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Fire activity and hydrological dynamics in the past 5700 years reconstructed from *Sphagnum* peatlands along the oceanic–continental climatic gradient in northern Poland

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A B S T R A C T

Fire is a critical component of many ecosystems and, as predicted by various climate models, fire activity may increase significantly in the following years due to climate change. Therefore, knowledge about the past fire activity of various ecosystems is highly important for future nature conservation purposes. We present results of high-resolution investigation of fire activity and hydrological changes in northern Poland. We analyzed microscopic charcoal from three *Sphagnum*-dominated peatlands located on the south of Baltic, on the oceanic–continental (west–east) climatic gradient, and reconstructed the history of fire in the last 5700 years. We hypothesize that air circulation patterns are highly important for local fire activity, and that fire activity is more intensive in peatlands influenced by continental air masses. We have found out that forest fires have been occurring regularly since the past millennia and were linked to climatic conditions. We show that fire activity (related to climate and fuel availability) was significantly higher in sites dominated by continental climate (northeastern Poland) than in the site located under oceanic conditions (northwestern Poland)—microscopic charcoal influx was 13.3 times higher in the eastern study site of the gradient, compared to the western study site. Recorded fire activity patterns were different between the sites in a long timescale. Moreover, most of the recorded charcoal peaks occurred during high water tables. Rising human pressure has caused droughts and water table instability, and substantial increase in fire activity in the last 400 years.

1. Introduction

Current and predicted changes in global temperature and precipitation patterns will have an influence on the functioning of ecosystems (IPCC, 2014). For central and eastern Europe, expected changes include increase of temperature extremes, reduced summer precipitation leading to droughts, and greater risk of forest fires (EEA Report, 2012). Current examples of dramatic fires from different parts of the world include massive and long-lasting peat fires recorded in Russia in the summer of 2011, Fort McMurray wildfire in Canada in May 2016, or recent wildfires in Chile in January 2017. If climate change progresses the way it is anticipated, such disastrous fires will be recorded more frequently and will progressively disturb the functioning of ecosystems (EEA Report, 2012).

Alternation of extreme events and consequent gradual increase of fire activity are especially dangerous for water-dependent ecosystems, that is peatlands, where water table depth regulates peat decomposition and accumulation rates (Limpens et al., 2008; Rydin and Jeglum, 2006). Water table lowering in peatlands and removal of anaerobic controls on decomposition stimulate peat carbon loss

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to the atmosphere (Freeman et al., 2001). Droughts affecting peatlands promote peatland burning (Kettridge et al., 2015; Zoltai et al., 1998), which influences peatland microforms (Benscoter et al., 2015) and leads to carbon stock disturbances (Fenner and Freeman, 2011; Turetsky et al., 2015). Wildfires are another threat for dried peatlands, as combustion of the local vegetation stimulates the loss of peat carbon (Harden et al., 2000; Zoltai et al., 1998). Another effect of wildfires in the peatland area is runoff changes after rapid vegetation removal (Sillasoo et al., 2007; Väliranta et al., 2007) and peatland flooding. Further runoff changes after the flooding may lead to peatland dehydration, especially if the mire is located in the sandy area that loses water quickly (Marcisz et al., 2015).

Besides climate changes, human presence and activity can accelerate fire activity (1) by burning for the landscape opening for settlements and/or cultivation of fields (Büntgen et al., 2011; Colombaroli et al., 2010; Valsecchi et al., 2006; Vannière et al., 2008), and (2) as an effect of drainage that leads to water table lowering in peatlands (Lamentowicz et al., 2015b; Marcisz et al., 2015; Sherwood et al., 2013). Those effects of human presence and anthropogenic burning on ecosystems are well recognized in many areas (Feurdean et al., 2013; Froyd, 2006; Marlon et al., 2008; Maxwell, 2004; Rey et al., 2013; Vannière et al., 2010), but there is still a gap in the knowledge on when humans significantly altered the natural fire activity in many parts of the world. Moreover, recognition of past fire–climate–human linkages is highly important to produce new and synthesize existing palaeoecological records.

Peatland functioning is highly dependent on the water availability, and disturbed and dried peatlands that experience drought are susceptible to fire (Kettridge et al., 2015; Sillasoo et al., 2011). Therefore, it is very important to compare long-term fire activity with hydrological dynamics to separate between climatic and anthropogenic origins of droughts. Comparing sedimentary charcoal records with quantitative testate amoeba-based depth to water table reconstructions is a useful approach for such purposes (Kajukało et al., 2016; Lamentowicz et al., 2015c; Marcisz et al., 2015).

Compared to other areas in Europe, that is, Mediterranean Basin (Beffa et al., 2016; Colombaroli and Tinner, 2013; Morales-Molino et al., 2013; Tinner et al., 2016), the Alps (Dietre et al., 2017; Putzer et al., 2016; Schwörer et al., 2014), the Carpathians (Feurdean et al., 2013, 2017), or northern Baltic (Brown and Giesecke, 2014; Niklasson et al., 2002; Sillasoo et al., 2011), central Europe and southern Baltic coast are still a blank spot in the Global Charcoal Database (www.paleofire.org, Fig. 1A), and, so far, there were only few attempts to understand the fire activity from peat sediments. Based on lake sediments and peat, Latałowa (1992) showed that humans in Wolin Island (northern Poland) were using fire to open the landscape. High-resolution palaeoecological study from Stążki bog in northern Poland (Gałka et al., 2013) reported that highest number of charcoal particles was found in the peat samples dated to the third millennium BCE (Before Common Era, = years BC). Comparison between high-resolution micro- and macroscopic charcoal analysis and palaeohydrology from Linje mire, central Poland (Marcisz et al., 2015), revealed that fire activity increased in the thirteenth century CE (Common Era, = years AD) due to human activities, and that it influenced peatland hydrology—in response to vegetation removal and run-off changes, water table dropped significantly after few years. A study from the mountainous peatland, Jagnięcy Potok, south western Poland revealed low fire activity in Sudety Mountains (Kajukało et al., 2016). Therefore, we believe that such scarce knowledge about long-term fire activity in central eastern Europe should be deepened.

In this paper, we focus on the past fire activity and hydrological changes of three *Sphagnum*-dominated Baltic bogs located in northern Poland along the west–east gradient. All peatlands are located under transitional climate; however, a strong climatic gradient can be observed—the site located in the western end of the gradient is mostly influenced by oceanic air masses, whereas the site located in the eastern end of the gradient is mostly influenced by continental climate (Fig. 1B). Those differences in climatic conditions are important for the development of peatlands and affect fire activity and hydrological dynamics. Our data sets cover the time period up to 1 CE (Mechacz Wielki), 2100 BCE (Bagno Kusowo), and 3700 BCE (Gązwa); therefore, in Poland, we focus on the comparison of bogs in the past 2000 years. Moreover, in the long timescale (reaching 3700 BCE), we compare fire activity and hydrological changes in a regional scale with other records from central and eastern Europe: from around the Baltic Sea and in the Carpathians. We hypothesize that air circulation patterns (connected with climatic/temperature gradient) were highly important for local fire activity, and that fire activity was more intensive in peatlands influenced by continental air masses. We expect that fire activity was significantly higher in the last centuries when human impact was rising, and that fires were present during dry phases of peatlands' development. We aim to recognize how long-term fire activity patterns were changing in northern Poland in response to climatic changes and human pressure.

2. Methods

2.1. Study sites and palaeoecological data sets

We investigated three bogs located in northern Poland along the west–east geographical gradient and oceanic–continental climatic gradient: Bagno Kusowo (western site dominated by oceanic air masses), Gązwa, and Mechacz Wielki (eastern site dominated by continental air masses) (Fig. 1B). All mires are located in the glacial area formed by the activity of the last Scandinavian ice sheet.

The environmental history and development of chosen mires were studied before, focusing on the vegetation and hydrological changes (Gałka et al., 2015, 2017c; Lamentowicz et al., 2015a). All peat cores were sampled using Russian corer and then subsampled in the laboratory for multiproxy analyzes. Dating and age–depth models were prepared and published in the previous studies (Gałka et al., 2015, 2017c; Lamentowicz et al., 2015a). Detailed description of studied mires, core sampling and resolution of the previously done analyses is presented in Table 1.

2.2. Sample preparation and laboratory analyses

Analyzes of pollen, plant macrofossils, and testate amoebae were done to reconstruct past vegetation and hydrological changes, and those data are published elsewhere; samples preparation was done following the standard preparation methods, and detailed information about the samples preparation for each of the analyzes is available in previously published studies (Gałka et al., 2015, 2017c; Lamentowicz et al., 2015a).

However, in the previous studies, analysis of microscopic charcoal was not performed and the past fire activity was not investigated. In this study, based on the archived palynological samples, microscopic charcoal particles were analyzed to define the history of fire activity in the area of each of the mires. Samples for pollen and microscopic charcoal analyzes were prepared following standard preparation procedures (Berglund and Ralska-Jasiewiczowa, 1986). One *Lycopodium* tablet (20,848 spores, produced by the University of Lund) was added to every sample for further calculation of charcoal concentrations (CHAC, particles/cm^3) (Stockmarr, 1971). Microscopic charcoal was analyzed using a light microscope