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Exploring the influence of local controls on fire activity using multiple charcoal records from northern Romanian Carpathians

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ABSTRACT

Although our understanding of key drivers of fire activity (climate, vegetation and humans) has improved, considerable uncertainty remains regarding the relative importance of these drivers and how they vary across spatial and temporal scales. Notably missing from our use of sedimentary charcoal records as a way to reconstruct past fire activity is the role of local controls on burning, and the relationships between different charcoal sizes, source area and types of depositional environment. To address these issues, we used seven sedimentary charcoal records within a small climatically homogenous area, but with heterogeneous vegetation and human history in the Eastern Romanian Carpathians. On a temporal scale, we found more homogenous fire histories during the early and mid Holocene (11,000–6000 cal yr BP), which became more heterogeneous thereafter. This suggests that climate exerted a stronger influence on fire activity during the early Holocene, whereas local controls (vegetation type and load, land cover and -use) became more important over the mid and late Holocene. On an elevation gradient, we found discrepancies in trends in fire activity between the coniferous forest, treeline and subalpine vegetation that could have resulted from variability in fuel availability in response to changes in the elevational climate gradient and degree of anthropogenic impact. For the coniferous forests, anthropogenic activities enhanced biomass burning from ca 2000–1500 cal yr BP through the use of fire to open up the forests. For the treeline – subalpine areas, humans enhanced fire activity earlier, i.e., from 8000 to 4500 cal yr BP, and reduced burning activity through clearance and hence decrease in fuel load, from ca. 3000 cal yr BP. Our determination of macro-charcoal size-classes show that the 150–300 μm fraction is present in the highest proportion at all sites, with most of this fraction perhaps connected to a combination of local and regional fires, and not strictly to local fire activity. Lakes provide higher charcoal influx and larger sizes of charcoal particles than peat, and this suggests that peat - lake sediment lithological transitions within the same record can contribute to a taphonomic change in apparent rates of charcoal deposition.

1. Introduction

In the context of a changing climate, increasing fire activity constitutes a significant unknown in the land-cover feedbacks to climate change and global carbon cycle and a potential threat to ecosystem services (Bowman et al., 2009; Hantson et al., 2016). Fire behavior is complex and controlled by an interplay of factors ranging from climate (temperature and soil moisture), vegetation (fuel load, connectivity, and flammability) and soil types, to ignition sources (natural or anthropogenic) and landscape configuration (slope angle and exposure, elevation) (Whitlock et al., 2010; Krawchuk and Moritz, 2011; Daniau et al., 2012). In addition, humans can introduce changes in fuel characteristics through changing land cover and use (Pausas and Keeley, 2014; Vannière et al., 2016). All these parameters have spatial and temporal non-linear contributions to fire activity (Leys and Carcaillet, 2016; Dearing, 2006). Determining the past fire history and interactions between its drivers over multiple spatial (local to global) and temporal (years to millennia) scales are necessary to accurately project fire occurrence under future conditions (Leys and Carcaillet, 2016; Jouffroy-Bapicot et al., 2016).

Sedimentary charcoal analysis in lacustrine and peat deposits has emerged as a powerful tool to reconstruct long-term fire variability (Whitlock and Larsen, 2001; Whitlock and Anderson, 2003; Valese et al., 2014). Comparison between multiple charcoal records at subcontinental to global scales has revealed differences in patterns of fire

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activity over the Holocene across latitudes and elevations (Power et al., 2008; Vannière et al., 2011; Marlon et al., 2016). These studies have shown that at large spatial scales, climate exerts the dominant effect on biomass burning. Conversely, studies concerning fire activity at smaller spatial scales, generally report a high temporal variability in biomass burning (e.g. Gavin et al., 2006; Feurdean et al., 2012, 2017a; Leys and Carcaillet, 2016). Given the spatial and temporal heterogeneity in variables controlling fire, merging charcoal records with different local particularities is biased towards the dominant factors such as climate, while obscuring local-scale influences (Blarquez et al., 2015). Site-specific histories are therefore needed to show how fire activity has been modulated by microclimate, vegetation, topography and land-use (Gavin et al., 2006; Whitlock et al., 2010; Rius et al., 2011). This is particularly necessary for montane areas, where the high landscape heterogeneity has been shown to induce additional variability (Leys and Carcaillet, 2016), and where higher frequency of fire-related disturbances is predicted in the coming decades (Wastl et al., 2012).

The Central Eastern Europe (CE Europe) is a particular area underrepresented in the European fire activity reconstructions (Global Charcoal Database: www.paleofire.org). Few studies thoroughly explored the subject, either by employing quantitative reconstructions of fire regime in lowlands (Feurdean et al., 2013a; Bobek et al., 2017) or at timber and treeline (Feurdean et al., 2017a; Finsinger et al., 2016), by performing multi-site comparison at larger spatial scale (Feurdean et al., 2012; Marcisz et al., 2017), or assessing post-fire erosion (Haliuc et al., 2016). However, prior to this study, the use of multiple sites from a confined area, to assess how and why fire histories varied at the local scale, has not been undertaken in the region. Moreover, no studies in this region have addressed the variation in differently-sized charcoal particles in relation to source area, type of depositional environment (lake, bog) and potential drivers. These aspects are highlighted as important for charcoal analysis, in order to determine how they alter the performance of fire activity reconstructions (Hawthorne et al., 2017).

Here we employ a multi-site comparison of seven micro- and macro-charcoal records within a small, climatically homogenous area in the Northern Romanian Carpathians (~1500 km^2), in order to test three major research topics:

1) Firstly, we assessed spatial and temporal patterns in charcoal records in this confined area. We hypothesized that if the dominant control on the fire regime was climate, the patterns in fire activity should be synchronous across all sites. By contrast, if superimposed on climate, the local-scale factors (e.g. vegetation composition and land-use, elevation) had a significant role on biomass burning, differences between sites should become evident.
2) Secondly, we investigated the source area for microscopic and macroscopic charcoal at given depositional locations. We hypothesize that: a) If micro- and macro-charcoal data show similar trends, this indicates that the dominant signal of both charcoal size-categories relates mainly to local fires; and b) if the variability in the two charcoal fractions diverges, it may suggest a difference in local compared to regional contributions.
3) Thirdly, we examined how charcoal deposition in different environments, i.e., lakes and bogs, compares. We assumed that if both lake and bog environments are similarly effective in retaining a primary fire signal, then the proportion of different charcoal sizes will be similar in the two depositional environments.

2. General background of the study area and sites

Our study area is located in northern Romania and comprises a part of the Eastern Carpathians, i.e., the Rodna, Maramureș and Bucovina Mts (Fig. 1). A moderate temperate continental climate with Atlantic and Baltic influences characterizes the area (Donita, 2005), with mean annual temperature of 1.4 °C and annual precipitation 1240 mm at the Iezerul Pietrosului Meteorological Station (1785 m a.s.l.). Rainfall is highest, but most variable in the summer, and lowest in winter (Dragotă and Kucsicsa, 2011), with the highest precipitation amounts falling in the 1400–1700 m elevation interval. The degree of landscape fragmentation is high with alternation of moist shady glacial valleys with steep slopes and dry insolated cirque walls and rocky tops (Geography of Romania, 1987). The dominant wind directions are from SW, NE and E (Dragotă and Kucsicsa, 2011). Vegetation is structured in belts (see Table 1 for the vegetation composition at each site). It should be noted that the position of the timberline and treeline ecotone in this region has been subjected to anthropogenic change over the last millennia/centuries (Feurdean et al., 2016; Geantă et al., 2014; Tanţău et al., 2011). Forests and subalpine grasslands are presently grazed by sheep or cattle during the warm season.

Changes in macro- and micro-charcoal accumulation rate were assessed in seven lacustrine and peat sediment sequences located at an elevation ranging from 930 to 1920 m a.s.l. All sites have small surfaces (< 1.6 ha) and are fed from small catchments (0.12–3.5 km^2), which provides conditions conducive to recording palaeoecological processes at the local scale. Details of the location and physical characteristics of the sites and their watersheds are provided in Table 1. The sites and their location in vegetation belts are as follows:

i) the conifer forest (Tăul Muced peat bog (TM), 1340 m a.s.l., Lake Iezerul Sadovei (IZR), 930 m a.s.l.);
ii) the treeline limit (Poiana Stiol peat bog (PS) - 1540 m, Lake Ştiol (LS) - 1640 m), Lake Vinderelu (VD), 1680 m a.s.l). It should be however noted that the catchment of Lake Vinderelu is presently completely treeless.
iii) the subalpine vegetation (Lake Gropile (GR), 1920 m a.s.l., Lake Buhăiescu Mare (BM), 1918 m a.s.l.).

3. Material and methods

3.1. Sampling and chronology

All sites with the exception of Lake Vinderelu were sampled using a Russian corer for deeper sediments. Lake Vinderelu was cored with a Livingstone piston corer. A gravity corer was used for the lake sediment-water interface. Sediment age was established based on AMS radiocarbon and ^{210}Pb measurements. The age-depth models for Lake Iezerul Sadovei, Tăul Muced, Poiana Ştiol, Lake Stiol and Lake Buhăiescu are published (Appendix A). For lakes Vinderelu and Gropile, radiometric measurements and the age-depth models are presented in Appendix A (Table A1; Fig. A1).

3.2. Charcoal analysis

Micro-charcoal (10–150 µm) was identified and counted on pollen slides (Whitlock and Larsen, 2001). *Lycopodium* tablets of known concentration were added to all samples prior to chemical treatment in order to estimate microcharcoal concentration (Stockmarr, 1971). For macroscopic charcoal analysis, contiguous 2–3 cm^3 sub-samples were retrieved at 0.5–1 cm intervals and gently wet-sieved through a 150-µm mesh. Peat-samples were bleached, whereas for the clay-rich samples we used 5% KOH solution. The total number of macro-charcoal particles in each sample was estimated under a stereomicroscope. During counting, macro-charcoal was separated in four size-classes, i.e., 150–300 µm, 300–500 µm, 500–1000 µm and > 1000 µm. The size boundaries were established taking into account the transport distance from the source as described in the literature (Whitlock and Larsen, 2001). Macro- and micro-charcoal were expressed as accumulation rates (particles cm^{-2} yr^{-1}) based on macro- and micro-charcoal concentration and sediment deposition time as derived from the age-depth models.

3.3. Vegetation composition

Past vegetation composition was estimated from published (Tăul Muced, Poiana Ştiol, Lake Ştiol, Lake Buhăiescu Mare and Lake Iezerul