The comparative use of charcoal frequency, area and morphology to reconstruct fire history in a late Holocene peat sequence from NW Romania

Ancuţa Petraş, Diana Istrate

Department of Geography, Stefan cel Mare University, Suceava, Romania

SUMMARY

Ombrotrophic peatlands are ideal archives for reconstructing charcoal fluxes resulting from vegetation burning. This is because they are sensitive to local environmental changes and the deposition of allochthonous material is exclusively atmospheric. This article presents a charcoal analysis in which two generally accepted research methods were compared, namely (i) quantification of the frequency of occurrence (number), and (ii) quantification of the size (area) of charred particles. The peat cores were extracted from the ombrotrophic bog of Tăul Mare in the Eastern Carpathian Mountains (northern Romania). The two methods for quantifying the occurrence of charcoal yielded similar results showing increasing variability of fire activity during the last ~ 3000 years. Charcoal peaks were best defined in the charcoal area dataset and indicated an increase in charcoal particle size during periods of high charcoal abundance, which points to local fires. Analysis of charcoal morphology showed that, during time intervals with high charcoal abundance, there was a gradual increase in the proportion of burnt wood. This suggests that episodes of high and/or low intensity burning, on both long and short timescales, may play an important role in determining the charcoal signature of these events. The high level of detection of high intensity fires suggests that charcoal records may be most useful in systems with high intensity fires.

KEY WORDS: bog, Eastern Carpathians, human activity, ombrotrophic peatland, Tăul Mare

INTRODUCTION

Charcoal is produced by the incomplete combustion of organic matter during a natural or anthropogenic fire. The rate of charcoal accumulation in a peat bog is dependent on the characteristics of the fire (how much charcoal is produced), vegetation (how much biomass is available for combustion), the degree of openness of the environment in which the sample is taken, and the transport and delivery of charcoal to the bog (Whitlock & Larsen 2001; Figure 1). Primary charcoal refers to the material that is deposited in the bog during or in the immediate aftermath of a fire event. Secondary charcoal particles are deposited during years without fires due to surface runoff and peat-sediment mixing, which causes redeposition (Whitlock & Larsen 2001).

Charcoal analysis of peat sediment is used to reconstruct long-term variations in fire occurrence, complementing and extending information from historical records (Feurdean *et al*. 2015). Fire can be inferred from sedimentary charcoal records by examining total charcoal abundance (per unit of sediment). This has been shown to be proportional to the total biomass burned (Andreae 1991, Marlon *et al.* 2009). In most cases, charcoal data from sediment cores have been used to examine the links between fire and past climate, vegetation, and sometimes anthropogenic activities (Bal *et al.* 2011, Blarquez *et al.* 2015, Leys & Carcaillet 2016, Vannière *et al.* 2016).

The increasing use of fire activity reconstructions based on charcoal analysis over the last decade reflects a growing tendency within the palaeoecological scientific community to consider fire as an ecosystem process operating over both long and short timescales, as well as the increasing need of forest managers to understand prehistoric fire regimes in order to identify sustainable management strategies for current and future landscapes (Whitlock & Larsen 2001, Whitlock *et al.* 2018). Numerous global studies based on fossil charcoal analysis reflect the need for an understanding of past vegetation fires, particularly during the late Holocene (Whitlock & Anderson 2003, Whitlock *et al.* 2010). The Late Holocene is a key time interval for the reconstruction of past fire activity because of both the greater human impact on the environment and the ability of palaeoecologists to more accurately assess its influence on the fire regime.

In recent years, several publications (Mooney & Tinner 2011, Mustaphi & Pisaric 2014) have reviewed methods for charcoal analysis in peat cores and their use as a tool for reconstructing fire history.

These studies show that macroscopic charcoal fragments > 90–150 µm are useful in reconstructing fire history because they cannot be transported long distances from their point of production (Mîndrescu *et al.* 2013, 2023). Thus, the sources of macroscopic charcoal fragments may be local fires (i.e., occurring within the hydrological catchment), extra-local fires (nearby but not within the same catchment) (Gavin *et al.* 2003, Higuera *et al.* 2005), or even regional fires if the fragments are smaller than 300 µm (Adolf *et al.* 2018, Florescu *et al*. 2018, Mîndrescu *et al.* 2023). Currently, two main methods are available for quantification of macroscopic charcoal in peat sediments, namely charcoal number (frequency) and charcoal area. The use of charcoal area can reduce uncertainties in charcoal analysis due to taphonomic processes and breakage during sample preparation. However, it can also introduce measurement errors due to very large individual particles that cannot be associated with a fire event (Finsinger *et al.* 2014). Therefore, in environments where taphonomic processes are considered important, such as the Mediterranean (Leys *et al.* 2013), charcoal area may be preferred. Conversely, taphonomic processes may be at a minimum in environments at higher latitudes or in ombrotrophic peatlands (Mustaphi & Pisaric 2014, Florescu *et al.* 2018). Therefore, for reliable reconstructions of fire activity, several studies (Finsinger *et al.* 2014, 2018) recommend the combined use of both methods, which also helps to distinguish between the types of material burned. Despite this, few studies in Europe (e.g., Leys *et al.* 2013, Finsinger *et al.* 2014, Carter *et al.* 2018, Dietze *et al*. 2018) have compared the use of frequency- and area-based macroscopic charcoal methods for fire activity reconstruction. Furthermore, only two studies in Romania (Retezat Mountains) have reconstructed fire regime history on the basis of both charcoal number and charcoal area (Finsinger *et al.* 2014, 2018) and none have added information obtained from the analysis of macroscopic charcoal morphology.

This article provides the first comparison between macroscopic charcoal number and charcoal area for north-western Romania, derived from the sediments of the Tăul Mare, an ombrotrophic peatland (bog) located in the Lăpuș Mountains (Mîndrescu *et al.* 2013, 2023). The Late Holocene time period is chosen because it is characterised in regional palaeoecological reconstructions by increased human impact (deforestation, grazing, mining activities) (Mîndrescu *et al.* 2013, 2023).

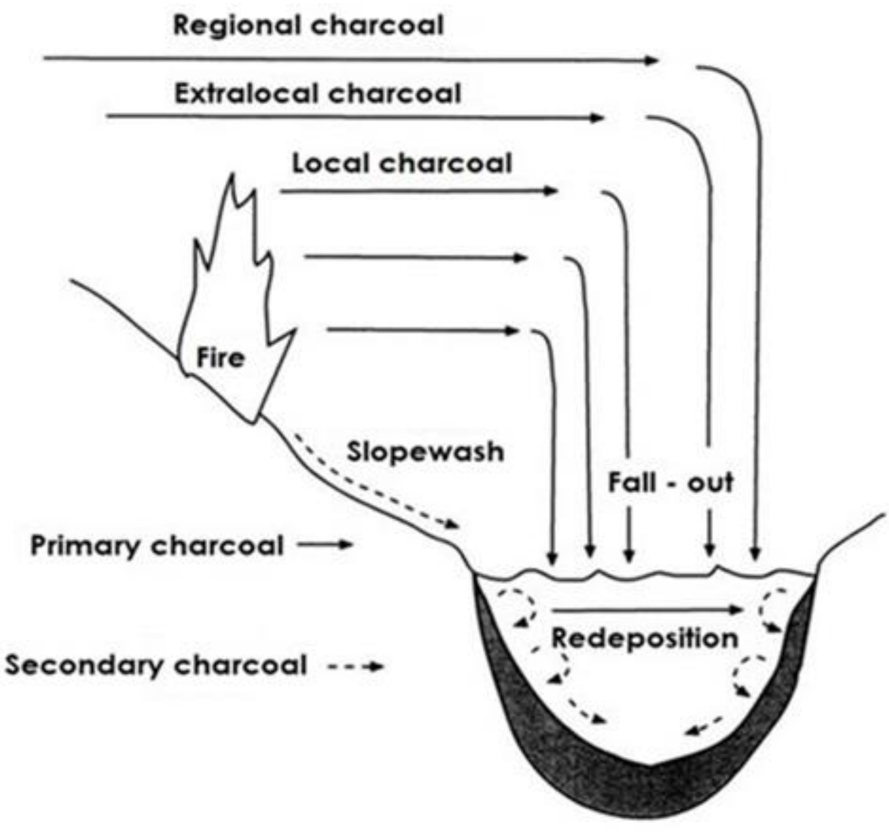

Figure 1. Schematic diagram illustrating the sources of primary and secondary charcoal in a hydrological catchment (Whitlock & Larsen 2001).

METHODS

Study site

The Tăul Mare peat bog (47° 39' 42.33" N, 24° 01' 14.72" E) lies at an elevation of about 1,066 m a.s.l in the Lăpuș Mountains (Eastern Carpathians, Romania). The bog is situated near Băiuț village, north of the Tăul Rosia UNESCO site (Figure 2). The local geology includes sedimentary rocks (flysch, composed of mainly sandstone and soft clay strata) and igneous rocks rich in valuable ores such as gold, silver and selenium (Badea & Gâştescu 1983). The land morphology is characteristic of low elevation mountains, highly fragmented by river valleys and with frequent peat deposits (Badea *et al.* 2012). The climate is moderately continental with Atlantic and Baltic influences, characterised by a mean annual temperature of 8 °C and mean annual precipitation of 1400 mm at Baia Mare weather station (Stoenescu & Tistea 1962).

Local vegetation is composed of *Sphagnum* and *Polytricum* alongside *Poaceae* and *Carex*, whereas regional vegetation comprises *Picea abies* with *Salix cinerea*, *Vaccinum myrtillus* and herbaceous plants with *Homogynea alpine*, *Eriophorum* sp., *Carex* sp., *Phegoptiris connectilis* (Peters *et al.* 2019, Mîndrescu *et al.* 2023) (Figure 3). Regionally, and in the catchment of the study area, the dominant vegetation types belong to the mixed mountain forest belt, where stands of *Fagus sylvatica* L. and *Abies alba* Mill. are often mixed with spruce. The latter species can form pure stands at the subalpine level (*Homogyno-Piceetum*), as is the case above the peat bog. Due to recent deforestation, open mountain heaths are also present (Badea *et al.* 2012, Mîndrescu *et al.* 2023).

Sampling, chronology and core correlation

Two cores were extracted from the Tăul Mare bog in 2017 (221 cm long) and 2018 (420 cm long), using a Russian type chamber corer for the extraction of deep deposits and a box corer for surface deposits. Plant remains of above-ground origin were collected from four selected peat depths and measured by accelerator mass spectrometry (AMS) in the Beta Analytic Radiocarbon Dating Laboratory Miami in Florida (USA) and Isotoptech Zrt Radiocarbon Dating Laboratory in Debrecen (Hungary) (Table 1).

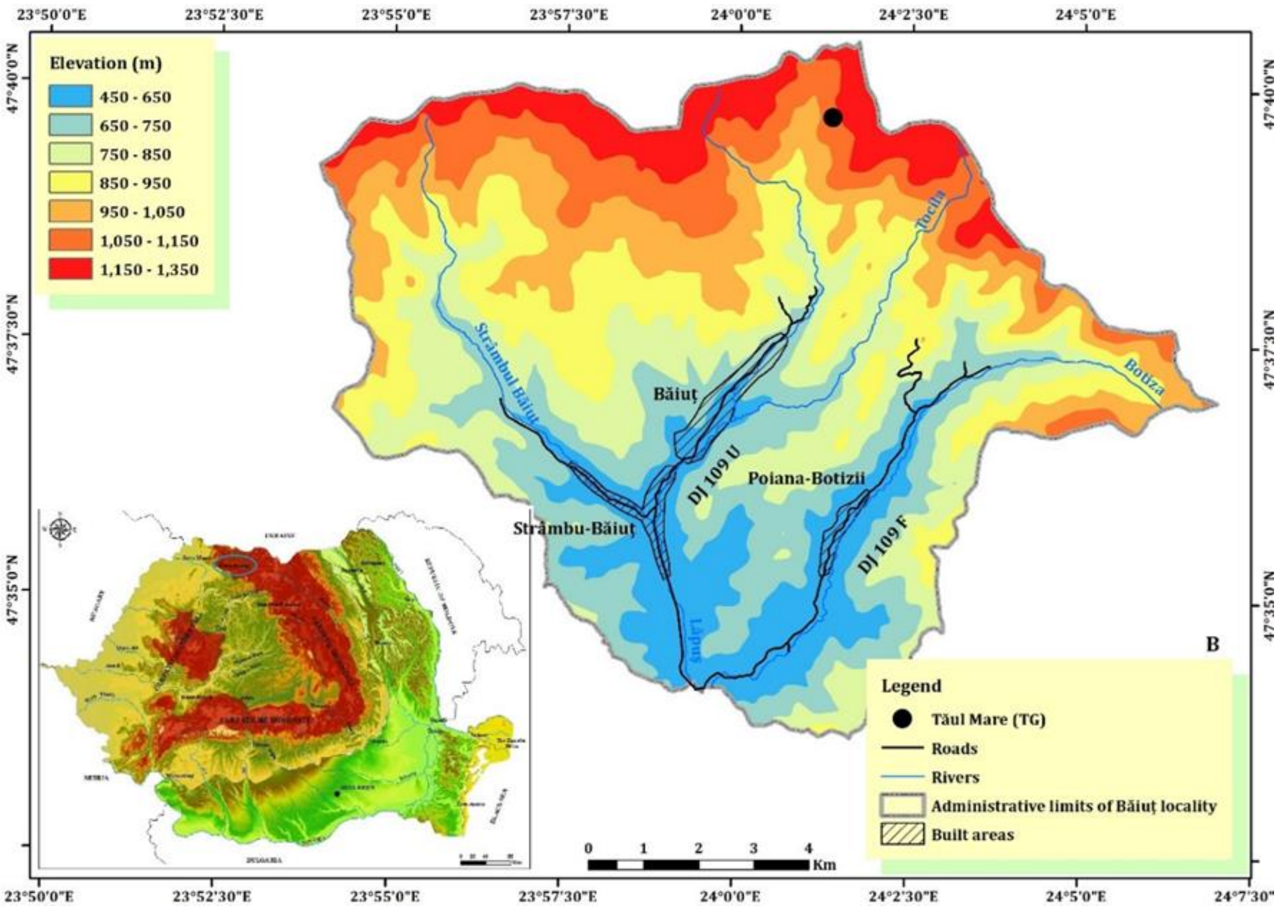

Figure 2. Location of Tăul Mare (black dot) in the upper catchment of the Lăpuș River in NW Romania (inset).

Calibration of ^{14}C dates to calendar years was performed using the INTCAL13 dataset (Bronk Ramsey 2009, Reimer *et al.* 2013). Both profiles were subjected to geochemical analysis using a non-destructive Niton XL3t 900 X-Ray Fluorescence analyser (fpXRF) (Hutchinson *et al.* 2016). Of the geochemical elements, titanium (Ti) was selected as the most stable lithogenic element, and is used here for core correlation.

Quantification of macroscopic charcoal frequency (number)

Samples of 2 cm^3 each were taken contiguously at 1 cm intervals along the 2017 peat profile, soaked in chlorine bleach for 24 hours, and wet sieved through a 150 μm mesh. All of the material retained by the sieve was examined in a Petri dish using a stereomicroscope at 30× magnification (Whitlock & Larsen 2001, Mustaphi & Pisaric 2014, Feurdean *et al.* 2017a, 2017b; Florescu *et al.* 2018), and the macro-charcoal particles were counted. The macro-charcoal counts were divided by the sample volume and expressed as particles cm^{-3}.

Quantification of macroscopic charcoal size (area)

Samples of volume 1 cm^3 were taken contiguously at 1 cm intervals along the 2018 peat core. After bleaching with NaOCl solution, 5 % KOH was added and the samples were heated at 40–60 °C for one hour to digest organic matter then wet sieved (mesh size 150 μm). The area of each individual charcoal particle was determined using a binocular microscope (25–50×) and a grid. The areas of the individual charcoal particles in the total (sample) area were then summed (Bal *et al.* 2011, Finsinger *et al.* 2014) and expressed in mm^2 cm^{-3}.

Analysis of charcoal morphology

The samples used for charcoal number quantification were subsequently examined for charcoal morphology. Each macrocharcoal particle was examined under a stereomicroscope and classified according to its shape (morphotype), according to Mustaphi & Pisaric (2014). The morphotypes identified were then separated into categories corresponding to wood, grass and forb morphotypes (Feurdean *et al.* 2017b, Florescu *et al.* 2018).

Figure 3. Photographs of vegetation at the Tăul Mare coring site, showing *Sphagnum* growing alongside Poaceae (left) and with *Carex* species (right).

Table 1. Radiocarbon data from the Tăul Mare bog.

Depth (cm)	Median age (cal. yr BP) (2σ)	^{14}C age (years BP)	Lab code	Sample type
91	1167	1146 ± 28	DeA-28361	Conifer needles
133	1972	2076 ± 27	DeA-28361	Twig
147	2220	2220 ± 30	Beta-483484	Wood
212	2853	2733 ± 30	DeA-28361	Conifer needles

RESULTS

Core correlation and chronology

Core correlation based on titanium (Ti) values suggests that the 2018 profile contained a longer peat sequence than the 2017 profile. This is probably due to the greater peat thickness at the 2018 sampling point (Figure 4). The fact that both of the peat profiles (cored in 2017 and 2018) reached the base of the peat layer supports this inference and suggests that the rate of peat accumulation is spatially variable, increasing towards the centre of the bog.

Radiometric results for a sample taken from the base of the 2017 peat profile showed an age of 2220 ± 30 calibrated years BP (95.4 % confidence). This places the time of the onset of peat formation in the middle part of the Late Holocene (Figure 5).

Charcoal number and area

The charcoal concentration (CHAC) at the Tăul Mare bog was calculated using charcoal number for the 2017 core and charcoal area for the 2018 core (Figure 6). The results show both similarities and differences in charcoal concentration fluctuations between the two cores and, thus, in the evidence they offer as a basis for the reconstruction of local fire history. Both profiles show three main periods of increased charcoal concentration during the last ~ 3000 years.

Charcoal morphologies

The most common charcoal morphotypes at Tăul Mare (TG) were elongated and thin, mostly derived from burnt grasses and/or wood (Mustaphi & Pisaric 2014). The results of concentrating charcoal morphotypes at Tăul Mare also show that charcoal morphotypes associated with herbs were the most abundant in the entire profile (Figure 7). Conversely, charcoal morphotypes associated with grasses were least abundant. Bulky foliated and lignified morphotypes of types A1 and B1 were also present (Figure 7 and Figure 8).

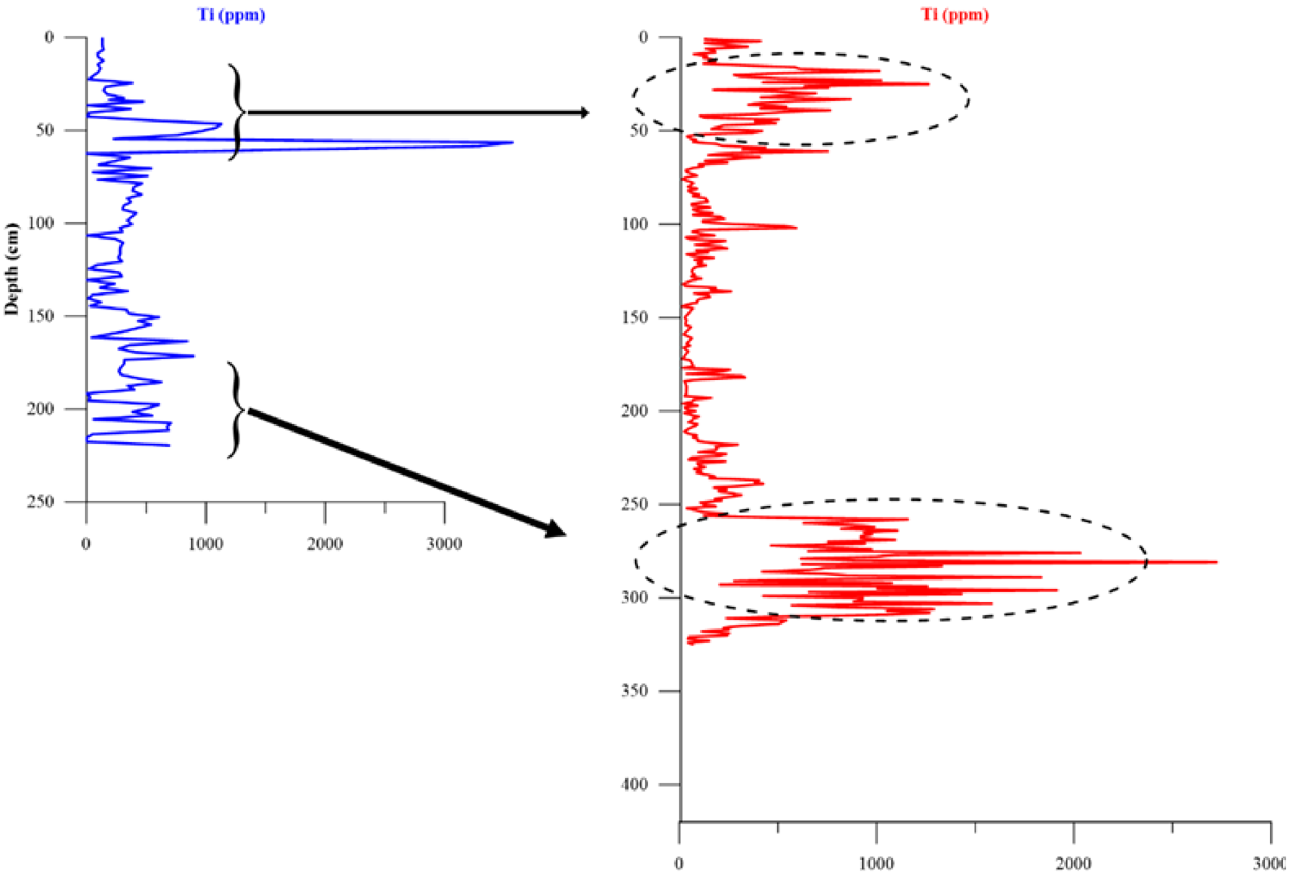

Figure 4. Core correlation at Tăul Mare based on titanium (Ti) content, in the 2017 (left) and 2018 (right) peat profiles.

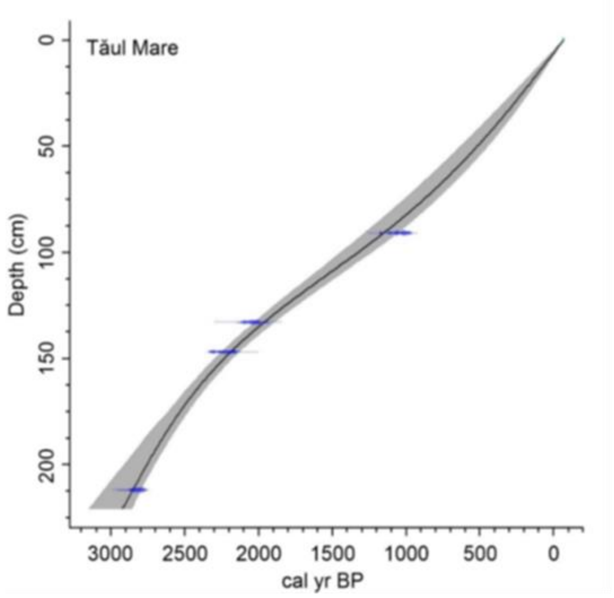

Figure 5. Tăul Mare age-depth model. Data points are shown in blue.

DISCUSSION

Our charcoal-based reconstruction of fire activity from bog deposits in the Lăpuș Mountains spans most of the Late Holocene period, for which the transformation of landscapes by humans is becoming increasingly characteristic. Overall, peaks of charcoal concentration are more pronounced and very large values more frequent in the area-based reconstruction (e.g. 2018 core) than in the number-based reconstruction (e.g. 2017 core). This indicates the presence of large charred particles, so the peaks from the 2018 core can be interpreted as reflecting the occurrence of fires that were closer to the study area and/or burned with greater intensity. For example, experimental studies and model simulations have shown that large charcoal fragments are more abundant in areas close to or directly affected by a fire (Clark 1988, Ohlson & Tryterud 2000). On the other hand, high-intensity wildfires have been shown to deposit larger charcoal fragments even several

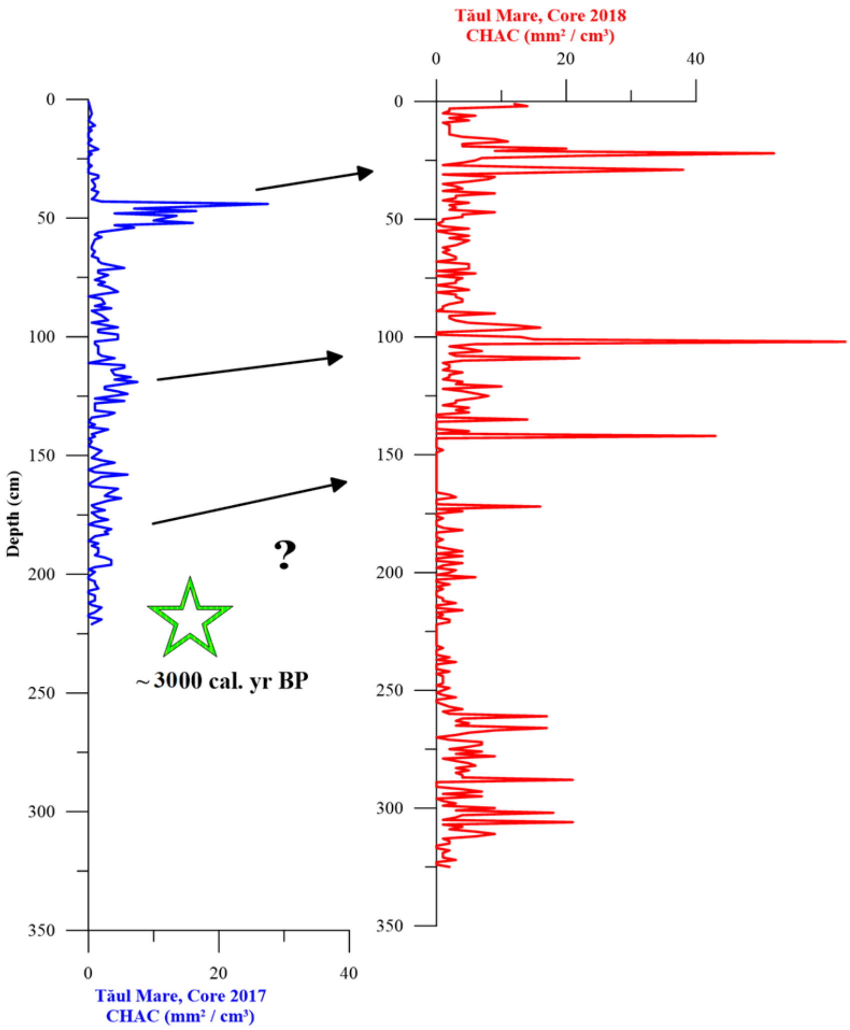

Figure 6. The abundance of macroscopic charred particles in the Tăul Mare peat profile based on charcoal number (blue) and charcoal area (red).

kilometres from the fire site (Tinner *et al*. 2006, Conedera *et al*. 2009). These results also highlight that combining the two methods (i.e., charcoal number and area assessment) can deliver a more complete picture of variability in the charcoal record, and the reconstruction of local fire regime is further improved by adding a robust age-depth model.

It was difficult to infer what type of material burned to produce the elongated and very thin charcoal particles (type D1 according to Mustaphi & Pisaric 2014), as this morphotype can either result from the burning of grass leaf veins and awns or be rays and tracheids from burnt wood (Schweingruber 1978, Mauquoy & Van Geel 2007). However, the elongated shape of type C and D fragments combined with their light weight and consequent portability suggests they may have arrived by long-distance, or at least extra-local, transport (Enache & Cumming 2006, 2009). In contrast, the bulky morphotypes are likely to have originated from burning wood

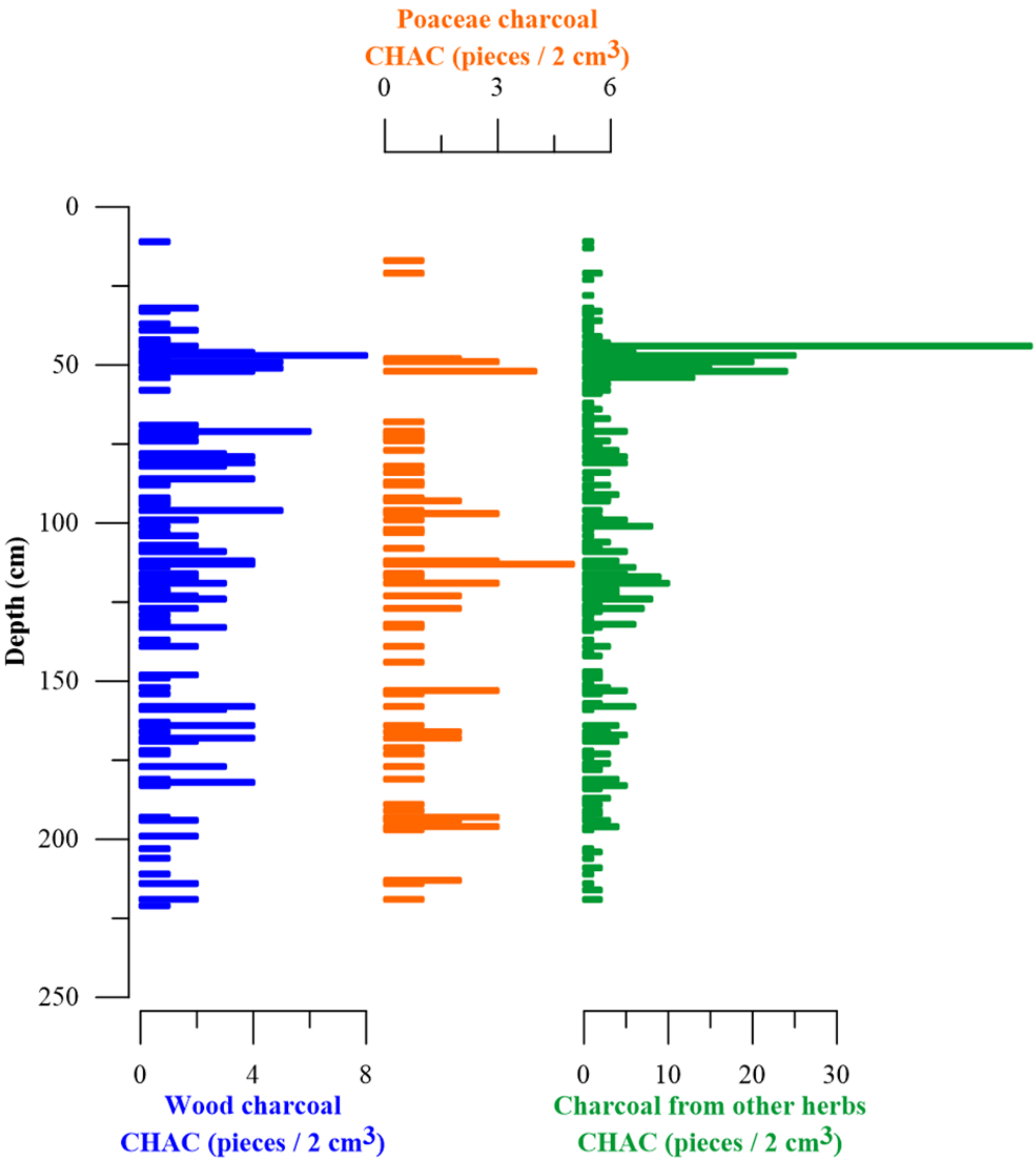

Figure 7. Profiles of macrocharcoal morphotypes from Tăul Mare, indicating the types of material that burned.

(Mustaphi & Pisaric 2014), and their 3-dimensional shapes and greater weights suggest short-distance transport from the charcoal source area. Therefore, they can be regarded as reliable indicators of local wood burning.

There are three main wood morphotype peaks in the 2017 core record from Tăul Mare, which coincide with peaks in total charcoal concentration determined by both (frequency-based and area-based) methods (Figure 6), suggesting periods of increased fire intensity (Feurdean *et al*. 2017a). The maxima of woody morphotypes and total charcoal concentration in the subsurface peat (~ 50 cm depth) may be related to mining in the area, indicating that mining activity was probably regional in scale and associated with the clearance of forest around the peatland using fire. Fire may also (or otherwise) have been involved in local production of charcoal for ore smelting.

It is predicted that the threat of wildfires will increase in future, even in regions such as the northern Carpathians that are presently considered to be unthreatened. This will have costly ecological and economic consequences. Therefore, more charcoal-based studies are needed to improve our understanding of local fire history. Our results show that macroscopic charcoal analysis in sedimentary sequences that adopts a combined methodological approach (based on the number, area and morphology of charred fragments) has potential to provide important additional information about the charcoal source area and fire intensity that aids the interpretation of charcoal records in the context of reconstructing historical fire regimes.

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AUTHOR CONTRIBUTIONS

AP carried out fieldwork, undertook the laboratory work and data analysis, and wrote the first draft of the manuscript. DI helped to rewrite drafts.

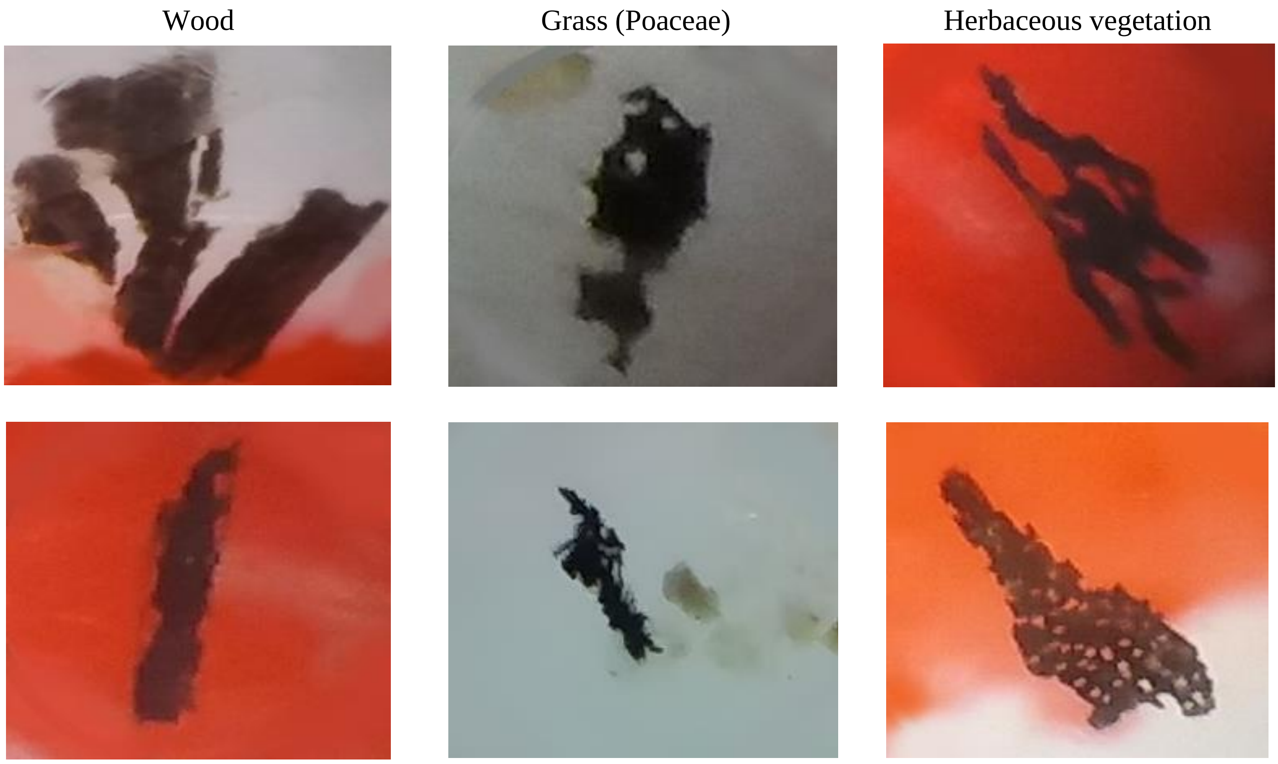

Figure 8. Example charcoal morphotypes from Tăul Mare, classified according to Mustaphi & Pisaric (2014).

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Author for correspondence: Ancuța Petraș, Department of Geography, Stefan cel Mare University, 720229 Suceava, Romania. E-mail: ancuta.petras@usm.ro