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Holocene-scale fire dynamics of central European temperate spruce-beech forests

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ABSTRACT

This study investigated the long-term role and drivers of fire in the central European temperate spruce-beech forests from Prášilské jezero, Czech Republic. The results illustrate the complex relationship between broad-scale climate, vegetation composition, and local human activities on fire throughout the Holocene. Biomass burning was the highest (average 3 fires/1000 years) and most severe during the early Holocene when fire resistant taxa (*Pinus*, *Corylus* and *Betula*) dominated. Using a Generalized Additive Model to assess the response of dominant canopy taxa to changes in biomass burning and fire severity, response curves demonstrate a positive relationship ($p < 0.01$) between fire resistant taxa and increases in biomass burning. Norway spruce (*Picea abies*) established ~10,000 cal yr BP and expanded during peak biomass burning. Response curves show a slight negative relationship with *Picea* and increasing biomass burning, and a positive relationship with increasing fire severity. This suggests that central European spruce forests may not be significantly impacted by fire. Regional biomass burning dramatically decreased with the expansion of fire sensitive taxa (e.g. *Fagus sylvatica*) ~6500 cal yr BP, yet no dramatic reduction in local fire frequency occurred. This suggests either human activities or rare fire-promoting climatic events were important in shaping local fire regimes. Fire activity peaked (6 fires/1000 years) ~2500 cal yr BP and paralleled increases in anthropogenic pollen indicators. *Fagus* response curves illustrates a negative ($p < 0.01$) relationship with increasing biomass burning and fire severity suggesting that natural *Fagus* forests may be increasingly vulnerable to projected increases in wildfire occurrence.

1. Introduction

Fire is an important disturbance agent driving changes in vegetation composition, ecosystem structure and function, and nutrient cycling (Boerner, 1983; Bowman et al., 2009; Carcaillet et al., 2002; Whitlock et al., 2003). Paleoecological studies have documented the vital role of climate, vegetation, and human activities on global fire activity over millennia (Marlon et al., 2013; Power et al., 2008). Yet, knowledge gaps pertaining to the long-term role of fire in particular regions, specifically central Europe, still exist (Feurdean et al., 2012; Feurdean and Vannière, 2017). More important is the lack in understanding how forest canopy taxa will respond to changing fire regimes as a result of anthropogenically-induced climate change. Temperate forest fires in central Europe are often considered as a negligible ecosystem disturbance (Adámek et al., 2015) because of the assumed low flammability of deciduous forests (Ellenberg, 1982). Yet, over the past decade emerging literature has demonstrated that fires have occurred for millennia in central European forested ecosystems (e.g. Clark et al., 1989; Bobek et al., 2018; Niklasson et al., 2010; Novák et al., 2012). However, crucial parameters of fire regimes i.e. fire frequency and drivers of biomass burning, are neither fully understood nor discussed (Niklasson et al., 2010), specifically from central European Norway spruce (*Picea abies*) and European beech

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(*Fagus sylvatica*) forests.

Climate models predict more frequent and extreme climatic events such as heat-waves and droughts throughout Europe (Rajczak et al., 2013; Seneviratne et al., 2012), which can elevate fire risk and impact on vegetation (Camia et al., 2017; Lavalle et al., 2009; Linder et al., 2014). For instance, as a result of increasing temperature and drought, the susceptibility of mountain plant communities to mortality has increased (Allen et al., 2010). Because extreme climatic events also contribute to an increase in fire risk, composition and structure of particular plant communities may adapt to include more thermophilic species (Gottfried et al., 2012), thus favoring more fire-prone ecosystems. As future projections suggest an increase in fire risk in central European ecosystems by the end of the 21st century (Lung et al., 2013), it is important to understand long-term fire dynamics in order to determine how increasing wildfire activity may impact future temperate forests.

Fire activity is determined by both top-down (e.g. climate) and bottom-up (e.g. vegetation and human activities) drivers which combine to create different fire regimes across varying spatial and temporal scales. Climate variability is considered to be the dominant top-down driver of fire through its influence on broad-scale energy budgets and variations in moisture and temperature, which typically results in regional to continental-scale synchronization of fire activity (Falk et al., 2011). Local factors such as topography (i.e. slope and aspect) and fuel type (i.e. vegetation composition) typically create different mosaics of fire severities (Falk et al., 2011). However, human land use also significantly influences local fire regimes (Gill and Taylor, 2009), yet estimating the extent and magnitude of human-caused fires and land-use activities on natural fire regimes has proven to be difficult (see Kaplan et al., 2016). Because top-down and bottom-up factors vary spatially and temporally (Courtney Mustaphi and Pisaric, 2013; Gavin et al., 2003; Gedalof, 2011), long-term fire histories are necessary in order to investigate the relationship between drivers of fire and their influence on local fire regimes (Whitlock et al., 2010).

As the role of fire in central European temperate forests is often deemed unimportant, there is a clear lack of understanding in: i) the relative importance and role of fire in these forests, and ii) the relationship between the dominant forest canopy taxa and changing fire regimes (i.e. changes in biomass burning and fire severities). To fill these gaps, we present a ~11,500-year high-resolution paleoecological reconstruction of vegetation dynamics and fire history from lacustrine sediments obtained from Prášilské jezero (Šumava Mountains, Czech Republic). This record explores for the first time drivers of fire dynamics in these primary temperate spruce-beech forests. The main objectives are to: 1) identify the key drivers of Holocene fire regimes; and 2) assess the response of the dominant forest canopy to changes in biomass burning and fire severities.

2. Study area

Prášilské jezero (49° 04′ 30.684″ N, 13° 23′59.136″ E, 1079 m a.s.l.) (Fig. 1) is located within the unmanaged portion of Šumava National Park within a relatively steep glacial cirque, which deglaciated ~14,000 years ago (Mentlík et al., 2010). Tree-covered flanks extend 200–300 m above the lake. It is a small oligotrophic lake (3.7 ha) with a relatively large (52 ha) catchment, and a catchment area to lake volume ratio of 1.93 (Vrba et al., 1996, 2000). The catchment bedrock is composed of metamorphic crystalline rocks with gneiss, migmatite, and quartzite with local areas of granite (Mentlík et al., 2010; Pelc and Šebesta, 1994).

The surrounding vegetation is dominated by Norway spruce with minor components of European beech, rowan (*Sorbus aucuparia* L.), silver birch (*Betula pendula* Roth), sycamore maple (*Acer pseudoplatanus* L.), and silver fir (*Abies alba* Mill.). The understory is dominated by common mountainous spruce forest vegetation such as grasses (*Avenella flexuosa* L., *Calamagrostis villosa* J.F. Gmel., *Luzula sylvatica* Huds.), herbs (*Prenanthes purpurea* L., *Senecio ovatus* Willd., *Soldanella montana* Willd., *Trientalis europaea* L.), and small shrubs (*Rubus idaeus* L., *Vaccinium myrtillus* L., *V. vitis-idaea* L.). Sedges and shade-tolerant species (*Carex canescens* L., *C. echinata* Murray, *Juncus effusus* L., *J. filiformis* L., *Oxalis acetosella* L.) occur in shady and mesic areas along the inflowing stream, Jezerní potok. Ferns (*Athyrium distentifolium* Tausch ex Opiz, *Blechnum spicant* L., *Dryopteris dilatata* Hoffm.) and ground pine (*Lycopodium annotinum* L.) are also common in the understory vegetation.

Based on >50-year long meteorological data (Czech Hydrometeorological Institute) from the closest weather station, Churáňov (Fig. 1), the modern Šumava region is characterized as a semi-humid continental climate with wet and cold winters, and wet and mild summers. Interpolated mean annual temperature and precipitation average 4.5 °C and 941 mm year^{-1}.

3. Methods

3.1. Core retrieval, sediment limnology and radiocarbon dating

In August 2015 a 2.18 m sediment profile comprising of one gravity core (PRA15-2GC) and two parallel and overlapping long-cores (PRA 15–2–1 and PRA 15–2–2) were collected from the deepest (14.8 m) part of Prášilské jezero from a floating platform. The sediment-water interface was collected using a gravity corer (Boyle, 1995), and the longer profiles with a Russian corer (1.5 × 0.075 m). Sediments were taken back to the University of Liverpool where they were subsampled at high-resolution (contiguous 0.5 cm intervals). Samples were then shipped to Charles University where the paleoecological analyses were conducted.

Age-depth relationships were established using ten ^{14}C and a ^{210}Pb series (Appleby, 1978) (Table SI1). Age-depth relationships were modeled in a Bayesian framework using 'BACON' (Blaauw and Christen, 2011) using the ^{210}Pb and ^{14}C dates. All ^{14}C dates were calibrated with the IntCal13 dataset (Reimer et al., 2013), and a Student-*t* distribution was used to account for scatter in the ^{14}C measurements, and for statistical outliers (Blaauw and Christen, 2011). The weighted mean modeled ages against depth were smoothed using a 21-point moving average (Fig. 2), and was used to calculate sediment, pollen, and charcoal accumulation rates.

3.2. Plant macrofossils and pollen analysis

To investigate the connection between the local fire history and local vegetation development, plant macrofossils were analyzed at 1–2.5 cm resolution. Sample volume was measured by measuring the displacement of water (on average 6 cm^3), and then washed through a 100-μm sieve following Birks (2007). Plant macrofossils (needles, seeds, buds, bud scales, etc.) were counted under a stereomicroscope at 15–45× magnification and identified with the aid of identification keys (Cappers et al., 2006; Bojňanský and Fargašová, 2007; Katz et al., 1977; Tomlinson, 1985), and by comparing macrofossils with the reference material stored in the