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Trends in biomass burning in the Carpathian region over the last 15,000 years

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A B S T R A C T

Fire is recognized as a critical process with significant impacts on biota and the atmosphere. In this study, 11 micro- and macrocharcoal sedimentary records extracted from peat bogs and lakes at different elevations in the Carpathian region (in Hungary and Romania) were used to explore the patterns and the potential underlying mechanisms in biomass burning in this region during the last 15,000 years. Results from micro-charcoal and macro-charcoal data show similar trends in biomass burning and suggest that the major signal of both charcoal size-fragments relates mainly to local fires. Fire activity was low during the lateglacial, attained maximum values in the early Holocene (11,700–8000 cal. yr BP), become lower than present during the mid-late Holocene (8000–1000 cal yr BP), and increased again over the last 1000 years. The reconstructed spatial trends in biomass burning display different degrees of heterogeneity through time. Generally, there was more spatial similarity in fire activity across the study region during the lateglacial and early Holocene (15,000–8000 cal yr BP), followed by increased spatial heterogeneity from ca 8000 cal yr BP onwards. Biomass burning appears to have been primarily modulated by climate during both the lateglacial and Holocene, through its effect on vegetation productivity and therefore fuel availability (lateglacial), and fuel structure, moisture and flammability (the Holocene). Onsite human activities are likely to have provided an extra ignition source already in the early Holocene. However, evidence suggest that anthropogenic activities have markedly altered the natural trends in biomass burning from about 5500 yr BP (lowlands) and over the last 2000-1000 years (in the mountain environments), by either removing the biomass (in the lowlands) or igniting fire where it seldom occurs naturally (i.e., in the mountain environments). On the other hand, burning activity also appears coincident with significant changes in tree species compositions, indicating that fire has likely acted as a driving factor in forest dynamics. Results also suggest that peat deposits provide a more localized fire record than lakes, and that trends and patterns of change can be different even for sites situated close to each other.

1. Introduction

Fire is an important environmental process that drives significant changes in ecosystem structure and function, species evolution, biomass dynamics, and in the global cycling of carbon, nitrogen, and aerosols (Bond and Midgley, 1995; Carcaillet et al., 2002; van der Werf et al., 2006; Hély et al., 2010; Pausas and Schwilk, 2012). For example, simulations using dynamic global vegetation models that include constraints on fire-caused ecosystem disturbance show that in the absence of fire activity (i.e. fire switched off in the model), many regions that currently support shrubs and herbaceous vegetation would rapidly turn into forested lands (Bond et al., 2005; Spessa et al., 2005, 2010; Thonicke et al., 2010; Friedlingstein et al., in press).

Fire dynamics and the controls on fire activity at seasonal and annual temporal scales have been more thoroughly documented for many regions and palaeo-climatic settings (see for example

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review by Whitlock et al., 2010), but there remain many gaps in our knowledge concerning the long-term and broader spatial scale trends in fire regimes for particular regions. Nonetheless, recent methodological and data quality improvements in the use of sedimentary charcoal records for reconstructing past fire regimes have permitted insights into both the temporal patterns and spatial variations in biomass burning, as well as on the long-term relationship between fire, climate, and vegetation (Marlon et al., 2008, 2009; Power et al., 2008; Higuera et al., 2009; Keeley, 2009; Blarquez and Carcaillet, 2010; Hély et al., 2010; Jeffers et al., 2011; Rius et al., 2011).

Power et al. (2008) recently reviewed the existing sedimentary charcoal data and reported a complex pattern on past global fire regimes: the biomass burning has been low over Europe during the last glacial maximum (LGM) and lateglacial (21,000–11,000 cal yr BP); it reached a maximum in the early Holocene (11,000–8000 cal yr BP), was lower than at present between 6000 and 3000 cal yr BP, and increased again over the last 3000 years. Nevertheless, the results also show a remarkable homogenous pattern in fire regimes during the LGM and lateglacial at continental scale, likely linked to limited biomass availability. This contrasts with the significant regional heterogeneities observed for the Holocene, which could be explained by a general increase in the spatial-temporal diversity of fire drivers, including distinct regional climatic fragmentation, various vegetation assemblages and occasionally anthropogenic-related biomass ignitions. Despite their far-reaching conclusions, Power et al. (2008) acknowledge that the worldwide distribution of the charcoal records is relatively sparse and thus, a denser network of sites in order to better understand changes in fire regime at regional scales is urgently needed. Notably, no charcoal records from central-eastern Europe were included in that study. This is because, research concerning palaeo-fire regimes in Europe has focused either on the fire-vulnerable Mediterranean region (Carrion et al., 2003; Colombaroli et al., 2008; Vannière et al., 2011) or on northern Europe, a region known for a dense network of high-resolution palaeo-records (Pitkaänen et al., 2001; Bradshaw and Lindbladh, 2005; Girardin et al., 2009; Olsson et al., 2010; Ohlson et al., 2011).

This paper is the first attempt to analyze charcoal datasets from the Carpathian region (Hungary and Romania) and assess patterns in biomass burning during the last 15,000 years in this region. Our study addresses several research questions: i) What was the relative influence of changes in climate on vegetation productivity and fuel moisture in the region? Especially whether the dry and cold climate with low CO_2 atmospheric concentration of the lateglacial supported biomass burning, whereas abundant but moist fuel content inhibited burning activity; ii) How and when have humans altered the natural trends in biomass burning during the Holocene? iii) To document the spatial coherence in the charcoal records in relation to site-specific bio-physical characteristics and analytical constraints.

The relationship between fire activity and vegetation productivity is determined by comparing sedimentary charcoal abundances with arboreal pollen percentages (proxy for woody vegetation cover), pollen accumulation rates (proxy for biomass), and the composition of the pollen assemblages (Seppä et al., 2009; Gaillard et al., 2010). The role of climate in controlling the fire regime is explored by comparing the charcoal data with regional and local palaeoclimate records. If the dominant control on the fire regime was climate, we expect that climatically-driven fires should be observable at regional scale, or at least, to be replicable in areas characterized by similar climate and vegetation settings. By contrast, local-scale burnings should be manifested as a highly variable spatial-temporal pattern in charcoal abundance in the site-to-site direct comparison (Clark and Royall, 1995; Gavin et al., 2006; Carcaillet et al., 2007a).

2. Study area

2.1. Geographical and vegetation settings

Changes in fire activity are inferred based on published charcoal datasets from north-eastern Hungary, and the Carpathian Mountains in Romania (Fig. 1). The studied sites are distributed at elevations ranging from 86 to 1740 m, and the climate and vegetation differ considerably among sites. Details on the modern vegetation settings around each site are provided in Table 1. All the charcoal datasets reviewed in this study are accompanied by pollen data based on which inference of trends in the vegetation dynamics are made (Table 2).

2.2. Anthropogenic impact estimates from land use changes and demographic growth

The comparison of charcoal records with estimates on the demographic growth, cropland, and pasture dynamics over the last 12,000 years (information taken from the HYDE 3.1 population database of Klein Goldewijk et al., 2011) was used to assess the potential impact of population growth and land-use changes on vegetation and fuel demands.

3. Materials and methods

3.1. Charcoal data type contents

The charcoal particles were extracted from both peat and lacustrine sediment sequences. A summary on the extraction techniques, sediment sample size, sampling interval, and measurement types is given below and in Table 3.

Two class sizes of charcoal particles were examined: microscopic charcoal particles (10–150 μm) and macroscopic charcoal particles (>150 μm). Microscopic charcoal was extracted together with pollen from 1 cm^3 sediment samples from the Molhaşul Mare, Padiş Sondori, Călineasa, Doda Pilii, and Kis Mohos sedimentary records following the standard pollen protocol of Bennett and Willis (2001), whereas for the records of Steregoiu (1 cm^3), Sarló-hát (2 cm^3), Saint Ana (1 cm^3), Nagymohos (1–2 cm^3) and Tăul dintre Brazi (1 cm^3) the extraction followed the protocol of Berglund and Ralska-Jasiewiczowa (1986). Microscopic charcoal particles were either tallied simultaneously with pollen during routine pollen counting (Molhaşul Mare, Padiş Sondori, Călineasa, Doda Pilii and Tăul dintre Brazi) or were estimated by the point–count method of Clark (1982) for Saint Ana, Sarló-hát, Nagymohos and Kis Mohos sequences (Table 1). The temporal resolution covered by each micro-charcoal sample varies from site to site and the ranges are given in Table 1.

Macroscopic charcoal represents the fraction of charcoal: i) retained on 150 μm sieve mesh (Molhaşul Mare, Padiş Sondori, and Călineasa) during pollen preparation (1 cm^3), and includes treatment with HCl and NaOH; ii) during sieving of 1 cm^3 sample with water (Doda Pilii); or iii) the particles counted on larger sediment samples volume (10–40 ml) during routine plant macrofossil analysis (Molhaşul Mare, Doda Pilii, Tăul dintre Brazi, Saint Ana, Steregoiu, Preluca Tiganului) (Table 1).

3.2. The relevant charcoal source area

Experimental and simulation studies on charcoal dispersal and accumulation show that the small, light micro-charcoal particles (10–100 μm) provide basic information on regional fires (Clark, 1988; Tinner et al., 1998; Carcaillet et al., 2001; Whitlock and Larsen, 2001; Duffin et al., 2008). Conversely, larger and heavier charcoal particles (>100–200 μm) are generally deposited in the proximity of the