthropogenic impacts on lake ecosystems have increased substantially towards the present. However, the strength and timing in most cases are not evaluated in detail, missing valuable information on the response and recovery of an aquatic system. In this study, we use the sediment total organic carbon/total nitrogen ratio (C/N) and inductively coupled-optical emission spectroscopy (ICP-OES) elements and the available information about the biological processes to explore anthropogenic land use impact on the lake ecosystem. As a case study we selected a hemiboreal lake Trikātas (Latvia, NE Europe). The Pearson correlation was used to statistically test the correlations of all variables. Our results show that the C/N ratio lowered immediately with the onset of crop cultivation at 500 BCE. Extensive forest clearance and an abrupt increase in land use are reflected through the associated chemical elements from ICP-OES and the increasing presence of herbivore dung spores since 1200 CE. These changes concur with the excess of fish remains suggesting a decrease in fish populations. Interestingly, anthropogenic land use driven erosion and accompanied calcium carbonate (CaCO\textsubscript{3}) matter influx favoured the abundance of Chara spp. in Lake Trikātas since 500 CE, which currently forms the protected specific habitat-type (H3140) of the European Union. At present, specific submerged macrophyte Chara habitat-type diminished almost entirely due to increased nutrient input, phytoplankton blooming, hypertrophic conditions and reduced light availability. The continued land use practices led to a switch in organic matter source in the lake from macrophytes to solely algal origin. The current study underlines the need of additional methods used to detect the sensitivity of lake ecosystem to external disturbances such as minor anthropogenic land use that might not necessarily be apparent in more traditional analyses such as palynology.

1. Introduction

Knowing the timing of first external disturbances on lake ecosystems provides valuable data on the response of an aquatic complex and provides essential insight into the legacy of human impacts on the contemporary aquatic system (Dubois et al., 2018). Historical baselines, in the relative absence of humans, are the conceptual benchmark for biodiversity assessment and management, but it is reasonable to ask whether past conditions remain relevant reference points for the restoration and management of contemporary human-altered systems (Kopf et al., 2015; Dietze et al., 2018).

Climate and anthropogenic activity are two of the most critical factors affecting freshwater lakes in the Northern Hemisphere (Douglas and Smol, 1999; Smol et al., 2005; Rantala et al., 2015). Climate change influences lake ecosystems both directly and indirectly (Fritz and Anderson, 2013; Smith et al., 2015; O’Reilly et al., 2015). Although climate change and lake ontogeny drive the development of lake ecosystems over the long-term, it was the impact of human activities that act as a trigger for noticeable aquatic changes. Bradshaw et al. (2005) demonstrated that human activities over thousands of years not only impacted and shaped the Danish terrestrial landscape but played a significant role in lake development. More recent studies showed that specific human activities such as flax retting, biomanipulation and catchment land use could lead to drastic changes in nutrient cycling in...
Lake Trikātas (57°32′N, 25°42′E) is situated in the boreo-continental with mean annual precipitation of 700–1000 mm and +16.5 °C, respectively, and overall climate can be characterised as eutrophic/hypertrophic. Under thin (2–5 m thick) quaternary glacial till and alluvial deposits lies the Devonian sandstone bedrock. The sandstone outcrop can be seen on the western slope of the lake where it is covered only by a half to 1 m of till/soil. The till is rich in carbonates (most likely of limestone origin) brought to this territory by the last Weichselian glaciation from Estonia and accumulated during deglaciation stages. The mean winter and summer temperatures are −6 °C and +16.5 °C, respectively, and overall climate can be characterised as continental with mean annual precipitation of 700–800 mm (Stivrins et al., 2016a).

There is a medieval stone castle constructed by the Livonian Order (Marzecová et al., 2017; Liiv et al., 2018). An increase in the intensity of agricultural and industrial activities can lead to nutrient over-enrichment of water and oxygen depletion at the lake bottom (Paerl and Huisman, 2008). As a consequence, the strength and direction of human activities in the vicinity of lakes can have an immediate and/or cumulative effect on an aquatic ecosystem.

Aquatic and terrestrial organisms use cross-system subsidies to a comparable extent and addressing reciprocal subsidies is therefore necessary in order to understand the biodiversity and functioning of both aquatic and terrestrial ecosystems (Soininen et al., 2015). Hence, the signals of human-induced changes in the structure and functioning of aquatic ecosystems need careful investigation using multiple proxies (Dubois et al., 2018). In palaeoecology, the human impact on the environment commonly is traced by classical methods such as palynology (Behre, 1981; Poska et al., 2004). While pollen data is used to reveal the human presence (Alenius et al., 2017) rising question whether this truly reflects the timing of agricultural activities and the start of human impact on the environment. Fortunately, numerous proxies can be combined to track the human activities, e.g. diatoms, plant macrofossils and geochemical elements reflecting changes at the local scale (Bradshaw et al., 2005; Gaillard and Birks, 2007; Battarbee and Bennion, 2011; Brown et al., 2015). It is, however, less known whether the sediment total organic carbon/total nitrogen ratio (C/N ratio) and inductively coupled-optical emission spectroscopy (ICP-OES) methods reflect the human impact on environment and lake ecosystem in the same strength and timing in comparison to palaeobotanical methods. Sedimentary C/N ratio has shown great sensitivity in detecting the impact magnitude of changing human activity on the well-being of lakes (Liiv et al., 2018; Bradshaw et al., 2005). Therefore, lake's response to even the slightest external disturbance, which may have been overlooked in more traditional analyses, is expected. This work demonstrates the sensitivity of aquatic ecosystems to minor human impacts, using a novel combination of C/N ratio and ICP-OES. Combined results of ICP-OES and C/N ratio can confirm each other’s accuracy, validate against palaeobotanical methods and help to make correct interpretations.

We hypothesise that human impact is a significant driver in aquatic ecosystem change, which can be linked to critical cultural changes and that has had an immediate and cumulative long-term impact. We use the C/N ratio and ICP-OES elements and the available information about the biological processes (pollen, non-pollen palynomorphs, plant macrofossils, diatom) to reconstruct anthropogenic land use impact on Lake Trikātas (NE Europe, Latvia). Through these reconstructions, we compare does C/N ratio and ICP-OES independently reflect similar results about the human impact on the environment as more traditional palaeoecological methods such as palaeobotany. Despite continuous agricultural land use from 500 BCE, the local landscape surrounding Lake Trikātas was still densely wooded until the start of the crusades in 1198 CE when a diversified pattern of pasture, meadow and arable land use was established (Stivrins et al., 2016a). In addition, diatom results indicate the water quality has sharply deteriorated since the Industrial Revolution (1850 CE) and the Soviet Union occupation period (1940–1991 CE), allowing sewage of different origins to pass directly into the lake (Stivrins et al., 2018). Therefore, studying the sediment of Lake Trikātas can potentially reveal the degree to which culturally and politically driven land used patterns impacted on lake ecosystems, and whether the same impact was evident in different proxies.

2. Study area

Lake Trikātas (57°32′N, 25°42′E; 50 m a.s.l.) is situated in the boreo-continental with mean annual precipitation of 700–800 mm and +16.5 °C, respectively, and overall climate can be characterised as continental with mean annual precipitation of 700–800 mm (Stivrins et al., 2016a).

There is a medieval stone castle constructed by the Livonian Order
on high ground adjacent to the lake, which may have been built on an earlier Iron Age stronghold (Stivrins et al., 2016a). The earliest evidence of human presence is a brooch of 3rd century AD. During the medieval period, the castle and associated settlement at Trikāta, formed part of a network of subsidiary castles within the commandery (medieval administrative unit) of Čēsis castle (Caune and Ose, 2004), located 37 km to the southwest. Overall, there is a lack of documentary or archaeological information on Trikāta. Beyond the medieval castle and village, and a few isolated findspots, there is little evidence for the pattern of settlement and land use beyond the palaeoecological evidence recovered from lake Trikātas (Stivrins et al., 2016a). An elementary school and former manor are located on the valley edge looking over the southern shore and a former distillery and dairy overlooking the northern shore.

3. Materials and methods

Fieldwork to obtain sediment from Lake Trikātas was conducted from the ice-covered surface in March 2012 and 2013. The deepest point of the lake (water depth 4 m) was selected for coring in both years. Altogether four meters of sediment was obtained which lithology consisted mostly of calcareous gyttja that visually differed by colour (Table 1). The uppermost unconsolidated sediment was sampled using a Willner-type (gravity) sampler and subsequent denser sediment using a 10-cm diameter 1 m long Russian peat sampler (Stivrins et al., 2016a).

The age model of the Lake Trikātas sediment sequence was established by six accelerator mass spectrometry (AMS) 14C dates and microscopic volcanic ash shards – tephra of Askja 1875 CE eruption (Table 2, Stivrins et al., 2016a, 2016b). The AMS 14C samples were measured at the Poznań Radiocarbon Laboratory, Poland, and the Scottish Universities Environmental Research Centre, United Kingdom. Due to the Weichselian glaciation, large volumes of carbonaceous sediment were brought from Estonia and deposited over most of Latvia in the process of deglaciation. Accordingly, the AMS bulk samples from the lake contain carbonaceous material that produces old radiocarbon ages, i.e. even > 1500 years offset (Stivrins et al., 2016a). Bulk samples were excluded from the age-depth modelling. Only terrestrial organic plant macrofossil dates by the AMS14C were useful in further age-depth modelling. Even under such precaution, one AMS date – a seed of Spergula arvensis, was excluded from the age-depth model, because was not fitting in the model. A possible explanation was a reworking of older material into earlier sediments (Stivrins et al., 2016a). Radiocarbon dates were converted to calendar years using the IntCal13 calibration dataset (Reimer et al., 2013), and the age-depth model was produced using Bacon 2.2. (Blauw and Christen, 2011). All age modelling was performed in the R environment (version 3.0.3.) (R Core Team, 2014).

The mean value of the modelled age was selected. Organic matter content of the sediment was determined for consecutive cm sub-samples by loss-on-ignition at 550 °C for 4 h. The mineral matter and carbon carbonate (CaCO3) content was estimated based on weight loss after sample combustion at 550 and 920 °C (2 h). Because the weight loss after 920 °C is the amount of CO2 evolved from carbonate minerals, to get the actual percent of CaCO3, the weight after 920 °C combustion was multiplied by 2.27 (Dean, 1974).

Pollen and plant macrofossils have been published by Stivrins et al. (2016a). For the first time information on non-pollen palynomorphs, such as the abundance of herbivore dung spores and fish remains obtained from the plant macrofossil analysis is presented here. Altogether 65 samples (50 cm3) were analysed for plant macrofossil analysis following Birks (2001). Plant macrofossils were analysed at 5-cm intervals. Pollen and non-pollen palynomorphs analysis (36 samples) were processed using standard procedures (Stivrins et al., 2016a). Pollen and non-pollen palynomorphs were analysed at 10-cm intervals. Approximately 1000 terrestrial pollen per sample were counted and identified to the lowest possible taxonomic level and non-pollen palynomorphs were identified using published literature (Miola, 2012). Counts of spores were calculated as percentages of the total sum of terrestrial pollen.

In total, 34 samples, taken at 10-cm intervals were analysed for total organic carbon (TOC) and total nitrogen (TN) content through combustion in a FLASH 2000 Organic Elemental Analyser. Approximately 10 mg of freeze-dried powdered sediment was put into silver containers, pre-treated with 4 M HCl, dried on a hotplate and packed into tin containers to facilitate combustion. For the measurements, BBOT (C66H73N3O5S) or Cystine was used as a standard (Thermo Fisher Scientific), and the algae Spirulina or high-organic sediment was used as reference material (IVA Analysetechnik e. K.). Analyses were performed in triplicate (standard deviation of triplicate samples < 0.3%), the average was calculated by selecting the two (in some cases all three) samples that had the most overlapping results. The average relative standard deviation of replicate samples was 0.12%. The TOC/TN (C/N) ratio values are expressed as atomic ratios and were calculated to estimate the organic material (Meyers and Teranes, 2001).

Element concentrations were determined for 18 elements using ICP-OES. In order to look at sedimentation history and human impact, a wide range of elements was analysed. Some elemental enrichment, such as potassium (K) (Fernandez et al., 2002) and lead (Pb) (Cook et al., 2016; Panerjea et al., 2017) are known to be strongly associated with anthropogenic activities. Some elements, such as calcium (Ca) and titanium (Ti) (Lomas-Clarke and Barber, 2007; O’Connell et al., 2013; Brown et al., 2015) are known to be associated with precipitation, increased sedimentation and erosion processes. Oven-dried sediment samples from Lake Trikātas were pre-treated by nitric acid digestion and analysed with soil and element standards and blanks analysed alongside using a Perkin Elmer Optima 7300 DV ICP-OES. Elemental analysis was carried out to emphasize the human-induced impact on Lake Trikātas. Geochemical concentrations were expressed as parts per million (ppm) per 0.5 g of dried sediment. Data visualisation of all data was done using Tilia (Grimm, 2012) and SigmaPlot (Systat Software ©) software.

All results were discussed within a cultural context and therefore were divided according to established Latvian archaeological periods: Bronze Age (1200–500 BCE), early Iron Age (500 BCE–400 CE), middle Iron Age (400–800 CE), late Iron Age (800–1200 CE), medieval (1200–1550 CE), post-medieval (1550–1850 CE) and Modern (1850 CE–present; Vasks et al., 1999; Graudonis, 2001).

Statistical correlation of analysed variables was tested by using a linear r(Pearson) correlation in Past v.3 (Hammer et al., 2001). Pearson’s r is the most commonly used parametric correlation coefficient. Prior to the correlation we used a Box-Cox data transformation with the purpose of making data more normally distributed, which also support missing values (Hammer et al., 2001). The significance of correlation was reported in table format (statistic/p(uncorr)) with p > 0.05 blank and p < 0.05 colour (from red – significantly positive to blue – significantly negative).

4. Results

The Lake Trikātas sediments consist of silty and homogeneous

<table>
<thead>
<tr>
<th>Depth, cm</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>400–410</td>
<td>Gyttja, silty, calcareous, yellow</td>
</tr>
<tr>
<td>410–445</td>
<td>Gyttja, silty, calcareous, black</td>
</tr>
<tr>
<td>445–514</td>
<td>Gyttja, silty, calcareous, dark brown</td>
</tr>
<tr>
<td>514–537</td>
<td>Gyttja, silty, calcareous, light brown</td>
</tr>
<tr>
<td>537–575</td>
<td>Gyttja, silty, calcareous, light grey-brown</td>
</tr>
<tr>
<td>575–642</td>
<td>Gyttja, silty, calcareous, dark grey-brown</td>
</tr>
<tr>
<td>642–663</td>
<td>Gyttja, silty, calcareous, dark brown</td>
</tr>
<tr>
<td>663–800</td>
<td>Gyttja, silty, calcareous, dark grey</td>
</tr>
</tbody>
</table>
gyttja. The sediment chronology indicates a constant sediment accumulation rate but with a higher rate during the last 200 years (Fig. 2). Higher sedimentation towards the present day may reflect the less compacted and higher water content of the deposits at the top of the sediment profile. Narrower chronology uncertainty bands occur towards the present day, particularly at 1875 CE where the tephra shards of Askja volcanic eruption have been recovered (Stivrins et al., 2016b).

TOC and TN range from 8.9 to 24.3% and 0.9 to 1.9%, respectively and show a similar trend of changes over the studied time period (Fig. 3). Before Late Iron Age (1000 BCE–1000 CE), TOC and TN contents show an overall decreasing trend with some minor fluctuations. During the Late Iron Age up until Post medieval (1000–1800 CE) TOC and TN values fluctuate notably, reaching higher concentrations ca. 1140 CE (17.8 and 1.9%, respectively) and ca. 1735 CE (17.7 and 1.9%, respectively) with the lowest values occurring around ca. 1350 CE (8.9 and 0.9%, respectively). Starting at 1800 CE, TOC and TN content remains stable at around 11.7 and 1.3% respectively but increases once again in the topmost part of the studied sediment sequence (Fig. 3).

CaCO3 content increases from ca. 400 BCE rising from 10% up to 65% during the period from ca. 200 BCE–1200 CE (Fig. 3). The medieval period is characterised by lower carbonate values, as well as during the transition from post-medieval to modern periods, increasing after that towards the present. Organic and mineral matter content respond oppositely to each other. A significant increase in mineral matter is evident since ca. 1200 CE with a decrease in ca. 1600–1750 CE.

Concentrations of Ca and Sr increase from ca. 200 BCE, peaking in the Late Iron Age ca. 800 CE (Fig. 4, Data in Brief 1). During this same period, concentrations of other major, and trace elements decrease, specifically Fe, Mn, K, Cr, Cu, Ti and V. Concentrations of P remain low and stable during this period. These increases and decreases in element concentrations are reversed during the period from 1200 to 1600 CE (the end of the Late Iron Age through to the end of the medieval period). There are additional increases in the concentrations of Pb and Zn, with the main increase in Pb concentrations peaking ca. 1800–1900 CE in the modern period (around the time of the Industrial Revolution). Mn does not reach the level of concentration that is recorded in the Bronze Age, prior to ca. 200 BCE. During the Bronze Age, C/N ratio was high and the surrounding landscape was forested with negligible soil erosion (Fig. 5). The majority of studied proxies indicate the establishment of cultivation in the Early Iron Age. Fe/Mn ratios suggest an increase in soil erosion towards the Middle Iron Age, with a corresponding increase in carbonates, mainly Ca values. In the Middle Iron Age, C/N ratios decrease while an increase and establishment of algae of Chara spp. occur in Lake Trikātas (Fig. 5). Chara spp. oospore concentration varies from two to 97 per sample (average 31 oospores per sample) from 470 to 1300 CE and only one to two oospores per sample afterwards (not presented in a graph here, but see Stivrins et al., 2016a).

There is evidence from the continuous presence of dung spores (Sporormiella sp., Sordaria sp., Podospora sp.) for the abundance of large herbivores in the vicinity of the lake. The Late Iron Age marks an increase in cultivation indicators and lead (Pb) concentrations. Our results show a significant positive correlation between C/N ratio, fish remains, forest cover, Mn and V; hence, high values of these variables indicating stable environmental conditions (Fig. 6). Contrary, human activity/land use is evident through the positive correlation between cultivated indicators (Cerealia pollen), herbs, large herbivore dung spores, charcoal (indicating fire events), Pb, K, Ti and mineral matter content. Another positive correlation was found between Chara spp., Ca, Sr and carbonates and a negative correlation between C/N ratio indicating a period of increased carbonate content in the Lake Trikātas and underline requirements for the growth of the Chara spp.
5. Discussion

5.1. Human impact on the lake ecosystem

Until ca. 500 BCE Lake Trikātas was in its natural, unaltered state. The constant C/N ratio of around 16 (Fig. 3) support this concept and suggest that the lake received its organic matter from a mixture of vascular and non-vascular plants, which is expected for most lakes (Meyers and Ishiwatari, 1993; Meyers, 1994; Meyers and Lallier-Vergès, 1999). Statistical correlations reveal that the high C/N ratio corresponds to a period of stable environmental conditions within the surrounding landscape (greatest relative forest cover and negligible soil erosion). Moreover, the C/N ratio of 16 could also indicate that a considerable proportion of the organic matter originated from aquatic macrophytes. C/N values between 10 and 20, reported for the aquatic macrophytes, support this notion (Herzschuh et al., 2005; Pu et al., 2013). However, C/N ratio starts to decrease simultaneously with the first recorded cereal pollen grains, occurring from ca. 500 BCE (Fig. 5), indicating that potential delivery of additional nutrients from the surrounding watershed may have increased the in-lake production of organic matter with lower C/N ratios. Therefore, in Lake Trikātas case, even minor changes in the local landscape were powerful enough to have an immediate impact on the lake ecosystem.

Clearance of woodland in the vicinity of Lake Trikātas started from ca. 1200 CE (Fig. 5), resulting in increased erosion of exposed soils within the lake catchment, and elevated nutrient input and enhanced aquatic productivity in the lake (Litt et al., 2003). All the above-mentioned factors may result in a lower C/N ratio values (Enters et al., 2006). C/N ratios (with minor fluctuations) continue to decrease, indicating that added nutrients via continuous agricultural land use practices affected the trophic status of Lake Trikātas towards a more eutrophic one (Figs. 5, 6). This process is evident by the negative correlation of C/N ratios against herbivore dung spores and indicators of cultivation (Fig. 6). Concentrations of Ti increase during this period (Fig. 4), which may reflect an increased sediment influx into the lake from soil erosion, and correlate strongly with inputs of mineral matter (Fig. 6). Increases in Ti concentrations are widely documented as being a reliable indicator of soil erosion resulting from human activity as it is both chemically stable and unaffected by biological transformations (Lomas-Clarke and Barber, 2007; Brown et al., 2015). For example, the evidence for Ti concentrations in the lake adjacent to the castle at Āraiši in central Latvia as well as in Lake Trikātas suggests that soil erosion began prior to 1200 CE (Stivrins et al., 2015). In addition, higher Fe/Mn ratio reflects similar evidence of increased soil erosion (Fig. 5).

From 1200 CE the Eastern Baltic witnessed significance political, economic and social changes occurring as a consequence of the Northern Crusades, that in turn had major impacts on patterns of land use. The crusades involved the conquest, colonisation and Christianisation of tribal pagan societies in the eastern and southeastern Baltic (present day Poland, Latvia and Estonia) by the Teutonic and its allies, beginning with the conquest of the Livs (1198–1209 CE) and Estonians (1208–1227 CE) by the Livonian Brothers of the Sword.
of heavily fortified castles and followed by the development of a network of towns and rural settlements and a pattern of agricultural intensification and trade (Pluskowski, in press).

The castle at Trikāta (next to the Lake Trikātas) was located on one of the main north-south routes within a relatively stable part of Livonia and is likely along with other key castles to have played an important provisioning role in the initial decades following the crusades, suggested by the pollen evidence for intensifying land use (Stivrins et al., 2016a). Documentary sources from the mid-sixteenth century list Trikāta as one of several castles acting as Kornhausen (from German corn houses), emphasising their role in the collection, storage and redistribution of agricultural produce (Caune and Ose, 2004).

However, colonisation occurred at a significantly lower rate within Livonia compared to Prussia (present day Poland), the population was sparser, and the extent of human impact appears more localised around urban and rural centres such as Trikāta. In comparison to Livonia, significant impacts on woodland are recorded from pollen sequences across Prussia, the first of these occurring during the medieval period prior to the arrival of the Teutonic Order; in Masuria (north-east Poland) this is a result of indigenous activity whilst in the area of the Vistula basin (central Northern Poland) intensifying anthropogenic land use results from increasing Slavic control over tribal lands occurring from the 11th century (Wacnik et al., 2012; Noryśkiwicz, 2013; Brown et al., 2015; Szal et al., 2017; Brown, in press). Extensive clearance of woodland and intensified agriculture continued with the arrival of the Teutonic Order and was accompanied by significant colonisation of the countryside occurring across Prussia from the 13th/14th century. The extensive use of timber in early towns and castles is likely to have placed significant pressure on timber resources already denuded in those areas that witnessed increasing colonisation from the 11th century. Geochemical and pollen analysis of lake sediments adjacent to the Teutonic Order Castle and town at Radzyń Chełmski (NE Poland) emphasises the scale of this impact, resulting in the development of a significantly open agricultural landscape with the lake containing elevated levels of contaminants by the 15th century (Brown et al., 2015).

The medieval period marks one more exciting feature – a low fish population and increase of Pb in Lake Trikātas (Fig. 5). These changes most likely are consequences of colonisation followed the crusades from 1200 CE. Similar evidence has been recorded at Radzyń Chełmski (NE Poland) where Pb levels in the lake sediments were recorded up to 13 times the background geological levels, argued to derive from industrial activities related to the castle and adjacent town (Brown et al., 2015). However, the increase of Pb concentrations could also be partly due to vertical (atmospheric) inputs, reflecting atmospheric pollution of Pb from increased industrial activity that has been well documented globally in lake sequences and the Ice Core record (e.g., Shotyk et al., 1998). Geochemical element (Pb) and continuous decline in C/N ratio reflect a cumulative effect of anthropogenic activities (Fig. 5).

While extensive land use decreased only after 1930 CE at Lake Trikātas, C/N ratios continued to decline with the lowest values of around 9 occurring in the topmost (nowadays) sediments, confirming that the source of lakes organic matter was irreversibly changed to a solely algal origin (Meyers and Ishiwatari, 1993; Meyers and Lallier-Vergès, 1999; Liiv et al., 2018). Indeed, human activities that vary both temporally and spatially leave pronounced footprints in lakes. Understanding the impact of agrarian and industrial pollutants on water quality and aquatic biota are becoming of increasing scientific and management concern (Dubois et al., 2018).

5.2. Anthropogenic land use drives the Chara spp. habitat

Anthropogenic land use initiated soil erosion, resulting in increased carbonate leaching into the lake from surrounding soils within the lake catchment, and most likely also from the sandstones containing carbonate cement. Low C/N ratios due to algae Chara spp. domination is provided through their negatively significant correlation (Fig. 6).
Although lawns of stoneworts (*Chara* spp.) can grow to a depth of 10 m depending on the water transparency (Hannon and Gaillard, 1997), it is most likely that *Chara* spp. was growing in Lake Trikātas due to the increased carbonate content in the water column. In the current study *Chara* spp. comprise a range of *Chara* (Characeae) species as they were not identified to the species level. *Chara* spp. lakes are typically hard water, low nutrient level systems with a high pH (> 7) and clear, transparent water column. *Chara* spp. forms specific habitat-type designated as H3140 (hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.) of the European Union which is threatened and to be protected and preserved. The main factors causing a decrease of the habitat areas are water pollution and change of hydrological regime (Council Directive, 1992).

Although many water bodies of this type today in Europe are severely degraded as a result of nutrient enrichment, our study indicates that land use with soil erosion most likely initiated *Chara* spp. growth in a first place. Afterwards, however, high nutrient load increased phytoplankton biomass and decreased the water transparency as suggested by the presence of planktonic eutrophic diatoms (Stivrins et al., 2018). Under light limiting conditions the abundance of *Chara* spp. decreased from 1250 to 1400 CE and 1750–1970 CE. Findings of *Chara* spp. macroscopic remains at 1970 CE and 2013 can be linked to two potential situations. First, the lake ecosystem shows signs of recovery after severe eutrophication during the 19th and the first half of 20th century. Second, the *Chara* spp. spores have been redeposited. The latter situation is considered less likely, however, as there is no evidence for re-deposition of sediment likely to result in reworking of spores through the profile. *Chara* spp. have been occurring at times of increased carbonates in the sediments. Carbonates also increase towards the present day, and thus probably in those years when the lake was not overwhelmed by hypereutrophic algae, *Chara* spp. could grow. This is only an assumption and the driving process behind *Chara* spp. growth is still unclear. Noteworthy, that the oospore concentrations were the highest from 470 CE to 1300 and only one to two spores per sample were found later. The low number of oospores suggest that the *Chara* spp. barely can establish for new due to unwelcome growing conditions. Recent findings of *Chara* spp. are somewhat surprising as the diatom evidence shows the presence of *Stephanodiscus parvus*, *S. hantzschii* and *Cyclostephanos invisitatus* suggesting a hypertrophic lake that switched from a clear-water to turbid phytoplankton dominated aquatic ecosystem (Bennion, 1994; Stivrins et al., 2018). In addition, the total algae turnover (algae composition) in Lake Trikātas during the last 2000 years reached SD 2.66, that when compared with reference conditions before the intensive human impact prior to 1200 CE, indicate a change of more than a half diatom community due to human impact (Stivrins et al., 2018). All in all, the current study underlines the sensitivity of lake ecosystems to even minor external disturbances resulting from short-term and/or small scale anthropogenic impacts. The cumulative effect of continues land use practices led to switch in organic matter source in the lake from macrophytes to solely algal origin.

6. Conclusions

We applied the methods of C/N ratio and ICP-OES to study the anthropogenic impact on the lake ecosystem. Our study on Lake Trikātas (Latvia, NE Europe) reveals that anthropogenic land use initiated soil erosion resulting in the increase of carbonate leaching into the lake from the soils and most likely also from the sandstones containing carbonate cement. Land use with soil erosion most likely initiated *Chara* spp. growth. Our results reveal that *Chara* spp. occurred at times of high CaCO₃ content in the lake water. The medieval period marks one more exciting feature – a low fish population and increase of Pb in Lake Trikātas. The cumulative effect of continued land use practices led to a switch in organic matter source in the lake from macrophytes to solely algal origin. The current study underlines the sensitivity of lake ecosystem to even minor external disturbances such as anthropogenic land use that can be missed if studying the lake only by palaeobotanical methods.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2019.01.007.

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