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Fire has been an important driver of forest dynamics in the Carpathian Mountains during the Holocene

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ABSTRACT

Fire frequency and severity are key parameters in evaluating fire-mediated changes in ecosystems, but these metrics are rarely reconstructed at extensive temporal scales. Notably our understanding of the role of fire regime dynamics in the functioning and biodiversity of Central Eastern European temperate forests is limited because investigation of the effect of fire has been neglected. To fill this gap in knowledge, we applied a multi-proxy approach (macrocharcoal, charred remains, pollen, plant macrofossils) to two sedimentary sequences spanning stands of closed canopy *Picea abies* to the *P. abies* treeline located in the northern Carpathians, Romania. We found that climate exerts a broad-scale influence, whereas vegetation feedbacks strongly modulate this fire-climate relationship. Fire has been almost continuously present throughout the Holocene with a remarkably stable mean fire rotation (~250 yr) with fires of mostly low to mid severity and/or small to medium size. Humans have shifted the fire regime during the last 2800 years to slightly longer fire return intervals (mean 300 yr) and more biomass consumption per fire. We found that *P. abies* was favoured by low to moderate fire severity/area burned. The establishment of late-successional, shade tolerant *Fagus sylvatica* was facilitated by fire disturbances, but its expansion coincided with major gaps in fire events. This highlights the key role of fire in the expansion of *F. sylvatica* that seems only possible in a low/small to mixed severity/size fire regime with a sufficiently long fire return interval. High magnitude charcoal peaks negatively affected *F. sylvatica*. We found more diverse pollen assemblages, especially taxa linked to anthropogenic impact, at times of moderate fire disturbance corroborating the intermediate disturbance hypothesis. In terms of forest management, our results show that, contrary to current understanding, fire is a natural and important driver of vegetation change in this region. The anticipated increase in fire activity with the climate warming and/or augmented fuel accumulation may threaten the dominant forest ecosystems, given that these are adapted to low frequency and severity fires. We advise forestry to consider the effects of fire as part of climate-change conservation strategies. Diversifying the forest tree mixture with more fire-resistant native species is desirable in order to mitigate the effects of increased fire occurrence and severity.

1. Introduction

Forest fires are essential for forest renewal, the removal of litter accumulating on the forest floor and the control of insect and disease damage (Shlisky et al., 2007). Plant species cope with recurrent fire disturbance in different ways and display a range of traits related to fire resistance and regeneration (Gill, 1981; Groot et al., 2013; Noble and Slatyer, 1980; Trabaud, 1987). For

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example, conifer forests are characterised by trees with a high resin content and low hanging branches, properties that foster more frequent fires (Mutch, 1970), and adaptation strategies for surviving periodic fires (Rowe, 1983). However, fire regimes can differ significantly between conifer species (Rogers et al., 2015). In contrast, broadleaf deciduous trees, typically with high leaf moisture and a lower rate of ignition, experience fires more rarely and with lower intensities. As a consequence of these characteristics, conifer forests are predicted to be subject to increased wildfire activity with the current and projected future increases in temperature, and frequency of extreme drought years (Wotton et al., 2010). However, whether tree species are adapted to the local fire regime, or fire regime dynamics are dictated by the functional traits of the dominant tree species, is still unclear and complicated to disentangle due to the complex dynamic interactions between fire, vegetation and climate (Kelly et al., 2013; Higuera et al., 2011, 2014).

Mountain regions dominated by conifers forests and alpine plants have recently encountered rapid temperature increases with important implications for the composition of these sensitive ecosystems (Solomon et al., 2007; Gottfried et al., 2012). Notably missing from our understanding of the ecology of mountain ecosystems is the significance of fire for long-term ecosystem functioning and biodiversity. This is because such inferences tend to be limited to a few decades of observational studies primarily derived from remote sensing (European Forest Fire Information System, EFFIS). However, because variations in fire frequency and vegetation succession cycles in forest ecosystems occur over decadal to centennial timescales, such short-term studies are often of limited use in fully understanding the fire regime dynamics of these ecosystems (Kelly et al., 2013; Higuera et al., 2014). One such region, where fire may have a long-lasting effect on ecosystems due to the longevity of trees, is the Carpathian Mountains; the largest mountain range in Central and Eastern Europe. The dominant mountain tree species in this region (*Picea abies, Fagus sylvatica, Abies alba*) do not have traits enabling them to survive fire (Bradshaw and Lindbladh 2005; Rogers et al., 2015); therefore their establishment is only possible where fires occur infrequently. Conservatively, the ecological role of fire in this region is largely neglected and considered unimportant, although recent research appears to contradict this assumption (Adámek et al., 2015). For example, palaeoenvironmental reconstructions of fire activity in the Carpathians have revealed that fire was prevalent throughout the Holocene, although with substantial regional variations in the patterns and drivers of biomass burning across this region (Feurdean et al., 2012; Finsinger et al., in press). However, forest fire regime dynamics, i.e., fire frequency, size and severity and the implications for long-term ecosystem functioning and biodiversity in this region, remains largely unknown. Furthermore, the Carpathians have recently undergone rapid transformation due to increasing temperatures (Gottfried et al., 2012) and a twofold change in landscape dynamics: farmland abandonment followed by woody encroachment, accentuated by the post-socialist economic collapse (after 1990); and substantial illegal forest clearance, often in protected conservation areas (Kuemmerle et al., 2011; Knorn et al., 2012). These changes are likely to significantly affect fire activity (Khabarov et al., 2016).

In this study we have used a multi-proxy approach (macrocharcoal, charred remains, pollen, plant macrofossils) on two sedimentary sequences from a *Picea abies* closed canopy site and a site at the treeline ecotone (*Picea abies*) located in the northern Carpathians, Romania, to determine Holocene fire regime dynamics under both natural conditions and with human impact. We have reconstructed fire metrics from macrocharcoal data and vegetation composition from the pollen and plant macrofossil records, whereas the functional fire traits of the most common tree species were compiled from literature. We have assessed past fire risk from published local hydro-climate reconstructions based on testate amoeba, stable isotopes, and chironomid records (Diaconu et al., submitted for publication; Panait et al., submitted for publication). We show that our findings are essential to quantify expected future changes in fire and vegetation, and provide a valuable basis to make preemptive forest management decisions for future ecosystem composition and diversity in order to facilitate the mitigation of anticipated changes in fire regime.

2. Materials and methods

2.1. Study area

We have inferred changes in fire activity based on two fossil records: Tăul Muced and Poiana Ştiol located in the Rodna National Park and Biosphere Reserve, in the Eastern Carpathians, Romania (Fig. 1). The climate can be characterised as moderate temperate continental (Dragotă and Kucsicsa, 2011).

Tăul Muced (47°34′26″N, 24°32′42″E; 1360 m a.s.l.; 2 ha) is an ombrotrophic bog with a western exposure. The onsite woody vegetation is composed of *Picea abies, Pinus mugo*, and various species of Ericaceae (Feurdean et al., 2015), whereas the surrounding forest is dominated by closed forests of *Picea abies* with *Abies alba* (~40%) and *Fagus sylvatica* (~10%) stands on the southern slopes (Topographic Maps of Romania, 1986). Poiana Ştiol (47°35′14″N 24°48′43″E; 1540 m a.s.l., 1 ha) is a poor fen formed over a small limestone sinkhole and has a northern exposure. It is located at the current treeline ecotone formed by a mixture of trees and subalpine shrubs including *P. abies, Pinus cembra, P. mugo*, and *Juniperus communis* ssp. *nana* (Tantau et al., 2011; Feurdean et al., 2016). The approximate composition of the surrounding forest is *Picea abies* (80%) and *Abies alba* (20%) (Topographic Maps of Romania, 1986). The mountain forest belt (800–1200/1300 m) at both sites is dominated by *Fagus sylvatica*.

Forest fires, mostly of small size (<100 ha) are characteristic for the region, but no information on the fire return interval is available (European Forest Fire Information System, http://forest.jrc.ec.europa.eu/effis/). However, natural fires are not considered a disturbance agent by forest managers (Management Plan of Rodna Mountains National Park, 2013). In terms of management practices, the natural regeneration of harvested forests is promoted.

2.2. Sampling and chronology

We have taken sediment cores at both sites with a Russian corer from a central location, sealed for transportation and stored at 4 °C. We determined the age of the sediment samples based on radiocarbon measurements using the AMS facilities at the Chrono Centre in Queen's University Belfast, UK and the Poznan Radiocarbon Laboratory, Poland and a ^{210}Pb profile measured at the University of Babeş-Bolyai, Cluj, Romania. For a detailed list of depths, material dated and age–depth model at Tăul Muced see Feurdean et al. (2015), for Poiana Ştiol see Feurdean et al. (2016).

2.3. Fire history reconstruction from charcoal records

We estimated changes in local scale fire activity from sedimentary samples of mostly 2 cm^3 in 1 cm contiguous intervals at both sites. We bleached and wet-sieved these samples through a 160-μm mesh, then identified and counted the total number of macrocharcoal particles (opaque, angular particles) using a stereomicroscope (Whitlock and Larsen, 2001). We transformed the