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Fire frequency during the Holocene in central Latvia, northeastern Europe

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Abstract. Fire is today a pan-European issue and is expected to be more salient because of climate and land use changes. Even though natural and anthropogenic fires have shaped forest composition and landscape characteristics since the last glacial retreat from northeastern Europe, fire frequency is an understudied topic. To address this issue, we analysed macroscopic charcoal (>160 µm) from two sediment sequences located in the central and littoral parts of Lake Bricu (central Latvia) revealing the fire frequency during the Holocene. The chronology of the analysed sediment sequences is based on spheroidal fly-ash carbonaceous particles and accelerator mass spectrometry radiocarbon dating. Macroscopic charcoal results were examined in detail using the CharAnalysis approach. The mean fire return interval for the entire Holocene was 372 years (261–494 years). Fire reconstructions revealed higher fire frequency during the early and late Holocene (cool climate), but lower frequency during the middle Holocene (warm climate). Although our study underlines that natural fire frequency might decrease during warmer climate, the anthropogenic fire use already has surpassed the baseline of natural fire frequency.

Key words: macroscopic charcoal morphology, climate change, lake-dwelling.

INTRODUCTION

Fires are a key disturbance in forests, and fire regimes are among the most important factors explaining the variation in forest and landscape structure and species composition (Clear et al. 2014; Aakala et al. 2018). Furthermore, fires are necessary for the persistence of key ecosystems and characteristics of their landscapes (Molinari et al. 2020; Seidl et al. 2020). At the landscape scale, fires are of mixed severity – parts of a landscape may have burnt often as low-intensity fires, while other parts may have remained untouched by fire (Kuuluvainen et al. 2017). This spatial variability is driven by landscape structure, including topography, fire breaks (area where fire is not able to move further), and soil type and moisture capacity (Deane et al. 2020).

Assessing past patterns and trends of forest fires, and the factors controlling their occurrence is imperative for understanding long-term forest dynamics, but also for anticipating future changes in fire occurrence and the potential feedbacks between climate and fire (Kasischke et al. 1995; Kuosmanen et al. 2016; Seidl et al. 2020). In palaeoecology, sedimentary charcoal has been used as evidence of fire occurrence in the past (Stivrins et al. 2019a). Empirical studies show that larger charcoal particles (>150–160 µm) fall out relatively close to the emission source (<100 m), while smaller particles can be windblown from a broader region (Whitlock & Larsen 2001; Conedera et al. 2009). Some studies, however, suggest that the source areas for both microscopic and macroscopic charcoal particles are in a radius of approximately 40 km (Adolf et al. 2018).

Charcoal from sediments, along with the presence of crop pollen and plant macroremains as well as archaeological findings, has been interpreted as unequivocal evidence for fire management and use in prehistoric and historical daily life. Although fire has accompanied human evolution, our understanding of fire remains quite meagre, especially in Latvia, where only a limited number of long-term fire reconstruction studies involving fire record data have been conducted (e.g. Veski et al. 2012; Stivrins et al. 2015a, 2015b, 2016a; Feurdean et al. 2017; Kitenberga et al. 2019). The latest studies show that human-driven fires affected landscape transformation in the Central European Lowlands already 8500 years ago (Dietze et al. 2018). Hence, humans have significantly disturbed the composition of forests and natural fire regimes beyond the local scale – even in periods of low population density. It is known that the use of fire enabled the landscape to be cleared to provide new pasture for grazing and agricultural land. Slash-and-burn cultivation has been suppressed for almost a hundred years now (Donis et al. 2017), but what legacy this practice has left in today's landscape is not entirely clear. Removing fire from ecosystems imposes changes on the dynamics of ecosystems. Furthermore, the characteristics of the disturbance regimes are changing as well.

Although the relative roles of climate, vegetation and humans are still debated, climate is probably one of the superordinate drivers of fires at regional scales by controlling fire-weather, lightning-induced ignition and the flammable biomass. Recent studies underline not only the notion that fire frequency depends to a much greater extent on changes in precipitation than temperature alone, but also that there is a teleconnection between large-scale climate and ocean dynamics over the North Atlantic and regional boreal/hemiboreal fire activity in Northern Europe (Drobyshev et al. 2016; Aakala et al. 2018; Kitenberga et al. 2019).

In this study we analysed macroscopic charcoal (>160 μm) from two sediment sequences obtained from Lake Bricu (central Latvia) with the aim of revealing the long-term fire frequency during the Holocene. We are aware of the assumption that present-day relationships most likely cannot be linked linearly to historical non-analogue climate and environmental conditions. At the same time, the present-day landscape and fire occurrence are a result of the millennium-long interaction between the past climate, vegetation, and natural and anthropogenically induced disturbance dynamics. We selected Lake Bricu for the study, because it is the location of one of 12 lake-dwelling sites discovered in Latvia and can therefore both provide a baseline of natural fire occurrence without human presence and indicate how this pattern has changed since humans settled in this region. The cultural phenomenon of lake-dwellings spread into present-day Latvia during the Late Iron Age, while it was already in decline in the rest of Europe (Coles & Coles 1989; Menotti 2003, 2004; Menotti et al. 2005; Apals 2012). Despite the singularity of lake-dwelling sites, there have been few or no detailed palaeoecological studies aimed at understanding their environmental context and impact on the landscape (Stivrins et al. 2015b).

MATERIAL AND METHODS

Study area

Lake Bricu is located in central Latvia (57°6′ N, 25°17′ E; 208.4 m a.s.l.), in the central part of the Vidzeme Upland, 7 km northeast of Vecpiebalga. The lake is 16 ha in area and has a catchment area of ~6 km^2. The mean depth is 1.3 m and the maximum depth 2.7 m. The surrounding landscape comprises meadows and forests consisting mostly of spruce (*Picea abies*) and birch (*Betula pubescens*/*pendula*). The shores are flat and marshy except for the north shore, which is steeper. The bedrock consists of fine-grained Devonian sandstone covered by 80–100 m of Quaternary deposits. The climate in the area is continental, with a mean annual temperature of +6.4 °C, a mean January temperature of –5.8 °C and a mean July temperature of +16.9 °C. The mean annual precipitation is ~700 mm.

Information regarding lake-dwelling in the vicinity of Lake Bricu is limited. During the 1960s, the pioneering underwater archaeologist Apals (2012) and his research team discovered ten lake-dwelling sites in Latvia (Fig. 1B), but in recent years this number has increased to 12. A few on-site finds of pottery suggest that the fortified lake-dwelling was inhabited approximately in the ninth and tenth centuries, i.e. during the Late Iron Age (Apals 2012). Considering the limited archaeological information regarding these local lake-dwellings, our study aims to shed new light on human activities and the potential timing of the anthropogenic fire use in the area.

Sampling and chronology

Sediment sampling in Lake Bricu was done from a boat raft on 12 August 2018. Two sediment sequences were taken (Fig. 1): one at the deepest and central point of the lake (Bricu I) and the other in the littoral zone some 20 m from the lake-dwelling site (Bricu II). The topmost 0.35 m of unconsolidated sediment at Bricu I was sampled using a Willner-type gravity corer. Due to technical issues, the topmost 0.35 m of sediment was not taken at Bricu II. Further, we used a 1 m long Russian-type sediment corer to recover a 5.5 m long sediment sequence at Bricu I and a 2 m long sediment sequence at Bricu II. The chronology was based on AMS ^{14}C dates from plant macroscopic remains (Bricu I – five AMS ^{14}C datings; Bricu II – four AMS ^{14}C datings). The dated material, all of terrestrial origin, was processed at the Poznań radiocarbon laboratory, Poland (Poz). In addition, the upper sediment sequence of Bricu I was dated by the distribution of spheroidal carbonaceous fly-ash particles (SCP). Analysis of SCP followed the methodology of Rose (1990) and Heinsalu & Alliksaar (2009). The analysis was performed

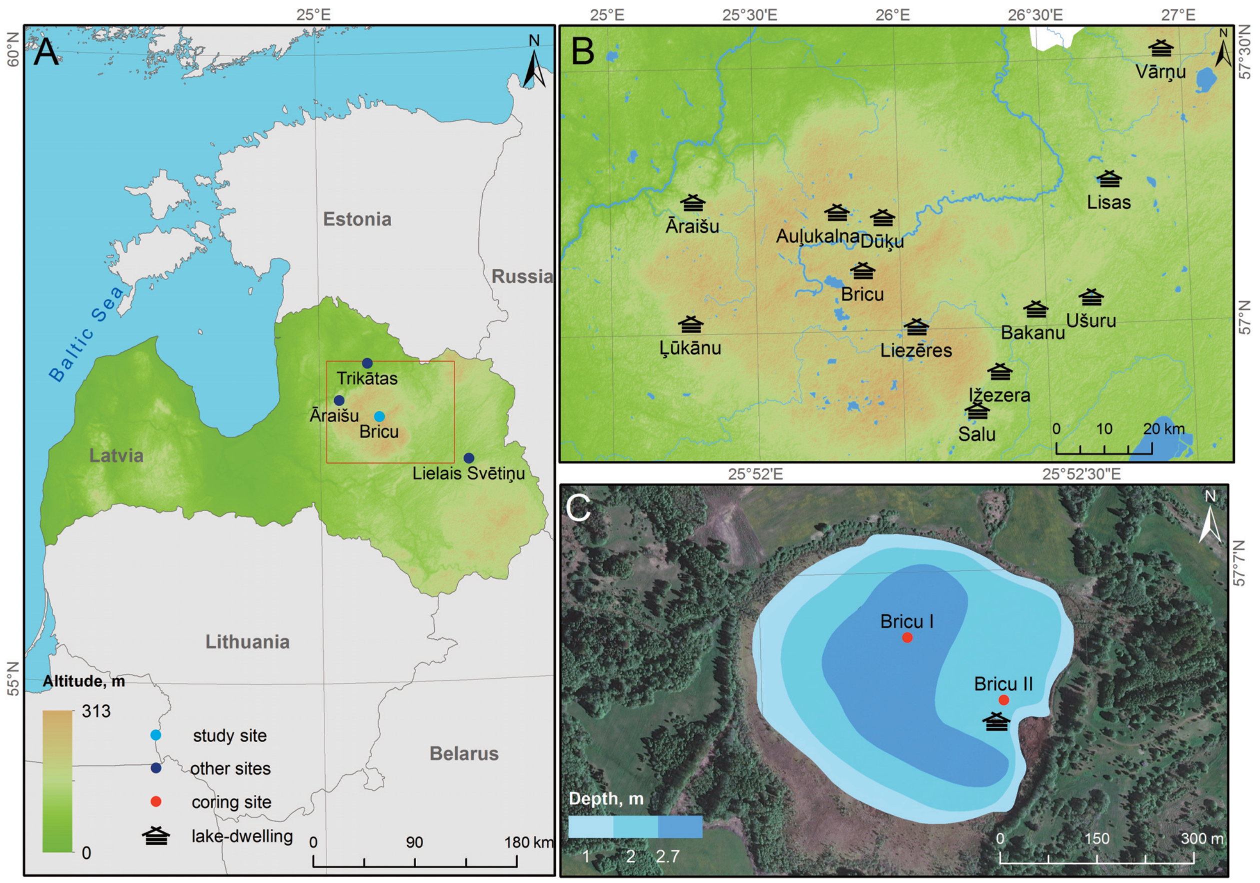

Fig. 1. Location of the study area in northeastern Europe and sites discussed in the text: **A**, Lake Lielais Svētiņu (Stivrins et al. 2015b; Feurdean et al. 2017), Lake Āraišu (Stivrins et al. 2015b) and Lake Trikātas (Stivrins et al. 2016a); **B**, Lake Bricu and other lakes in central Latvia where dwelling sites have been found; **C**, coring sites and the setting of Lake Bricu.

at the Department of Geography, University of Latvia. In the final step, we combined the results from AMS ^{14}C and SCP analyses to build an age–depth model using the Clam 2.2. deposition model (Blaauw 2010) with a 95.4% confidence level in R environment (R Core Team 2018). Prior to their use in the age–depth model, the radiocarbon dates were converted to calendar years using the IntCal20 calibration dataset (Reimer et al. 2020). Weighted averages before present were used (cal yr BP) for the Bricu I core, while the Bricu II core was discussed within a cultural context and therefore was divided according to established Latvian archaeological periods: Earliest Iron Age (500 BCE–1 CE), Early Iron Age (1–400 CE), Middle Iron Age (400–800 CE), Late Iron Age (800–1200 CE), medieval (1200–1550 CE), post-medieval/modern (1550 CE–present) (Vasks et al. 1999; Graudonis 2001).

Macroscopic charcoal analyses

Macroscopic charcoal analyses followed Courtney-Mustaphi & Pisaric (2014) and Feurdean et al. (2017) which include also morphological charcoal identification. Each consecutive 1 cm sub-sample (volume 1 cm^3, thickness 1 cm) was treated with dilute NaOCl to promote sediment bleaching and disaggregation before sieving at 160 µm (Magne et al. 2020). The sediment residue was added to 20 mL of distilled water and decanted to a petri dish for charcoal analysis. Charcoal was identified as brittle, black crystalline particles with angular broken edges using a stereomicroscope at 30–60x magnification. We have expressed raw charcoal data as concentration per sample while further we estimated charcoal accumulation rates.

We then used CharAnalysis (Higuera 2009), to identify fire events from the sedimentary charcoal record. This analysis is based on the charcoal peak screening process (Gavin et al. 2006), in which a threshold value is used to separate the background charcoal deposition (noise) from the occurrence of peaks that are indicative of actual fire events (Kelly et al. 2011). We first interpolated charcoal accumulation data to the median sample resolution of 24 years (Bricu I) and 15 years (Bricu II), then smoothed the values with moving average regression in a 500-year time window for the Bricu I core data and a 100-year time window for the Bricu II core data, since the latter covers a shorter time interval. Fire peaks were obtained by subtracting the background charcoal accumulation rate from the interpolated data. To distinguish noise-related variations from fire peaks, we used a Gaussian mixture model. Fire episode frequencies were smoothed in a 1000-year (Bricu I) and 500-year (Bricu II) window (Feurdean et al. 2017). In this study, we followed the assumption that the central sediment sequence (Bricu I) represents local to regional fire episodes, while the littoral sediment sequence (Bricu II), due to its closer location to the lakeshore and lake-dwelling site, displays more local fire episodes (Peters & Higuera 2007).

RESULTS

The Bricu I sediment sequence comprises, from bottom to top: till (5.50–5.36 m), soil (5.36–5.31 cm), fen peat (5.31–5.23 m), detritus gyttja (5.23–5.17 m) and homogenous gyttja (5.17–0 m). The Bricu II core contains till (2.00–1.95 m), sand (1.95–1.85 m) and gyttja (1.85–0.35 m). Relying on the ^{14}C AMS dating of the Bricu I core, we can say that the lake formed almost 11 000 years ago (Table 1; Fig. 2). Although the dates are from the basal part of the core, according to the lithology there is no evidence for possible hiatuses. Therefore, we can assume continuous sediment accumulation since the formation of the lake. Bricu II indicates continuous sediment accumulation for the last 2500 years. On the basis of the Bricu I SCP results, it was possible to define the years 1950 and 1991 with an error of ±10 years at depths of 40 and 35 cm, respectively (Trofimova 2019). According to the Hedges et al. (2000) and Masiello (2004) black carbon combustion continuum model, SCP forms only during industrial fuel combustion at high temperature (greater than 1000 °C). Therefore, ideally the SCP peak follows the fuel combustion pattern: 1950 – the rise in SCP, 1982 – the peak of SCP, 1991 – decrease in SCP. The peak in SCP emission has previously been established for Latvia as 1982 ± 10 years (Stivrins et al. 2016b).

During the macroscopic charcoal analyses we not only counted charcoal pieces, but also categorized them into charcoal morphotypes (reflecting fuel type) according to Courtney-Mustaphi & Pisaric (2014): A – polygonal charcoal (fuel: wood, herbaceous material, leaves), B – orthoangular polygons and polyhedra (blocky shaped) (fuel: wood, Poaceae leaves, grass), C – long and complex (fuel: conifer needles, twigs, roots, leaf stems and veins), D – long and simple (fuel: leaves, wood), E – spheroidal (fuel: seeds, sap, resin), F – irregular (fuel: root masses), G – glassy (fuel: resin, phytoliths), and defined one more group specifically for the Lake Bricu case: H – not corresponding to any other group (fuel: unknown). Our results revealed a higher macroscopic charcoal concen-

Table 1. Radiocarbon ages for Lake Bricu sediment cores

Depth (cm)	Laboratory code	^{14}C date	Calibrated age (cal yr BP) 2 sigma	Material dated
Bricu I 190	Poz-124404	2840 ± 30	2875–3050	Wood
Bricu I 350	Poz-124403	5940 ± 40	6680–6875	Wood
Bricu I 526	Poz-116939	9380 ± 50	10 480–10 695	Wood
Bricu I 540	Poz-117146	9510 ± 50	10 630–10 995	Wood
Bricu I 544	Poz-116940	9450 ± 50	10 645–10 950	Wood
Bricu II 94	Poz-116941	980 ± 30	760–900	*Picea abies* needles, *Betula* sect. Albae seed fragments
Bricu II 105	Poz-116942	935 ± 30	895–1040	Leaf of *Salix* sp.
Bricu II 115	Poz-117147	1245 ± 30	1035–1185	Wood
Bricu II 186	Poz-116943	2320 ± 30	2195–2355	Fragments of *Picea abies* and *Betula* sect. Albae seeds, *Pinus* bark

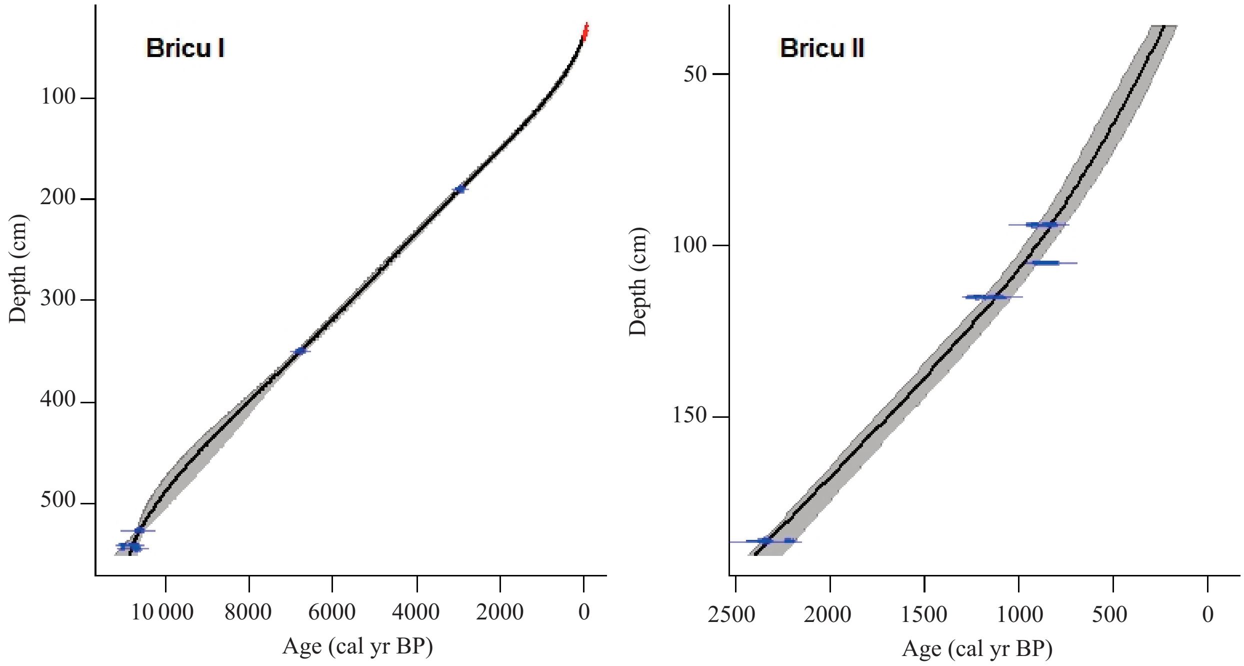

Fig. 2. Age–depth models for the sediment sequences of Lake Bricu cores I (Bricu I) and II (Bricu II) (grey area indicates a reconstructed 95% chronological uncertainty band). ^{14}C AMS dates are indicated in blue and spheroidal fly ash particles in red.

tration in the central core (Bricu I) during the early (in our case ~11 000–8200 cal yr BP) and late Holocene (last 4200 years) (Fig. 3A) and lower values during the middle Holocene (8200–4200 cal yr BP). Among the charcoal morphotypes, A1–A3, B1–B3 and D1–D2 predominated. The littoral core (Bricu II) showed a continuous distinct record of charcoal starting from 1400 cal yr BP. An increased charcoal concentration was observed at 1400–900 cal yr BP, 700–500 cal yr BP and during the last 400 years. Among charcoal morphotypes, B1–B2 dominated, to a lesser extent B3 and A1–A3 (Fig. 3B). As the Bricu II core covers the late Holocene, we divided this section into archaeological periods to characterize and discuss charcoal concentration variability more thoroughly. We then compared both charcoal records to see whether there is a similar pattern in the central and littoral zones (Fig. 4).

The results from CharAnalysis (Bricu I) (Figs 4, 5A) revealed higher regional fire frequency during the early and late Holocene and lower fire frequency in the middle Holocene. Our estimations show that the fire return interval (FRI) for the entire Holocene was 372 years (261–494 years). More specifically, the FRI is 392 years for the early Holocene, 494 years for the middle Holocene and 271 years for the late Holocene. According to the CharAnalysis results for the littoral sediment sequence (Bricu II; Fig. 6), FRI was 102 years. The results revealed a lower charcoal concentration and by inference also fewer local fire at 2400–1400 cal yr BP (450 BCE–550 CE, i.e. the Earliest–Early and Middle Iron Age). An abrupt increase in fire occurrence was recorded for the Late Iron Age, at 800–1200 CE (1150–750 cal yr BP). During the medieval period (1200–1550 CE) fire was less abundant, but this picture changed in post-medieval and modern times, when more local fire was detected (Fig. 6).

DISCUSSION

Natural fire

Fire behaviour is complex and regulated by the interplay between climate, fuel amount and composition, ignition regimes and landscape variables. The incomplete combustion of organic matter produces particulate charcoal, which after dispersal is deposited in lake sediments, permitting fire episode reconstructions. In this study we analysed macroscopic charcoal (>160 µm) from lake sediment sequences. According to Adolf et al. (2018), the source area for macroscopic charcoal particles (>160 µm) can represent information on fire episodes even within a 40 km radius of a lake. A comparison of two sediment sequences situated close to each other but at different locations (pelagial and littoral zones) may reflect differences between local and regional fire patterns.

The pattern of charcoal deposition depends on the ratio between the potential charcoal source area and fire size on the one hand, and on the absolute size and location of the fire within the potential charcoal source area on the

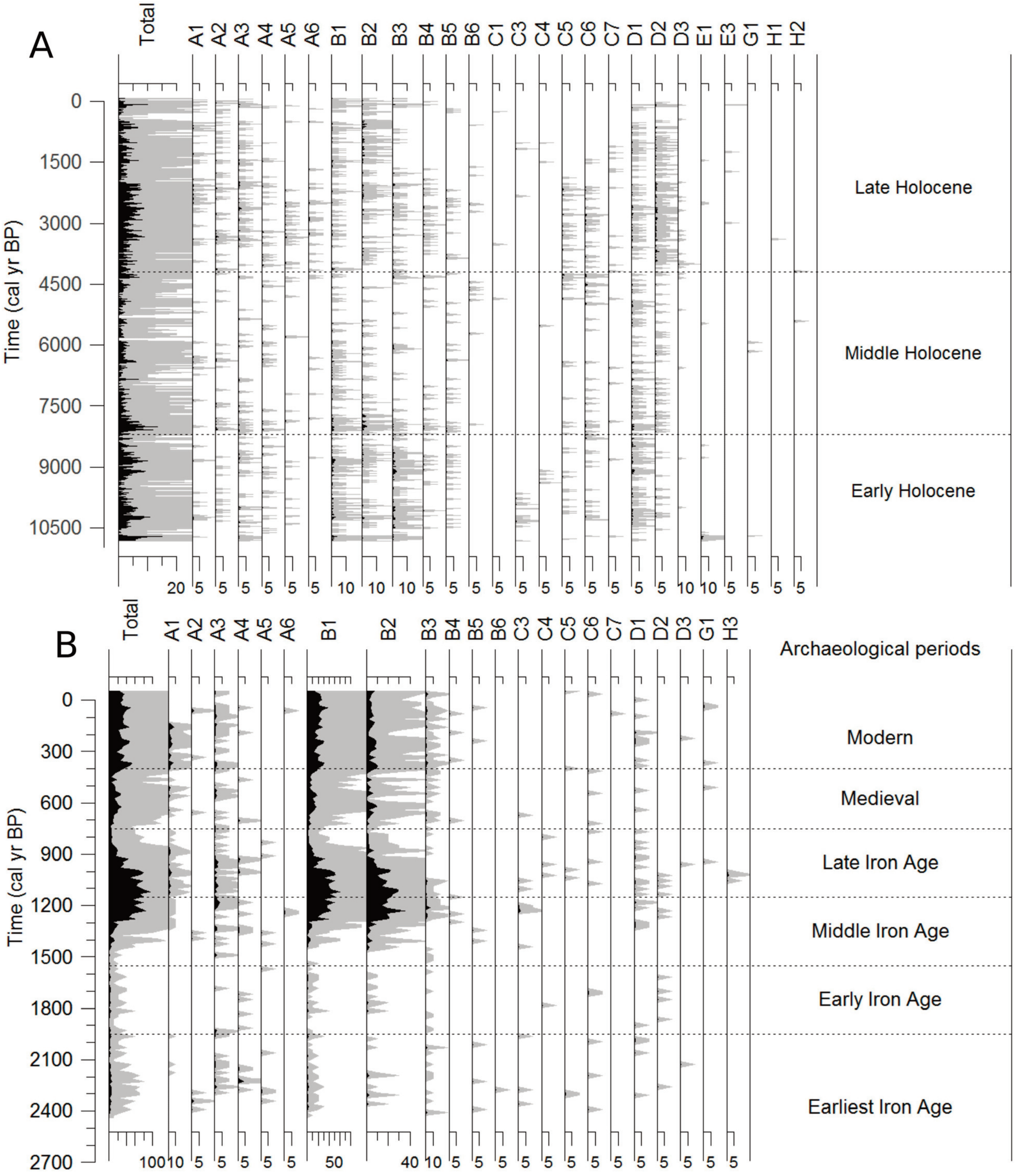

Fig. 3. Charcoal morphotypes from Lake Bricu (**A** – Bricu I; **B** – Bricu II). X-axes: charcoal counts per sample. Charcoal morphotypes indicated by letters and related typos within the group indicated by numbers: A – polygonal charcoal (fuel: wood, herbaceous material, leaves), B – ortho-angular polygons and polyhedra (blocky shaped) (fuel: wood, Poaceae leaves, grass), C – long and complex (fuel: conifer needles, twigs, roots, leaf stems and veins), D – long and simple (fuel: leaves, wood), E – spheroidal (fuel: seeds, sap), G – glassy (fuel: seeds, sap, resin). We defined one more group specifically for the Lake Bricu case: H – does not correspond to any other group (fuel: unknown).

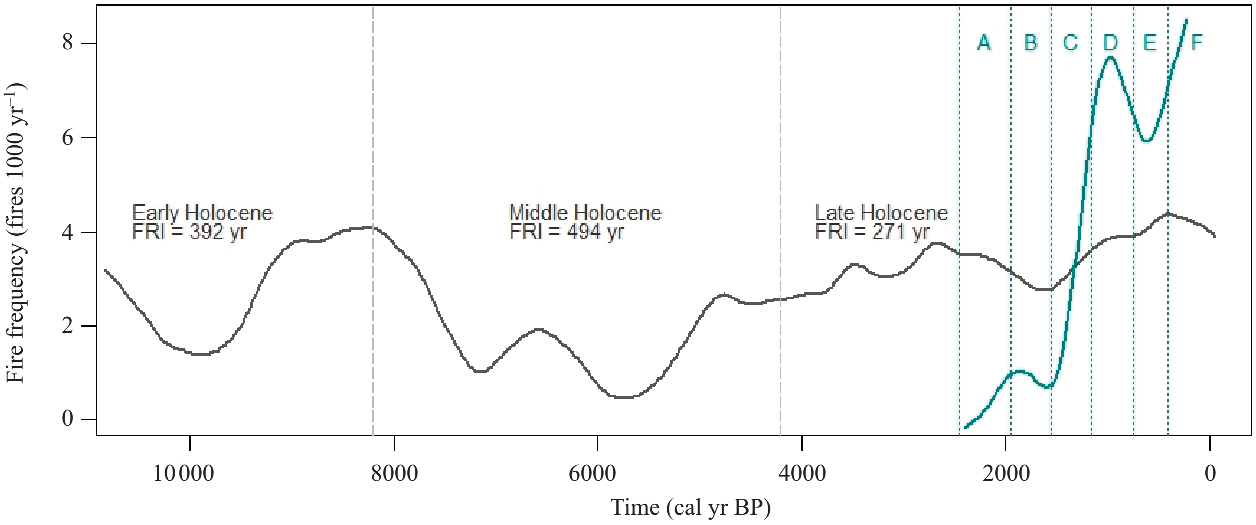

Fig. 4. Reconstructed fire frequency (fires per 1000 yr^{-1}) for Lake Bricu I (black solid line) and II (green solid line), raw results from CharAnalysis. A – Earliest Iron Age, B – Early Iron Age, C – Middle Iron Age, D – Late Iron Age, E – Medieval period, F – Modern times (archaeological periodization according to Vasks et al. (1999) and Graudonis (2001)).

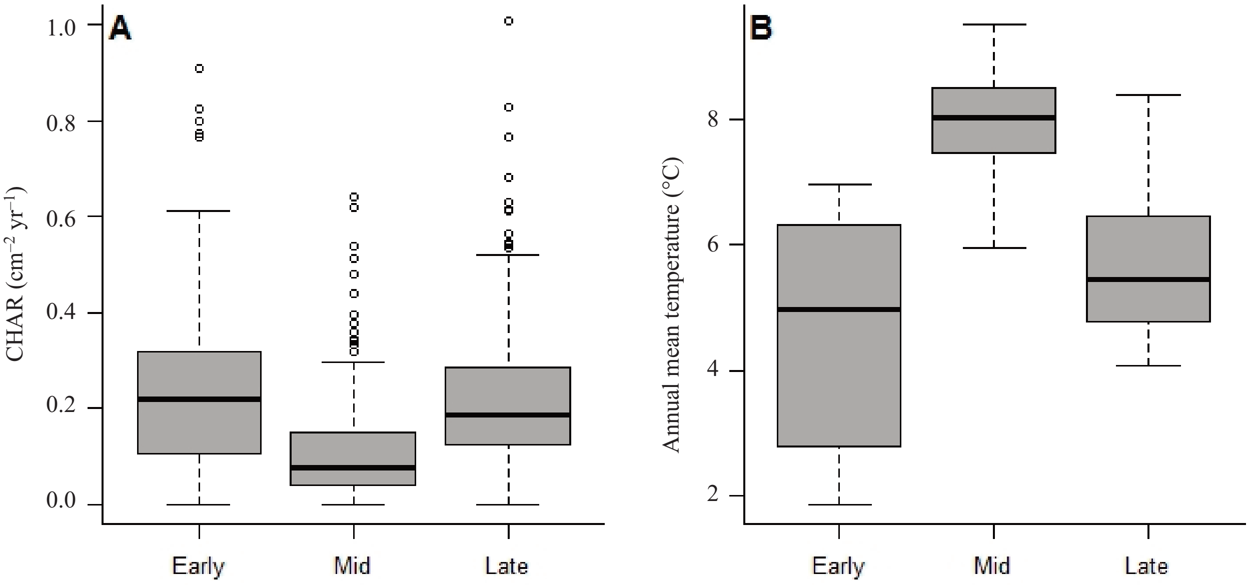

Fig. 5. A, Bricu I CHAR data (particles cm^{-2} yr^{-1}) reflecting fire during the early (11 700–8200 cal yr BP), middle (8200–4200 cal yr BP) and late (last 4200 years) Holocene; **B**, pollen-based mean air temperature (°C) pattern for the Holocene in eastern Latvia (Stivrins et al. 2015a).

other hand (Conedera et al. 2009). Depositional and taphonomic mechanisms influence charcoal accumulation differently throughout the lake, and the macroscopic charcoal may behave more like plant macroscopic remains, i.e. with a higher charcoal concentration closer to the littoral. However, Courtney-Mustaphi et al. (2015) suggest that the best record of past fires is preserved in sediment cores from the deepest area of the basin due to sediment focusing processes. During sediment focusing differential deposition results in the accumulation of greater amounts of sediment in the deeper parts of lake basins (Davis & Ford 1982) and therefore, such a sediment sequence can reveal information at higher temporal resolution than a littoral sediment sequence. Considering the differences in the potential charcoal source area, lake geomorphology and sediment focusing,

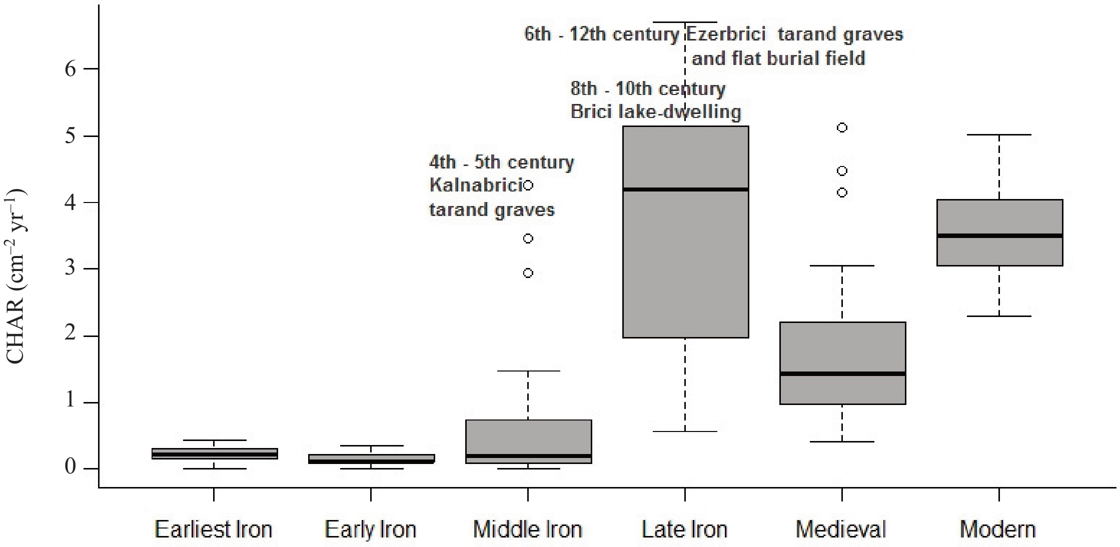

Fig. 6. Bricu II CHAR data (particles cm^{-2} yr^{-1}) reflecting fire during the Earliest Iron Age (500 BCE–1 CE), Early Iron Age (1–400 CE), Middle Iron Age (400–800 CE), Late Iron Age (800–1200 CE), Medieval period (1200–1550 CE) and Modern period (Post-Medieval and Modern periods combined, 1550 CE–present).

we analysed macroscopic charcoal from two sediment sequences. The central sediment core was used to reconstruct local to regional fire, and the littoral core to retrieve information on more local fire. This approach allowed us to gain insights into natural and possible anthropogenic fire occurrence. Indeed, our results show that there were differences in patterns of macroscopic charcoal concentrations (Fig. 3) for the overlapping time period (last 2400 years), supporting the importance of the above-mentioned aspects.

Our macroscopic charcoal results show a higher fire frequency during the early and late Holocene (Fig. 5A), while fire was less frequent during the middle Holocene. Interestingly, the regional climate trends for the territory of Latvia indicate a cool-moist early and late Holocene and a warm-dry middle Holocene (Fig. 5B; Kalnina et al. 2015; Stivrins et al. 2015a). During the middle Holocene, the mean air temperature in Latvia was 2.5–3 °C higher than at present, i.e. similarly to the expected mean air temperature increases at the end of this century (Mitchell et al. 2016; Rogjel et al. 2017). Several studies suggest that fire activity increases under warm-dry climatic conditions (Khabarov et al. 2016), but as we show here, this is not the case for all regions. Our findings are in line with a study by Feurdean et al. (2017), who analysed macroscopic charcoal from Lake Lielais Svētiņu in eastern Latvia and state that a warmer and drier climate can enhance the fire risk on the one hand but promote the expansion of broadleaf deciduous forests that act as fire-suppressing landscape elements on the other hand. Our findings are supported not only by Feurdean et al. (2017) but also by Molinari et al. (2020) who detected a lower biomass burning trend within the boreal and cold temperate forests of Fennoscandia 7000–4000 years ago, at the time of an increased share of broadleaved trees in the landscape. Although there is no pollen (vegetation) record from Lake Bricu, pollen record from Lake Araisu (located 60 km NW from the study site) showed that boreal and hemiboreal forest existed in central Latvia during the early and late Holocene, respectively (Stivrins et al. 2015b, 2019b). Unpublished data from Lake Araisu and Lake Ķūži (60 km W from Lake Bricu) revealed the persistence of nemoral deciduous forest during the middle Holocene (Kangur et al. 2009). While boreal tree species acted as fire promoters, deciduous trees are characterized by low flammability due to a higher leaf moisture content reducing fire spread (Rogers et al. 2015; Feurdean et al. 2017). Hence, the fire frequency probably indirectly reflects boreal–nemoral–hemiboreal vegetation composition changes at a regional scale.

Although rarely applied, the implementation of macrocharcoal morphotype analysis, providing valuable information on the fuel source and fire severity, has made great progress (e.g. Feurdean et al. 2017). This additional information enhances palaeoecological inferences by providing more palaeoenvironmental information than studies of total charcoal concentration as the only metric (Courtney-Mustaphi & Pisaric 2014). However, the possibility of distinguishing surface fire from crown fire (i.e. fire behaviour type) by using charcoal morphology is supported neither by our results nor by previous research. Our results indicate a mixture of fuel types and there is no clear evidence whether surface or crown fire was occurring.

For instance, while proposing this morphological approach, Umbanhowar & McGrath (1998) concluded that this method was suited for distinguishing between fuel types (grass vs litter or wood), but not fire behaviour. Although Feurdean et al. (2017) discussed relationships between charcoal morphology and fire type and severity in hemi-boreal/boreal forests, they did not test this hypothesis explicitly. Tinner et al. (2006) examined the effects of a crown fire on sedimentary charcoal but did not report evidence supporting the hypothesis that fire behaviour can be inferred from charcoal geometry. Therefore, previous studies attempting to reconstruct fire regimes based on sedimentary charcoal concluded that a low to moderate severity fire regime, i.e. a mixture of ground fire, surface fire and crown fire, characterized central European temperate forests during the Holocene. Studies documenting current fire events in European temperate and hemi-boreal/boreal forests (e.g. Schimmel & Granström 1997; Marozas et al. 2007; Ascoli et al. 2015; Maringer et al. 2016) confirm that all types of fire behaviour alternate according to the interaction between fire growth, topography, wind direction and vegetation structure. Consequently, charred remains (i.e. needles, bark or branch) found in sediments can be produced by a complex combination of ground and surface fires (e.g. burning leaves and branches on the ground) and crown fires.

It is important to state that the study of macroscopic charcoal reveals a possible reference of natural forest fire frequency for the future. We are aware of the assumption that present-day relationships most likely cannot be linked linearly to historical non-analogue climate and environmental conditions, and knowledge transfer might be biased due to such circumstances. At the same time, the present landscape and modern-day forest structure are a result of the millennium-long interaction between the past climate, vegetation, natural and anthropogenically induced disturbance dynamics. As both natural and anthropogenic pressures are projected to increase, the implications of this study provide valuable insights for formulating forest management plans and understanding anthropogenic environmental impacts. The impacts of future climate change, such as changing fire risk, will be highly variable at the regional scale and dependent on preconditions that have shaped the landscape. If climate continues to warm, we might see a decrease in natural fire frequency and a change in fire patterns. Yet, the unknown element here will be human action, such as land and forest management, which might either increase or decrease the occurrence of fire events in the region.

Anthropogenic fire

It is challenging to distinguish between natural and anthropogenic fires. In a shallow lake such as Lake Bricu, sediment mixing and redeposition are more intense in the littoral areas, which may lead to more reworked sedimentary and soil charcoal. Therefore, the effects of these processes on the reconstructed fire in the littoral core and on the comparison with the fire reconstructed from the distal core must be well thought through. Considering the complex nature of fire, the true presence of humans in the vicinity of the lake and by inference, the fire usage by the humans can be aligned on the basis of sure evidence, such as archaeological findings. Archaeological data constrain anthropogenic activity in the vicinity of Lake Bricu in the 4th–5th centuries (Kalnabrici tarand graves), 6th–12th centuries (Ezerbrici tarand graves and flat burial field) and 8th–10th centuries (Bricu lake-dwelling) (Toropina 1990; Apals 2012).

On the basis of the archaeological background and increase in macroscopic charcoal values, we suggest that the first traces of anthropogenic fire use appear from the Middle Iron Age (1400 cal yr BP). However, an abrupt increase in human-induced fire is likely associated with the Late Iron Age (800–1200 CE, 1150–750 cal yr BP). As mentioned in the 'Introduction' chapter, Lake Bricu is one of the 12 lake-dwelling sites, which means that people were living both on the lake shore and on lake's island for a certain period. In this regard, only 60 km from Lake Bricu there is located Lake Āraišu, which experienced a distinct human-induced environmental change in the Late Iron Age, associated with the establishment and occupation of a lake-dwelling from 780 to approximately 1050 CE (Apals 2012; Stivrins et al. 2015b). Similar human impact is expected also at Lake Bricu. We are not able to identify specific uses of fire from the macroscopic charcoal record, but most likely these comprised slash-and-burn agriculture, domestic hearths, building fire episodes, kilns and furnaces for craft activities. We should also consider that the lake-dwelling community was inhabiting not only the shores of Lake Bricu, but also the lake-dwelling itself. Thus, a larger amount of macroscopic charcoal could be transported to the sampling site. Evidence through the tests in the future must be provided to support this assumption. An alternative explanation for the difference in charcoal concentration obtained from the two cores (pelagial and littoral) may be that larger, bulkier charcoal particles are heavier, have a lower buoyancy and tend to be deposited closer to the lake shores. For this reason, charcoal concentration may be higher in the littoral core than in the pelagial core – note that bulky morphotypes B1 and B2 are the most abundant in the littoral core (Bricu II). A size-based assessment of charcoal fragments in the future might shed more light on the matter.

Our results suggest a significant decrease in charcoal accumulation and fire frequency during the Medieval period (Figs 4, 6), which might point to the abandonment of the lake-dwelling (e.g. it was burned down during a battle, climate change – increased water level). It is also uncertain whether this can be because of the wars leading to substantial depopulation in the vicinity of Lake Bricu. The medieval period in the Baltic was dominated by crusades, a holy war led by the military order and bishops, who conquered modern-day Estonia, Latvia and western Lithuania with the aim of converting the indigenous pagan tribal societies to Christianity. Although subsequent wars and changes in political control had little apparent effect on agricultural land use in this region (e.g. Lake Āraiši), Lake Trikātas located in the northeast of Lake Bricu indicates that there are exceptions where immediate change is traceable both by pollen and charcoal data (Stivrins et al. 2016a). Suggested reasons remain inconclusive in the absence of additional archaeological and palynological evidence from Lake Bricu.

The modern period shows an increase in charcoal accumulation rates and fire frequency (Fig. 6). The charcoal accumulation rate is lower than during the Late Iron Age, but the total fire frequency increases towards the present day. This period includes several major economic and political trajectory changes, such as the Hanseatic League and the manorial system, and the industrial revolution boosting the use of natural resources to satisfy the growing demand for goods. This is the time when the fire frequency reaches its maximum in both Bricu I and II cores. From the fire frequency records we see that the natural baseline in the boreal forest is four fires per 1000 years, and this number should be lower within the hemiboreal forest (due to mixture of conifers and broadleaved trees). On the contrary, the results show increase in the fire frequency and therefore, we argue that the anthropogenic fire use has surpassed the natural fire frequency.

CONCLUSIONS

The current study presents the first macroscopic charcoal analyses from Lake Bricu, central Latvia. This site was selected for investigation because it is known to be a lake-dwelling site and can thus reveal a baseline of natural fire occurrence and additionally indicate how this pattern has changed since humans settled in this region. The aim of this study was to reveal the frequency and regime of the natural and anthropogenic fire events during the Holocene. Two sediment cores were analysed to reconstruct fire frequency. Our results show that the lake was formed approximately 10 800 years ago and is of glaciokarst origin. Fire reconstructions reveal higher fire frequency during the early and late Holocene (moist and cool climate), but lower frequency during the middle Holocene (warm and dry climate). Anthropogenic fire events can be traced back as far as 1400 years ago, but distinct fire use by humans is recorded during the Late Iron Age – possibly coinciding with the establishment and occupation of the dwelling site. We reveal a possible reference of natural forest fire frequency for the future fire studies.

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Kesk-Läti tulesündmuste sagedus Holotseenis

Dace Steinberga ja Normunds Stivrins

Tuli on muutnud meie tänapäevaseid maastikke jääaja lõpust alates. Käesolevas artiklis on käsitletud Bricu järve setetes leiduvaid makroskoopilisi söeosakesi (>160 µm) kahes puursüdamikus, järve sügavaimas osas ja litoraalis, kus paikneb rauaaegne järveasula. Söeanalüüsil kasutati CharAnalysise meetodit, mis näitab, et Holotseenis oli keskmine tulesündmuste sagedus umbes 372 aastat ja Kesk-Holotseeni soojal perioodil oli tuld vähem kui jahedamatel aegadel. Samuti on tulesignaal suurem järveasula lähedal alates hilisrauaajast.