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Fire occurrence and the current state of palaeofire reconstructions based on sedimentary charcoal from natural archives in Poland

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Abstract. Due to rising temperatures worldwide many areas are threatened with increasing numbers of fire occurrence. Poland is among these areas and is projected to experience over the next century an increase in both heat stress and wildfire activity with the potential to turn its fire-resistant forests into fire-prone forests. This paper aims to provide an introduction to the conditions favourable to fire occurrence in Poland, summarising the research on sedimentary charcoal analysis and reviewing fire reconstructions based on natural archives from Poland. Here, natural wildfires occurred at the beginning of the Holocene but, due to changes in climate (wetter summers) and vegetation after 6550 BC, the main trigger of fire occurrence became human activity, mainly as a result of forest clearance for agrarian purposes. However, there is evidence that prolonged droughts also triggered wildfires. Over recent decades, according to existing data, arson (44.85%) and negligence (34.43%) have been the most common causes of fire occurrence in Poland.

Key words:
annually laminated sediments,
charcoal,
paleofire,
natural archives

Introduction

Fire is an important disturbance that causes notable changes in vegetation composition, and the structure and function of the ecosystem (Carter et al. 2018). It is also a key component of many natural ecosystems. It is closely linked to climate (Marlon et al. 2009) and influences nearly all the biomes that play a critical role in nutrient cycling (McWethy et al. 2013). Fire activity has increased over the past few years and it is predicted to become even more intense with future warming (Blarquez et al. 2015). According to the Annual Report on Forest Fires in Europe by the European Commission (EC) (San-Miguel-Ayanz et al. 2018), Europe is likely to face an increasing threat of wildfire activity. Although the Mediterranean region remains the most affected area, in recent years unusually dry summers have led to large wildfires in countries such as Sweden, Germany and Poland (Fig. 1). Extreme climate events such as heat waves and prolonged drought episodes have become more frequent across Europe since the 1950s (IPCC 2014; Kundzewicz et al. 2018), making forests more vulnerable to disturbances such as fire (de Rigo et al. 2017). Climate models predict that extreme climate events will become more severe throughout Europe as a result of rising global temperatures (Kundzewicz et al. 2018). This temperature change will increase fire risk among central and southern European ecosystems by the end of the 21st century. As the risk of wildfire increases, so does the impact on vegetation, with forest ecosystems becoming less resilient and less adapted to changing fire regimes (Lindner et al. 2014). This is alarming because currently the role of fire as a

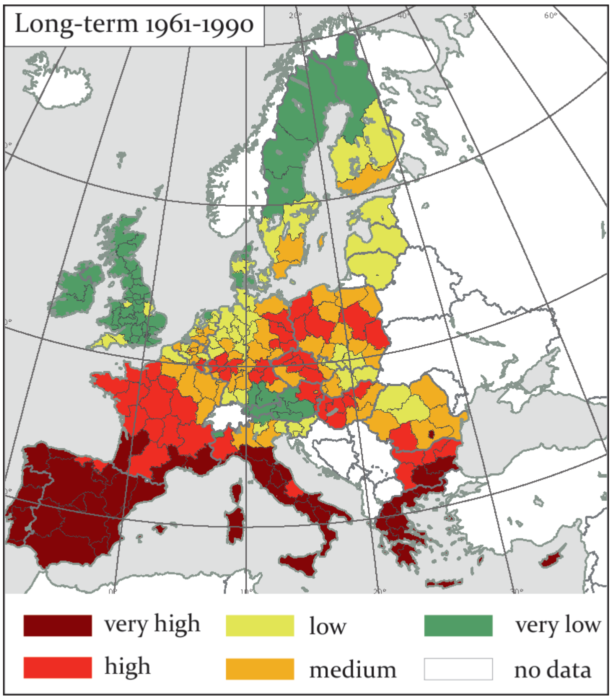

Fig. 1. Forest fire risk in Europe 1961–1990 (European Environment Agency 2019)

disturbance agent is deemed negligible in Central European temperate forests (Adámek et al. 2015; Dietze et al. 2018). Thus, future climate change may potentially threaten the resilience of temperate forests like the ones in Poland. The recent increase in fire activity has been accompanied by the rapid development of palaeofire science (Vanniére et al. 2013), which allows past fires regimes to be studied using a suite of proxies that may help to understand when, where and what type of fire occurred (Conedera et al. 2009).

Poland is projected to experience an increase in both heat stress and wildfire activity over the next century (Lung et al. 2013), which has the potential to turn these fire-resistant forests into fire-prone forests (Adámek et al. 2015). In addition, Polish forests are abundant with *Pinus sylvestris* (Scots pine) which is rated as a highly fire-prone fuel type. With current human-induced climate change, coupled with fire exclusion and the discontinuance of litter collection (Komarek 1983), this fire-prone species is experiencing a rapid increase in wildfire activity (Adámek et al. 2015). Therefore, the understanding of how wildfire activity may change with future climate change is critical. Investigating past wildfires by focusing on how certain components of fire regimes have changed during past warm periods offers a better understanding of how Polish forests may respond to future climate change. Thus, this paper aims to summarise i) conditions favouring fire occurrence in Poland, ii) recent fire causes, and iii) sedimentary micro and macro charcoal analysis and a review of fire reconstructions since the last glaciation retrieved from natural archives from Poland with special attention to lake sediments.

Climate of Poland

Poland is predominantly a lowland country located in a transitional (from maritime to continental) moderate climate zone where humid Atlantic air from the west collides with dry continental air from the east.

Temperature

The temperature varies most during winter months, which are influenced by either oceanic or continental air masses causing warmer or colder winters, respectively (Graczyk and Kundzewicz 2016). The mean annual air temperature (8.1°C) is highest in the southwest of Poland, while it is lowest (6.2°C) in the northeast (Matuszkiewicz 2005). Within the last decades there has been a significant air temperature increase, especially in February, March, May and August, when the temperature has risen from between 0.3°C and 0.7°C per 10 years. These changes are related to a stronger influence of the Atlantic Ocean on the climate of Poland (Michalska 2011). The number of hot days (t_{max}>30°C) and tropical nights (t_{min}>20°C) – both values after Niedźwiedź (2003) – has also significantly increased in recent years (Graczyk et al. 2017).

Precipitation

The amount of rainfall and evaporation influences the hydrological regime in warm seasons, while precipitation (snowfall and rainfall) are crucial factors determining the colder months (Szwed et al. 2017). The mean annual precipitation (calculated for the period 1961–2009) in Poland is 623.7 mm (IMGW-PIB 2012). Kundzewicz et al. (2018) noticed an increased number of days with intense precipitation, especially in northwest Poland during winter and spring seasons in recent years. On the other hand, the number of dry days increased in many parts of the country in the summer months.

Snow cover plays an important role in the hydrological cycle as a seasonal water reservoir. Earlier snow melting increases the likelihood of drought during the summer. In general, snow cover in Poland is observed from late November to late March. Snow cover thickness varies from 2.2 cm to 11.8 cm (mountain areas excluded) (Szwed et al. 2017).

Conditions favouring fire occurrence in Poland

Fire occurrence in Poland is most probable during spring and summer. According to the forest fire hazard map (http://bazapozarow.ibles.pl/zagrozenie/) the fire season lasts from 1 April to 30 September. According to the EC report (2016) favourable weather conditions brought the year 2015 close to record values of forest fires from the last years of the 21st century. The mean monthly air temperature that year was 0.5°C higher than long-term values (2001–2010) and was 9.43°C as measured by the Institute of Meteorology and Water Management (IMGW-PIB) in Poland. The average daily precipitation level in the 2015 fire season was 1.5 mm and was the lowest value noted in the 21st century (San-Miguel-Ayanz et al. 2016). The highest fire risk occurred in August, and the lowest in September. In the next years (2016 and 2017) the fire risk decreased. However, according to IMGW-PIB the year 2018 was warmer than 2015 by 0.03°C which again increased the fire risk. Despite changes in precipitation and temperature, another factor determining fire occurrence is litter moisture. The security level of moisture for dead pine is 30%. Lower values show an increasing risk of fire occurrence (e.g. San-Miguel-Ayanz et al. 2018). During the fire seasons (2007–2017) the litter moisture varied from almost 60% to below 10%. The driest season was 2015, with a mean pine litter moisture of only 14–19% depending on the measuring time (1 pm vs 9 am) (San-Miguel-Ayanz et al. 2015).

Polish forests

In the past, forests covered almost the entire territory of modern-day Poland. The composition of forest varied through the Holocene. During the early Holocene, open-land taxa (mainly grasses) and pine reached their maximum. After 8500 cal. BP these declined, and broadleaf forest expanded, reducing the area of flammable species (Dietze et al. 2018). A significant forest structure change has also been presented by Słowiński et al. (2019). The deciduous trees (mainly *Carpinus* and *Quercus*) in the Tuchola Forest (N Poland) decreased from 35% in 1200 CE to around 5% in 1750 CE. However, as a result of historic social and economic transformations, the development of agriculture and a strong demand for wood, forests underwent significant changes (Lasy Państwowe 2017). Nowadays, forest covers almost 30% of the area of Poland. Due to the abovementioned transformations (mainly after 1700 CE and later, between 1945 and 2016) forests composition changed from broadleaf-dominated into a *Pinus sylvestris* monoculture (Słowiński et al. 2019), which makes Polish forests especially at risk from wildfires under favourable conditions.

The forested area in Poland varies from 21.4% in Łódzkie Voivodeship to 49.3% in Lubuskie Voivodeship (Fig. 2). The growing stock of Scots pine in % of gross grand total timber is highest in Kujawsko-Pomorskie Voivodeship (83.7%) and lowest in Małopolskie Voivodeship (16.8%). In 13 out of 16 voivodeships in Poland the contribution of the fire-prone tree species (*Pinus sylvestris*) is higher than 50% of total timber, making these areas more vulnerable to fire occurrence (after Lasy Państwowe 2017; Adach-Stankiewicz et al. 2018).

Recent fire causes in Poland

Forest fires reflect the cultural background of human evolution, and most wildfires are caused by human activity. This is due to: i) unsustainable forest management; ii) degradation of ecosystems; and iii) planting of highly flammable forest species, which facilitates the ignition and spread of fires. According to the EC, in years 2004–2017 the most common

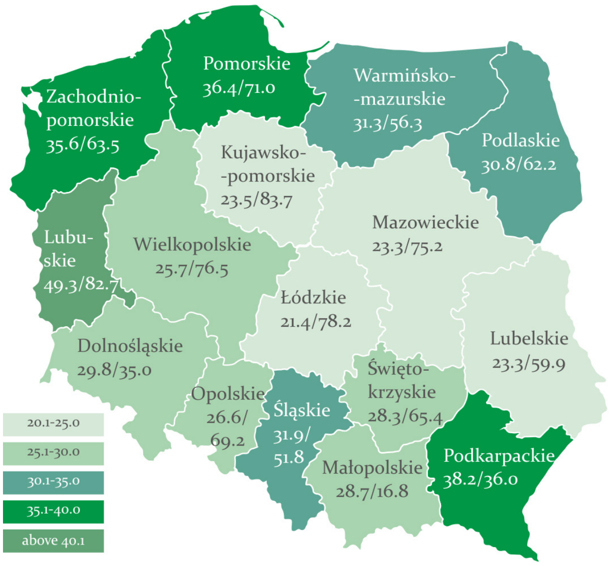

Fig. 2. Map of forest cover (%) in 2017/growing stock (volume of all living trees in a given area of forest or wooded land) of Scots pine in % of gross grand total timber by voivodeship (after Lasy Państwowe 2017 and Adach-Stankiewicz et al. 2018)

causes of fire in Poland (Table 1) were arson (44.58 %) and negligence (34.43%). Unknown source of fire was reported as 17.94% of all fire causes. In addition, in the years 2014–2017 fires were caused by accident in 6.51% of reported events. Destructive human activity was also mentioned by Marcisz et al. (2018) who concluded from questionnaires that in some regions of Poland up to 90% of recent fires are of anthropogenic origin.

Forest fire reconstruction: micro and macrocharcoal analysis

Fire is a natural process integral to the order and function of our planet. Studying the influence of fire in the Earth's ancient ecosystems helps to understand the flammability of vegetation and the environmental responses and hence, to predict future changes (Colombaroli and Tinner 2013; Sadori et al. 2013). To be successful, we need to better understand the drivers, because fire is not only driven by temperature but also by the flammability of vegetation (i.e. fuel) and ignition, which are both driven and triggered by either natural or human activity (Conedera et al. 2009; Dietze et al. 2018).

Micro and macrocharcoal characteristics

Past fires (palaeofires) can be tracked by analysing sedimentary charcoal. Particulate charcoal is produced by the incomplete combustion of organic matter, and therefore provides direct evidence of burning (Conedera et al. 2009; Scott 2010). It is produced between temperatures of 280°C and 500°C (Chandler et al. 1983). Higher temperatures convert the material into ash and lower temperatures may scorch material but not char it (Whitlock and Larsen 2001). Charcoal origins may be local (within the watershed), regional (distant), continental, or even global (Conedera et al. 2009) (Fig. 3). Microscopic charcoal (<100 microns) is usually counted as part of routine pollen analysis (Whitlock and Larsen 2001) and is assumed to be transported over long distances from the source and therefore to mostly reflect regional fire history (e.g. Tinner et al. 1998; Blackford 2000). In contrast, macroscopic charcoal (>100 microns) is usually not transported far from fires; thus it seems that it is more suitable for local fire events, mostly deriving from a few hundreds of metres. This assumption is based on several calibration studies that showed evidence for a local origin of macroscopic charcoal and regional origin of microscopic charcoal (Conedera et al. 2009).

Charcoal analysis

Fire is registered in sedimentary charcoal records through total charcoal abundance (per unit of sediment), which is proportional to the total biomass burned (Marlon et al. 2009). It occurs also as peaks in charcoal accumulation, which mark individual fires in sedimentary records. Peaks in abundance of macrocharcoal could also reflect higher energy sediment input to the depositional area, or rare instances of long-distance transport (Power et al. 2008).

The methodology can vary for different depositional environments but, in general, analysis of microcharcoal is usually performed during pollen analysis and thus, sample preparation follows the method applied to pollen slides. Analysis of mac-

Table 1. % of cause in the following years, NA – data not available, in grey estimated % of unknown cause (Unknown=100% – [arson + negligence]. From JRC Science for Policy Reports [2004–2017])

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average
Arson	44.23	50	47	49	47	45	43	43	4270	42.40	40.25	42.58	43.09	44.82	44.58
Negligence	40.17	39	43	41	37	38	39	33	30.50	26.00	29.49	29.45	28.64	27.73	34.43
Unknown	15.60	11	10	10	15	16	16	16	19.80	22.10	22.12	18.22	19.32	22.83	16.71
Accident	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.11	7.93	7.38	3.62	6.51

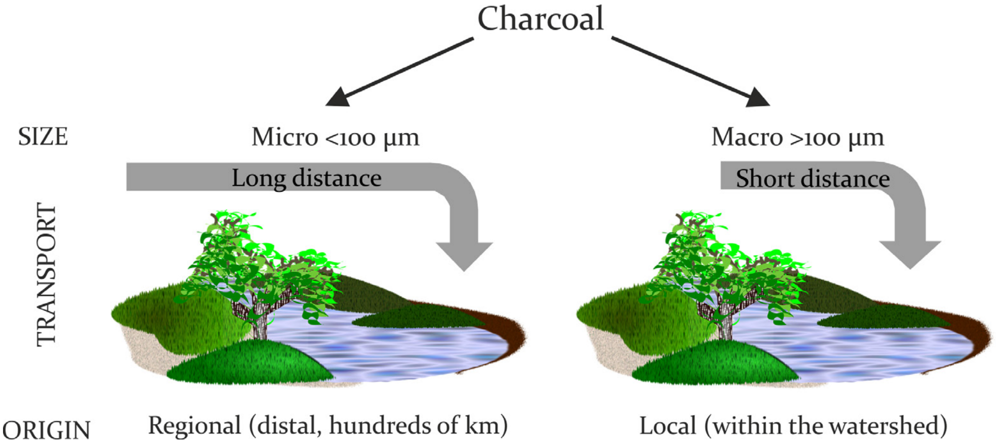

Fig. 3. Charcoal transport and accumulation in sedimentary basins

rocharcoal particles includes continuous sampling from sediment cores or peat/soil profiles. The particles are retrieved by disaggregating sediment in 20 ml solution of dilute sodium hexametaphosphate and 10 ml potassium hydroxide (5%). Next, the samples should be washed gently through a 250-micron sieve and then bleached using 1–2 ml of sodium hypochlorite (8% NaOCl) for the minimum time necessary to achieve a consistent bleaching effect. After this process, samples should be washed gently through a 125-micron sieve with the use of warm water. The macrocharcoal particles should be moved then to Petri dish and examined under a low-power binocular microscope with a magnification of 30–60× (Feurdean et al. 2017).

The total concentration of charcoal (pieces per cubic centimetre) should be later multiplied by sedimentation rate (centimetres per year) in order to obtain the charcoal accumulation rate (CHAR) (Higuera et al. 2009). To identify local fire events the CHAR is decomposed into CHAR-background, mirroring regional fire activity and secondary charcoal deposition, and into CHAR-peaks reflecting local fire events (Feurdean et al. 2017).

Charcoal deposited in natural archives

Usually, charcoal is transported to the deposition place by wind but can also float on the water. In certain cases, the macrocharcoal is not deposited immediately after a fire event (primary charcoal) but the deposition may occur over many years following the event (secondary charcoal) (Conedera et al. 2009).

Sedimentary charcoal can be found in natural archives as peatlands, soil or lake sediments. Although soil deposits and peatlands are valuable records for reconstructing fire history and provide substantial insights where lacustrine sediments are lacking, it is believed that they present a less powerful reconstruction than lake sediments (e.g. Tolonen 1983). For instance, the soil record can be vulnerable to erosion and the signal in peat records may be lost due to their burning in dry periods (Conedera et al. 2009). In general, lake sediments are one of the most important natural archives to allow the tracking of environmental changes. Among them, particularly valuable are varved sediments because they record with (sub-)annual resolution physical, chemical and biological conditions during sediment formation. While a resolution of 30 years is useful in detecting trends in biomass burning, this level of resolution is insufficient when trying to quantify annual to decadal triggers such as weather conditions favourable to fire occurrence or ignition likelihood. Annually laminated lake sediments (i.e. varves) offer the highest time resolution possible. A single annual unit – a varve – is composed of at least two different layers (seasonal laminae) that can be distinguished based on their composition, colour, structure and thickness (Zolitschka et al. 2015). The general preconditions and processes controlling the formation and preservation of varves depend on both natural and anthropogenic factors, such as seasonal differences in runoff, algal blooms, periods of intense calcite precipitation, and agriculture (Lotter and Lemcke 1999; Bonk et al. 2015). Individual sub-layers representing certain seasons or even short-term events are also common within each lamina, which offers the unique opportunity to study wildfire behaviour in a high-resolution approach. However, annually laminated sediments are relatively rare.

Possible pitfalls

There are a few possible pitfalls during reconstructing palaeofires from lake sediments. To be considered promising for palaeofire reconstruction, a lake should have: i) a catchment bigger than the size of the lake; ii) gentle slopes, to decrease the introduction of secondary charcoal through erosion; and iii) small or no inflowing streams that could transport secondary charcoal (Whitlock and Larsen 2001). One of the challenges of palaeofire reconstruction using sedimentary macrocharcoal is the timing of charcoal deposition. It can vary due to the weather and season during the fire, the geomorphological and topographical features of the area, and combustion intensity (Conedera et al. 2009). Charcoal could also float for a considerable time (hours to weeks) before being deposited and incorporated into sedimentary sequences (Scott 2010). However, the careful investigation of macrocharcoal particles can tell us whether or not the charcoal was transported far from the source. An assemblage of the same charred particle type (e.g. wood) would indicate sorting during transport, whereas an assemblage of various plant parts of different sizes may imply minimal transport and indicate a local fire (Scott 2010). The transport itself may also have some implications. Some of the bigger charcoal particles may be crushed during depositional or post-depositional processes and, thus, the record can show stronger regional signals.

Palaeofire reconstructions based on sedimentary charcoal from natural archives in Poland

Over the last few decades, the palaeofire discipline has rapidly evolved, allowing researchers to better understand past wildfire regimes (Conedera et al. 2009). Fire history records using sedimentary charcoal are abundant across Europe (Global Charcoal Database, https://www.paleofire.org), although there are only a few long-term fire history records from Poland. This is likely due to the country's presumed low vegetation flammability (i.e. generally humid conditions), low frequency of lightning strikes, and the presence of broadleaf forests, which typically rarely burn (Dietze et al. 2018). However, Carter et al. (2018) highlight that fire was an important disturbance factor throughout the Holocene in Central Europe, despite the perceived notion that fires are a negligible disturbance factor. They also point out that there is currently a lack of long-term information on past fire regimes to reliably assess the vulnerability of temperate zone forests to climate change and increasing fire risk.

Currently, there are several fire reconstructions from Poland (Fig. 3). Among them, only a few (Gałka et al. 2014; Marcisz et al. 2015, 2019; Kajukało et al. 2016; Dietze et al. 2019; Lamentowicz et al. 2019) provide fire reconstruction based on macrocharcoal from natural archives such as lakes and peatlands. However, there is more research on microcharcoal analyses, which provide regional fire histories in certain areas, mainly from the Polish lowland (Figs 4 and 5). These studies include variable time periods but, in general, reconstruct the forest fire history in Poland between ca. 5500 BC to 2011 AD, which is related to human activity. In addition, Di-

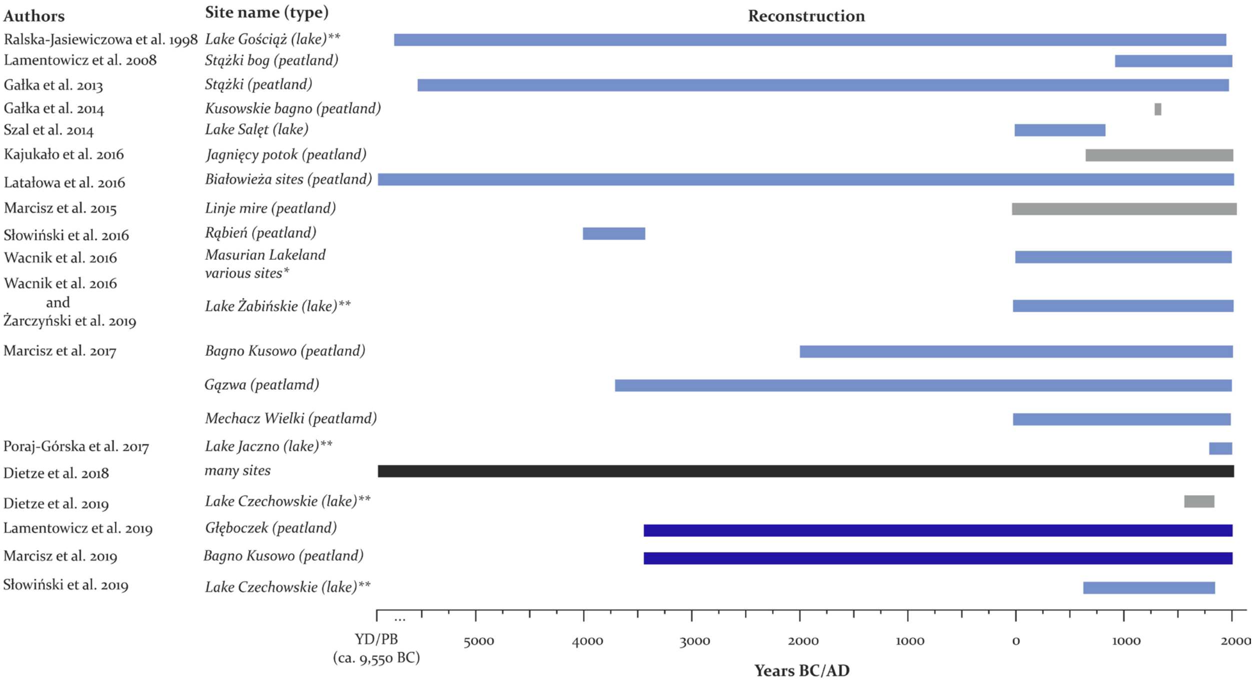

Fig. 4. Fire reconstructions from Poland based on microcharcoal (blue bar), macrocharcoal (grey bar) and both (dark blue bar) from various sites. Black bar represents extensive study on microcharcoal in northern Poland by Dietze et al. (2018), an asterisk (*) marks various sites: cemeteries, lake sediments, stronghold and settlements in NE Poland. Two asterisks (**) mark annually laminated lake sediments

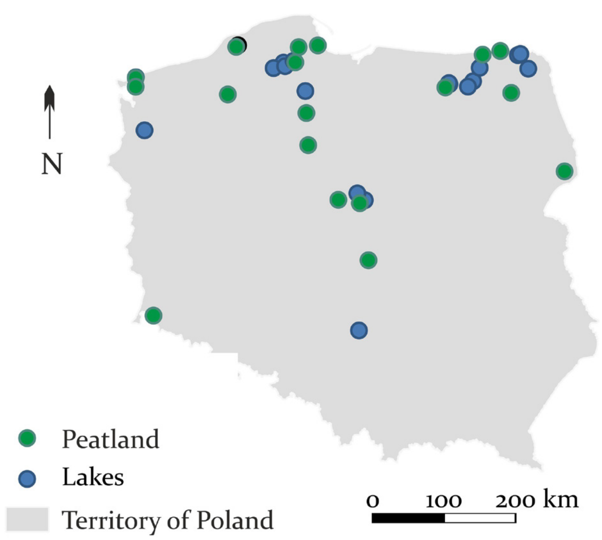

Fig. 5. Location of palaeofire study sites in Poland (micro and macrocharcoal); lakes (Ralska-Jasiewiczowa et al. 1998; Szal et al. 2014; Wacnik et al. 2016, Poraj-Górska et al. 2017; Dietze et al. 2018, 2019; Żarczyński et al. 2019) and peatlands (Lamentowicz et al. 2008; Gałka et al. 2013, 2014; Marcisz et al. 2015, 2017, 2019; Kajukało et al. 2016; Latałowa et al. 2016; Słowiński et al. 2016; Dietze et al. 2018; Lamentowicz et al. 2019)

etze et al. (2018) published an extensive study on Holocene fire activity in the Central European Lowland, including around 30 sites from Poland (Fig. 4). Microcharcoal was also observed throughout the Holocene in Lake Gościąż (Ralska-Jasiewiczowa et al. 1998) in central Poland.

The main trigger of fire occurrence is human activity. Widespread and potentially natural fires occurred only in the early Holocene (Dietze et al. 2018). The change in climatic conditions and the land cover limited fire occurrence from ca. 6550 BC. Since fire become a tool, humans have used it to transform the environment. Forest clearance using fire is quite well documented in various sites, including archaeological sites (cemeteries, settlements, strongholds) and natural archives (peatlands and lakes). Humans have had a significant influence on the environment since Mesolithic times (Szal et al. 2014; Wacnik et al. 2014; Poraj-Górska et al. 2017) but the last millennium is especially affected due to bigger societies and land transformations for agrarian purposes. The anthropogenic impact extended far beyond the local scale and was closely related to land-use strategies (Wacnik et al. 2016; Słowiński et al. 2019; Żarczynski et al. 2019). Unintentional forest fires were often related to local forest production (charcoal and tar production, beekeeping) as well as grazing associated with the burning off of undergrowth (Latałowa et al. 2016 and references therein). Beekeepers used to set bonfires at the base of a pine to cause the trunk injury. The obtained resinous wood was used as kindling or smoke fuel for use in extracting honey (Zin 2016).

Extreme droughts are the second most common reason for fire occurrence in Poland (Gałka et al. 2013; Słowiński et al. 2019). There are large coniferous monoculture forests which are highly susceptible to fires and other disturbances, especially during prolonged drought. Marcisz et al. (2017) suggest that local climatic conditions and fuel availability influenced fire events. In addition, stronger fire activity occurred in eastern Poland where a continental climate dominates, as compared to western Poland where the climate is more oceanic. Latałowa et al. (2016) noticed that prolonged droughts may have been a main trigger of forest fires in the Białowieża region (E Poland) between 4000 BC and 1800 BC, but human activity cannot be excluded.

Typically, micro and macrocharcoal analyses are conducted in an average resolution of 5–30 years in archives such as mires or peatlands. A higher resolution is not possible, due to the limitations of the dating method. To track palaeofires at the highest possible resolution, research should be based on annually laminated sediments. They allow for an understanding of what the environment was like in the past (before the fire event), how quickly forests can recover from disturbances, and how resilient they could be to changes in calendar years. Thus, new research should focus on long-term high-resolution reconstructions from natural archives that make it possible to predict how the forest can respond to disturbances in the future.

Another direction that palaeofire research should develop might be to apply reflectance microscopy to determine the minimum temperature of charcoal formation. It has been shown, by reflectance method with oil immersion, that the ordering of charcoal structure increases with increasing charring temperature, which translates into a predictable increase in the measurable amount of light reflected from the sample (Hudspith et al. 2015). Generally speaking, reflectance measurements can provide an indirect measure of the minimum temperature that material has been subjected to during fire. This method has been successfully applied to big charcoal particles (e.g. Hudspith et al. 2015; Belcher et al. 2018; New et al. 2018) and has improved the knowledge about fire-severity assessment, but the method is still applied only rather rarely.

Summary

It is predicted that in the upcoming years the threat of wildfires will increase even in regions considered to be unthreatened, such as the Polish Lowland, leading to disastrous environmental and economic consequences.

Due to historic social and economic transformations, Polish forest communities are dominated by *Pinus sylvestris* (Scots pine), known to be a fire-prone species, which makes many areas vulnerable to fire occurrence. Sedimentary charcoal is often used to reconstruct palaeofires, giving a means to predict future changes. Fire history studies using sedimentary charcoal are abundant across Europe; however, there are only a few long-term fire history records from Poland. This is likely due to the presumed low flammability of the vegetation and the low number of lightning strikes. Palaeofire reconstruction in Poland was based on micro and macrocharcoal for the interval of several hundred to several thousand years. Natural forest fires were common at the beginning of the Holocene. Later, due to forest clearance for agrarian purposes, past fire episodes were also triggered by human activity. However, prolonged droughts could also be considered as a trigger of fire. The existing research shows that, over the past decades, the most common trigger of recent fire events in Poland is human activity (arson or negligence).

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No potential conflict of interest was reported by the author.

References

ADACH-STANKIEWICZ E, BIELAK R, BIENIEK M, BŁAŻEJ M, JEZNACH M, KAMIŃSKA-GAWRYLUK E, KURSA L, MOJSIEWICZ M, ROGALIŃSKA D, STAŃCZAK J, SZUCHTA W, SZYDŁOWSKA G, WALKOWSKA K, WĘGŁOWSKA M, WOŹNIAK H, ZGIERSKA A and ŻYRA M, 2018, Statistical Yearbook of Forestry. *D. Rozkrut.* Warszawa.

ADÁMEK M, BOBEK P, HADINCOVÁ V, WILD J and KOPECKÝ M, 2015, Forest fires within a temperate landscape: A decadal and millennial perspective from a sandstone region in Central Europe. *Forest Ecology and Management* 336: 81–90.

BELCHER CM, NEW SL, SANTIN C, DOERR SH, DEWHIRST RA, GROSVENOR MJ and HUDSPITH VA, 2018, What Can Charcoal Reflectance Tell Us About Energy Release in Wildfires and the Properties of Pyrogenic Carbon? *Front. Earth Sci* 6: 169.

BLACKFORD JJ, 2000, Charcoal fragments in surface samples following a fire and the implications for interpretation of subfossil charcoal data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164(1): 33–42.

BLARQUEZ O, ALI AA, GIRARDIN MP, GRONDIN P, FRÉCHETTE B, BERGERON Y and HÉLY C, 2015, Regional paleofire regimes affected by non-uniform climate, vegetation and human drivers. *Scientific Reports* 5: 13356.

BONK A, TYLMANN W, AMANN B, ENTERS D and GROSJEAN M, 2015, Modern limnology and varve formation processes in Lake Żabińskie, northeastern Poland: comprehensive process studies as a key to understand the sediment record. *Journal of Limnology* 74(2): 358–370.

CARTER VA, MORAVCOVÁ A, CHIVERRELL RC, CLEAR JL, FINSINGER W, DRESLEROVÁ D, HALSALL K and KUNEŠ P, 2018, Holocene-scale fire dynamics of central European temperate spruce-beech forests. *Quaternary Science Reviews* 191: 15–30.

CHANDLER C, CHENEY P, THOMAS P, TRABAUD L and WILLIAMS D, 1983, *Fire in forestry. Volume 1. Forest fire behavior and effects. Volume 2. Forest fire management and organization.* John Wiley & Sons, Inc, New York.

COLOMBAROLI D and TINNER W, 2013, Determining the long-term changes in biodiversity and provisioning services along a transect from Central Europe to the Mediterranean. *The Holocene* 23(11): 1625–1634.

CONEDERA M, TINNER W, NEFF C, MEURER M, DICKENS AF and KREBS P, 2009, Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews* 28(5): 555–576.

DE RIGO D, LIBERTÀ G, HOUSTON DURRANT T, ARTÉS VIVANCOS T and SAN-MIGUEL-AYANZ J, 2017, *Forest fire danger extremes in Europe under climate change: variability and uncertainty*, Publications Office of the European Union. Luxembourg.

DIETZE E, BRYKAŁA D, SCHREUDER LT, JAŻDŻEWSKI K, BELARQUEZ O, BRAUER A, DIETZE M, OBREMSKA M, OTT F, PIEŃCZEWSKA A, SCHOUTEN S, HOPMANS EC and SŁOWIŃSKI M, 2019, Human-induced fire regime shifts during 19th century industrialization: a robust fire regime reconstruction using northern Polish lake sediments. *PLoS ONE* 14(9): e0222011, DOI: https://doi.org/10.1371/journal.pone.0222011

DIETZE E, THEUERKAUF M, BLOOM K, BRAUER A, DÖRFLER W, FEESER I, FEURDEAN A, GEDMINIENĖ L, GIESECKE T, JAHNS S, KARPIŃSKA-KOŁACZEK M, KOŁACZEK P, LAMENTOWICZ M, LATAŁOWA M, MARCISZ K, OBREMSKA M, PĘDZISZEWSKA A, POSKA A, REHFELD K, STANČIKAITĖ M, STIVRINS N, ŚWIĘTA-MUSZNICKA J, SZAL M, VASSILJEV J, VESKI S, WACNIK A, WEISBRODT D, WIETHOLD J, VANNIÈRE B and SŁOWIŃSKI M, 2018, Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe. *Quaternary Science Reviews* 201: 44–56.

FEURDEAN A, VESKI S, FLORESCU G, VANNIÈRE B, PFEIFFER M, O’HARA RB, STIVRINS N, AMON L, HEINSALU A, VASSILJEV J and HICKLER T, 2017, Broadleaf deciduous forest counterbalanced the direct effect of climate on Holocene fire regime in hemiboreal/boreal region (NE Europe). *Quaternary Science Reviews* 169: 378–390.

GAŁKA M, MIOTK-SZPIGANOWICZ G, GOSLAR T, JĘŚKO M, VAN DER KNAAP WO and LAMENTOWICZ M, 2013, Palaeohydrology, fires and vegetation succession in the southern Baltic during the last 7500 years reconstructed from a raised bog based on multi-proxy data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 370: 209–221.

GAŁKA M, TOBOLSKI K, GÓRSKA A, MILECKA K, FIAŁKIEWICZ-KOZIEŁ B and LAMENTOWICZ M, 2014, Disentangling the drivers for the development of a Baltic bog during the Little Ice Age in northern Poland. *Quaternary International* 328–329: 323–337.

GRACZYK D and KUNDZEWICZ ZW, 2016, Changes of temperature-related agroclimatic indices in Poland. *Theoretical and Applied Climatology* 124(1): 401–410.

GRACZYK D, PIŃSKWAR I, KUNDZEWICZ ZW, HOV Ø, FØRLAND EJ, SZWED M and CHORYŃSKI A, 2017, The heat goes on—changes in indices of hot extremes in Poland. *Theoretical and Applied Climatology* 129(1): 459–471.

HIGUERA PE, BRUBAKER LB, ANDERSON PM, HU FS and BROWN TA, 2009, Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs* 79(2): 201–219.

HUDSPITH VA, BLECHER CM, KELLY R and HU FS, 2015, Charcoal Reflectance Reveals Early Holocene Boreal Decidous Forests Burned at High Intensities. *PLoS ONE* 10(4): e0120835.

IMGW-PIB, 2012, Klimat. *Wpływ zmian klimatu na środowisko, gospodarkę i społeczeństwo (zmiany, skutki i sposoby ich ograniczania, wnioski dla nauki, praktyki inżynierskiej i planowania gospodarczego)*. Raport końcowy. Warszawa.

IPCC, 2014, *Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, Pachauri R and Meyer L. Geneva.

KAJUKAŁO K, FIAŁKIEWICZ-KOZIEŁ B, GAŁKA M, KOŁACZEK P and LAMENTOWICZ M, 2016, Abrupt ecological changes in the last 800 years inferred from a mountainous bog using testate amoebae traits and multi-proxy data. *European Journal of Protistology* 55: 165–180.

KOMAREK EV, 1983, Fire as an anthropogenic factor in vegetation ecology. In: Holzner W, Werger MJA and Ikushima I (eds), *Man's impact on vegetation*. Boston, 77–82.

KUNDZEWICZ ZW, PINIEWSKI M, MEZGHANI A, OKRUSZKO T, PIŃSKWAR I, KARDEL I, HOV Ø, SZCZEŚNIAK M, SZWED M, BENESTAD RE, MARCINKOWSKI P, GRACZYK D, DOBLER A, FØRLAND EJ, O'KEEFE J, CHORYŃSKI A, PARDING KM and HAUGEN JE, 2018, Assessment of climate change and associated impact on selected sectors in Poland. *Acta Geophysica* 66(6): 1509–1523.

LASY PAŃSTWOWE, 2017, Forests in Poland 2017. *The state forests information centre*, Warszawa.

LAMENTOWICZ M, KOŁĄCZEK P, MAUQUOY D, KITTEL P, ŁOKAS E, SŁOWIŃSKI M, JASSEY VEJ, NIEDZIÓŁKA K, KAJUKAŁO-DRYGALSKA K, and MARCISZ K, 2019, Always on the tipping point - A search for signals of past societies and related peatland ecosystem critical transitions during the last 6500 years in N Poland. *Quaternary Science Reviews*, 225: 1–21, DOI: https://doi.org/10.1016/j.quascirev.2019.105954

LATAŁOWA M, ZIMNY M, PĘDZISZEWSKA A and KUPRYJANOWICZ M, 2016, Postglacjalna historia Puszczy Białowieskiej – roślinność, klimat i działalność człowieka. *National Parks and Nature Reserves* 35(1): 3–49.

LINDNER M, FITZGERALD JB, ZIMMERMANN NE, REYER C, DELZON S, VAN DER MAATEN E, SCHELHAAS M-J, LASCH P, EGGERS J, VAN DER MAATEN-THEUNISSEN M, SUCKOW F, PSOMAS A, POULTER B and HANEWINKEL M, 2014, Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *Journal of Environmental Management* 146: 69–83.

LOTTER AF and LEMCKE G, 1999, Methods for preparing and counting biochemical varves. *Boreas* 28: 243–252.

LUNG T, LAVALLE C, HIEDERER R, DOSIO A and BOUWER LM, 2013, A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change. *Global Environmental Change* 23(2): 522–536.

MARCISZ K, GAŁKA M, PIETRALA P, MIOTK-SZPIGANOWICZ G, OBREMSKA M, TOBOLSKI K and LAMENTOWICZ M, 2017, Fire activity and hydrological dynamics in the past 5700 years reconstructed from Sphagnum peatlands along the oceanic-continental climatic gradient in northern Poland. *Quaternary Science Reviews* 177: 145–157.

MARCISZ K, LAMENTOWICZ M, GAŁKA M, COLOMBAROLI D, ADOLF C and TINNER W, 2019, Response of vegetation and testate amoeba trait composition to fire disturbances in and around a bog in central European lowlands (northern Poland). *Quaternary Science Reviews*, 208: 129–139.

MARCISZ K, TINNER W, COLOMBAROLI D, KOŁACZEK P, SŁOWIŃSKI M, FIAŁKIEWICZ-KOZIEŁ B, ŁOKAS R and LAMENTOWICZ M, 2015, Long-term hydrological dynamics and fire history over the last 2000 years in CE Europe reconstructed from a high-resolution peat archive. *Quaternary Science Reviews* 112: 138–152.

MARCISZ K, VANNIÈRE B, BLARQUEZ O and THE GPWG2, 2018, Taking Fire Science and Practice to the Next Level: Report from the PAGES Global Paleofire Working Group Workshop 2017 in Montreal, Canada – Paleofire Knowledge for Current and Future Ecosystem Management. *Open Quaternary* 4(7): 1–7.

MARLON JR, BARTLEIN PJ, CARCAILLET C, GAVIN DG, HARRISON SP, HIGUERA PE, JOOS F, POWER MP and PRENTICE IC, 2009, Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* 2: 307.

MATUSZKIEWICZ JM, 2005, *Zespoły leśne Polski*. Warszawa.

MCWETHY DB, HIGUERA PE, WHITLOCK C, VEBLEN TT, BOWMAN DMJS, CARY GJ, HABERLE SG, KEANE RE, MAXWELL BD, MCGLONE MS, PERRY GLW, WILMSHURST JM, HOLZ A and TEPLEY AJ, 2013, A conceptual framework for predicting temperate ecosystem sensitivity to human impacts on fire regimes, *Global Ecology and Biogeography* 22(8): 900–912.

MICHALSKA B, 2011, Tendencje zmian temperatury powietrza w Polsce. *Prace i Studia Geograficzne* 47: 67–75.

NEW SL, HUDSPITH VA and BELCHER CM, 2018, Quantitative charcoal reflectance measurements better link to regrowth potential than ground-based fire-severity assessments following a recent healthland wildfire at Carn Brea, Cornwall, UK. *International Journal of Wildland Fire* 27: 845–850.

NIEDŹWIEDŹ T (ed.), 2003, *Słownik meteorologiczny*. PTGeof./IMGW, Warszawa.

PORAJ-GÓRSKA AI, ŻARCZYŃSKI MJ, AHRENS A, ENTERS D, WEISBRODT D and TYLMANN W, 2017, Impact of historical land use changes on lacustrine sedimentation recorded in varved sediments of Lake Jaczno, northeastern Poland. *Catena* 153: 182–193.

POWER MJ, MARLON J, ORTIZ N, BARTLEIN PJ, HARRISON SP, MAYLE FE, BALLOUCHE A, BRADSHAW RHW, CARCAILLET C, CORDOVA C, MOONEY S, MORENO PI, PRENTICE IC, THONICKE K, TINNER W, WHITLOCK C, ZHANG Y, ZHAO Y, ALI AA, ANDERSON RS, BEER R, BEHLING H, BRILES C, BROWN KJ, BRUNELLE A, BUSH M, CAMILL P, CHU GQ, CLARK J, COLOMBAROLI D, CONNOR S, DANIAU A-L, DANIELS M, DODSON J, DOUGHTY E, EDWARDS ME, FINSINGER W, FOSTER D, FRECHETTE J, GAILLARD M-J, GAVIN DG, GOBET E, HABERLE S, HALLETT DJ, HIGUERA P, HOPE G, HORN S, INOUE J, KALTENRIEDER P, KENNEDY L, KONG ZC, LARSEN C, LONG CJ, LYNCH J, LYNCH EA, MCGLONE M, MEEKS S, MENSING S, MEYER G, MINCKLEY T, MOHR J, NELSON DM, NEW J, NEWNHAM R, NOTI R, OSWALD W, PIERCE J, RICHARD PJH, ROWE C, SANCHEZ GOÑI MF, SHUMAN BN, TAKAHARA H, TONEY J, TURNEY C, URREGO-SANCHEZ DH, UMBANHOWAR C, VANDERGOES M, VANNIERE B, VESCOVI E, WALSH M, WANG X, WILLIAMS N, WILMSHURST J and ZHANG JH, 2008, Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. *Climate Dynamics* 30(7): 887–907.

RALSKA-JASIEWICZOWA M, GOSLAR T, MADEYSKA T and STARKEL L (eds), 1998, *Lake Gościąż, central Poland a monographic study*. W. Szafer Institute of Botany Polish Academy of Sciences, Warszawa.

SADORI L, ORTU E, PEYRON O, ZANCHETTA G, VANNIÈRE B, DESMET M and MAGNY M, 2013, The last 7 millennia of vegetation and climate changes at Lago di Pergusa (central Sicily, Italy). *Climate of the Past* 9(4): 1969–1984.

SAN-MIGUEL-AYANZ J, DURRANT T, BOCA R, LIBERTÀ G, BRANCO A, DE RIGO D, FERRARI D, MAIANTI P, VIVANCOS TA, COSTA H, LANA F, LÖFFLER P, NUIJTEN D, AHLGREN AC and LERAY T, 2018, *Forest Fires in Europe, Middle East and North Africa 2017*. Ispra, Italy.

SAN-MIGUEL-AYANZ J, DURRANT T, BOCA R, LIBERTÀ G, BOCCACCI F, DI LEO M, LÓPEZ PÉREZ J, and SCHULTE E, 2015, *Forest Fires in Europe, Mid-*

dle East and North Africa 2015; EUR 28158 EN, DOI: http://doi.org/10.2788/914

SCOTT AC, 2010, Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 291(1): 11–39.

SŁOWIŃSKI M, LAMENTOWICZ M, ŁUCÓW D, BARABACH J, BRYKAŁA D, TYSZKOWSKI S, PIEŃCZEWSKA A, ŚNIESZKO Z, DIETZE E, JAŻDŻEWSKI K, OBREMSKA M, OTT F, BRAUER A and MARCISZ K, 2019, Paleoecological and historical data as an important tool in ecosystem management. *Journal of Environmental Management* 236: 755–768.

SZAL M, KUPRYJANOWICZ M, WYCZÓŁKOWSKI M and TYLMANN W, 2014, The Iron Age in the Mrągowo Lake District, Masuria, NE Poland: the Salęt settlement microregion as an example of long-lasting human impact on vegetation. *Vegetation History and Archeobotany* 23: 419–437.

SZWED M, PIŃSKWAR I, KUNDZEWICZ ZW, GRACZYK D and MEZGHANI A, 2017, Changes of snow cover in Poland. *Acta Geophysica* 65(1): 65–76.

TINNER W, CONEDERA M, AMMANN B, GAGGELER HW, GEDYE S, JONES R and SAGESSER B, 1998, Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920. *The Holocene* 8(1): 31–42.

TOLONEN K, 1983, The post-glacial fire record. In: Wein RW, MacLean DA (eds), *The Role of Fire in Northern Circumpolar Ecosystems*. John Wiley & Sons, New York, 21–44.

VANNIERE B, BLARQUEZ O, MARLON J, DANIAU A-L and POWER MJ, 2013, Multi-Scale Analyses of Fire-Climate-Vegetation Interactions on Millenial Scales. *Past Global Changes Magazine* 22(1): 40.

WACNIK A, KUPRYJANOWICZ M, MUELLER-BIENIEK A, KARCZEWSKI M and CYWA K, 2014, The environmental and cultural contexts of the late Iron Age and medieval settlement in the Mazurian Lake District, NE Poland: combined palaeobotanical and archaeological data. *Vegetation History and Archaeobotany* 23(4): 439–459.

WACNIK A, TYLMANN W, BONK A, GOSLAR T, ENTERS D, MEYER-JACOB C and GROSJEAN M, 2016, Determining the responses of vegetation to natural processes and human impacts in north-eastern Poland during the last millennium: combined pollen, geochemical and historical data. *Vegetation History and Archaeobotany* 25(5): 479–498.

WHITLOCK C and LARSEN A, 2001, Charcoal as a fire proxy. In: Smol JP, Birks HJB and Last WM (eds), *Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators*. Kluwer Academic Publishers. Dordrecht.

ZIN E, 2016, *Fire History and Tree Population Dynamics in Białowieża Forest, Poland and Belarus. PhD*, Swedish University of Agricultural Sciences.

ZOLITSCHKA B, FRANCUS P, OJALA AEK and SCHIMMELMANN A, 2015, Varves in lake sediments – a review. *Quaternary Science Reviews* 117: 1–41.

ŻARCZYNSKI M, WACNIK A and TYLMANN W, 2019, Tracing lake mixing and oxygenation regime using the Fe/Mn ratio in varved sediments: 2000-year-long record of human-induced changes from Lake Zabinskie (NE Poland). *Science of the Total Environment* 657: 585–596.

Electronic data sources:

European Environment Agency, www.eea.europa.eu (access 28.08.2019)

Forest fire hazard map, http://bazapozarow.ibles.pl/zagrozenie/ (access 10.12.2019)

Global Charcoal Database, https://www.paleofire.org (access 10.12.2019)

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