

Fire signal in lakes and peatlands in Romania during the Holocene: A review of methods, groundwork and achievements

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Abstract

In this article, we provide a review of research that explores the extensive history of wildfires across Europe, focusing specifically on Romania's territory. Lakes and peatlands serve as ideal sources for reconstructing charcoal fluxes resulting from vegetation burning. These natural resources are extremely sensitive to local environmental changes, and the deposition of allochthonous material is exclusively atmospheric. The analysis of macro-charcoal is the primary method for reconstructing local and regional wildfires. This article aims to emphasize the significant studies on paleofires, and the processing and identification methods of macroscopic charcoal particles, which include charcoal number, morphology, and CharAnalysis. The review of scientific achievements in Europe and Romania provides valuable insights into these methods. We aim to investigate the potential of modern international paleofire databases, such as the Global Charcoal Database and Reading Palaeofire Database, which provide updated information on local and regional paleofire occurrences during the Holocene period. We will also make use of software tools that generate maps based on network data, such as VOSviewer Bibliometric Analysis, to visualize and study the wildfire in Romania. Furthermore, we will analyze the publications related to this topic that are available in the Web of Science database. We analyzed the results of paleofire studies in Europe and Romania to determine the primary research directions linked to fire reconstruction. Our review revealed that most of the study sites in Romania are in the Carpathians, particularly at higher elevations, followed by mid-elevation areas. However, lowlands have been less investigated up to this date.

Keywords: macro-charcoal analysis, lake and peatland sediments, Holocene, paleofire

Introduction

Charcoal is the result of incomplete combustion of organic matter by a natural or anthropogenic fire (Whitlock & Larsen, 2001). In most cases, charcoal data from lake sediments and peat 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; Vanniere et al., 2016). The charcoal layers detected in the thickness of lake and peat deposits can indicate large local fires in certain areas, although they may not entirely reflect all the fires that have occurred in the region. Modern methods of investigation make it possible to reconstruct past fire activity in the local and regional landscape based on data from macro-charcoal analyses of lake and peatbog sediments (Mooney & Tinner, 2011). Moreover, approaches for researching past wildfires also rely on using dedicated software to determine local fire episodes, such as "CharAnalysis" (Higuera, 2009).

The increasing use of fire activity reconstructions based on charcoal analysis over the last millennium reflects the growing interest within the palaeoecological scientific community to consider fire as an ecosystem process operating at both long- and short-time scales, as

well as the need for forest managers to understand past fire regimes 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 Holocene (Whitlock et al., 2003; 2010), which represents a key interval for the reconstruction of paleofire activity due to the greater human impact on the environment and the ability to more accurately assess its influence on the fire regime. In recent years, several papers (Mooney & Tinner, 2011; Mustaphi & Pisaric, 2014) have reviewed methods for charcoal analysis in lake sediment and peat cores and their use as a tool for reconstructing fire history. The aim of our research is to review modern methods, achievements, foundations, and perspectives in the study of the long-term dynamics of past fires based on macro-charcoal analyses of various natural archives (lake and peat sediments), and to present a bibliometric analysis of Web of Science paleofire studies linked to climate change. To assess the performance of VOSviewer, paleofire simulations were performed and compared with proxy-based data. Although VOSviewer is primarily designed to analyze bibliometric networks, it can also be used to create, visualize, and explore maps based on any type of network data (Van Eck et al., 2018). Our

research on paleofires contributes to understanding the long-term variations in fire occurrence, by complementing historical records (Feurdean et al., 2015).

Long-term history determination methods for paleofires

The formation and evolution of environments are affected by any fire, natural or anthropogenic. After fires, "traces" in the form of ash and charcoal particles are dispersed by air and water currents and then deposited in peat sediments, preserving palaeoecological information for millennia. Such dispersed charcoal particles can be found and counted in fossil peat sediments using specific methods (macro-charcoal analysis) (Whitlock & Larsen, 2002; Mooney & Tinner, 2011). Peat records are considered the most suitable for reconstructing fire history because sedimentation is continuous, and these sediments preserve palaeodata for many thousands of years in their thickness (Conedera et al., 2009).

Macro-charcoal and dating analysis

In the international literature, two terms are used to designate the same method – macroscopic charcoal analysis (Whitlock & Larsen, 2002) or macro-charcoal analysis (Feurdean et al., 2020). Macroscopic charcoal particles ($> 90/150 \mu\text{m}$) are transported by the wind over short distances from the fire perimeter (up to 1-2 km), and within the local catchment area and deposited on the surface (Mîndrescu et al., 2013; 2023). Over time, they are buried under new layers of sediment in peat bogs where soil accumulates. Large macro-charcoal particles preserved in post-fire sediments indicate local wildfire activity (Whitlock & Larsen, 2002; Mooney & Tinner, 2011).

There are two main methods for quantification of macroscopic charcoal in lake and peat sediments, namely charcoal number and charcoal area. The use of the charcoal area can reduce uncertainties in the 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; 2016), charcoal areas 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).

For reliable reconstructions of fire activity, several studies (Finsinger et al., 2014; 2018) recommend combining both methods. Despite this, there are few studies in Europe (e.g., Leys et al., 2013, 2016; Finsinger et al., 2014; Carter et al., 2018) that compare number- and area-based macroscopic charcoal methods for fire activity reconstruction. Furthermore, there are only two studies in

Romania (Retezat Mts.) that reconstruct fire regimes based on both charcoal number and charcoal area (Finsinger et al., 2014; 2018). Macro-charcoal particles are therefore reliable indicators of palaeofires that are specific in systems. The statistical processing of the data obtained on the concentration of macro-charcoal preserved in sediments is carried out using the "CharAnalysis" software (Higuera, 2009), adapted for the R-space. The program uses calculations on a chronological basis to age the samples according to the depth-aged model of sediments based on available radiocarbon dates for the sediment section studied. In general, the data obtained from macro-charcoal analysis make it possible to reconstruct the local history of fire activity in each area, to identify relationships between changes in vegetation, climate, and fire, and to identify the possible causes of wildfire activity and its effects on the surrounding areas (Whitlock et al., 2010; Feurdean et al., 2020).

Current state of research on vegetation fires in Europe

Interest in studying paleofire appeared in the 1960s when the concept of fire regime was first introduced to the scientific community. The main issue on which the concept was based was the study of the ecological role of fires (Conedera et al., 2009). These first studies on the long-term history of paleofire were published in the 1970s and were based on novel methods for identifying paleofire in peatbog sediments using macro-charcoal analysis (Clark, 1983; Patterson et al., 1987). The studies focusing on the reconstruction of paleoecological and paleofire conditions (e.g., Barnosky, 1984) and the progress of charcoal analysis (Patterson et al., 1987; Whitlock & Larsen, 2002; Mooney & Tinner, 2011) describe the general features and properties of charcoals, the conditions for their deposition and accumulation, possible relationships between the components of systems, and the probable causes of fires (Whitlock & Larsen, 2002; Mooney & Tinner, 2011).

In several works (e.g., Enache & Cumming, 2006; Mustaphi & Pisaric, 2014; Feurdean et al., 2017) various morphotypes of charcoal particles are distinguished, such as wood, roots, needles, etc., revealing the type of burned vegetation. As these research methods become widespread, technologies for identifying fire episodes are being modernized through the development of software tools, such as CharAnalysis (Higuera, 2009), which allows for the calculation of the rate of accumulation of macro-charcoal particles, the background and threshold values of the concentration of charcoal in sediments and the identification of local fire episodes, and CharTool (The Charcoal Quantification Tool) dedicated to determining, identifying, and classifying the morphological type of charcoal (Snitker, 2020; Pupysheva et al., 2023).

The increasing interest in the reconstruction of wildfires in different parts of the world using macro-

charcoal analyses indicates the relevance of this field of research. In addition to general issues of reconstructing the history of vegetation, fires, and climate in certain areas, possible links between components are considered (Marlon, 2020). In these studies, fire is seen as a natural evolutionary factor contributing to the maintenance and increase of biodiversity, and as a response to changing climatic conditions. In addition, the authors question the dominant role of humans in the increase in modern fire activity, emphasizing the climatic factor. Fire control through changes in land use is considered, since it leads to the elimination of fires and the reduction of the consequences of fires for human infrastructure, while it also introduces an imbalance in the natural process of ecosystem development, sometimes creating favorable conditions for more powerful fires (Harrison et al., 2010; 2021). Another relevant area of wildfire research is to identify the mechanisms of control and variability of fires and their modelling to make probable forecasts on the dynamics of fires (Harrison et al., 2010; 2021). It is recognized that burning biomass has an impact on the climate itself and is a component of regional climate dynamics, as well as a key link in human interaction with the climate.

The purpose of the Global Paleofire Working Group (GPWG) was to collect and analyze data on the content of dispersed charcoal in sediments of different genesis around the world by creating the Global Charcoal Database (GCD) (Power et al., 2008; Harrison et al., 2022; Pupysheva et al., 2023). The main directions of paleofire

studies include reconstructing local and regional paleofire events to reveal the dynamics of fires in the Holocene; accumulating a database on paleofire history to identify local and global patterns; identifying relationships between fires and other components of environments including assessing anthropogenic impacts; contributing to the improvement of research methods including software development.

A review of palaeoenvironmental reconstruction research in Romania

Many studies on paleoenvironmental and paleoclimatic reconstructions in Romania have been carried out based on the analysis of sediments from lakes and peatbogs, due to their property of integrating and preserving climatic signals (Feurdean et al., 2012; 2017; 2020; Tanțău et al., 2011; 2014; Fărcaș et al., 2013; Florescu et al., 2017; 2018; Finsinger et al., 2014; 2018; Peters et al., 2020). This research was mostly conducted to understand the evolution of climate change, including the manner in which climate variability and anthropogenic disturbances relate to past fire history. In Romania, studies have been carried out at 15 sites to reconstruct the regime and impacts of wildfires in central and northwestern Transylvania, Retezat Mts. (Tăul between Brazi and Gales), Rodnei Mts., Țibles Mts., Maramureș Mts., and Apuseni Mts. (Feurdean et al., 2012, Mîndrescu et al., 2023) (Fig. 1 and Table 1).

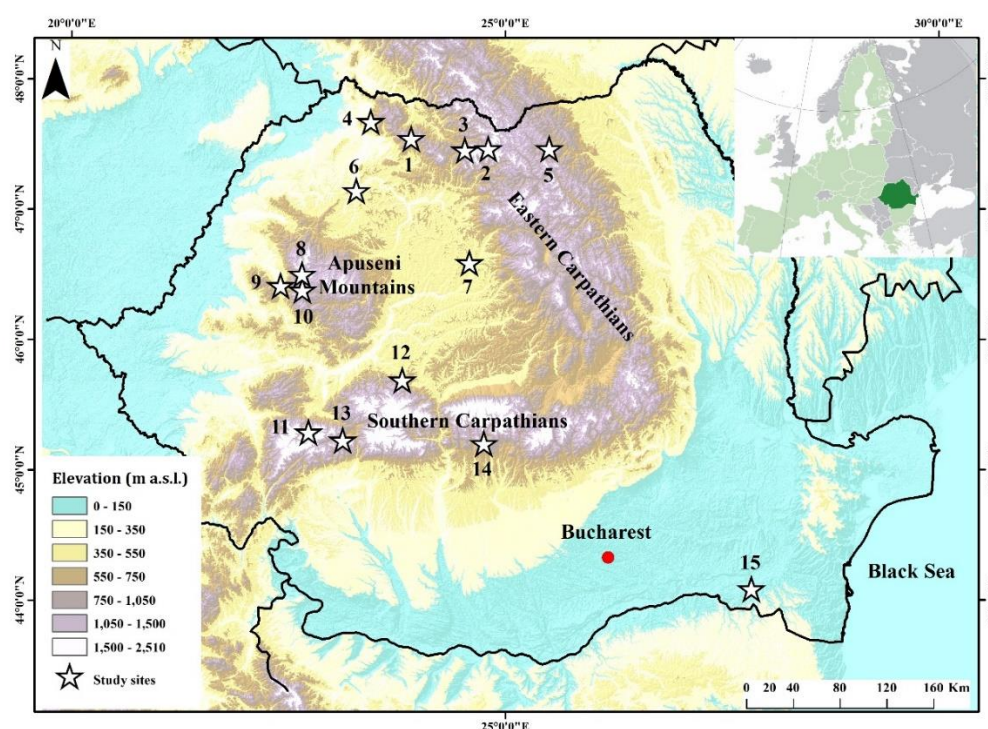


Figure 1. Map of sites where reconstructions of the paleofire regime have been carried out: 1. Tăul Negru; 2. Poiana Știol; 3. Tăul Muced; 4. Preluca Țiganului; 5. Iezerul Ferede; 6. Turbuța; 7. Știucii; 8. Padiș Sondori; 9. Pietrele Onachii; 10. Molhașul Mare; 11. Brazi (Tăul dintre Brazi); 12. Gales; 13. Lia; 14. Bucura; 15. Oltina

Table 1. Lacustrine sites investigated in Romania for various proxies, including charcoal

No.	Site name	Geographic location	General information (Elevation, area, maximum water depth, thickness of sediment sequence, age yrs. cal. BP)	Type of investigated site	Proxies	References
1	Tăul Negru	Eastern Carpathians-Lăpuș Mts. 47° 39' 38.39" N 23° 55' 58.43" E	Elev. = 1143 m a.s.l. Site = 2 ha Age = 10500 at 5.54 m	Peat bog Late Pliocene volcanic rocks (andesites)	Micro and macro-charcoal, lithostratigraphy, pollen.	Peters <i>et al.</i> 2020
2	Poiana Știol	Eastern Carpathians-Rodna Mts., northern slope 47° 35' 14" N 24° 48' 99" E	Elev. = 1540 m a.s.l. St = 3.20 m Site = 0.6 ha CA= 10 ha Age = 10380 at 2.93 m	Peat bog Located in a cirque floor sinkhole Rock type = crystalline limestone	Charcoal, lithostratigraphy, pollen.	Tanțău <i>et al.</i> 2011 a Tanțău and Fărcaș 2004 Tanțău 2006 Fărcaș <i>et al.</i> 2006 Feurdean <i>et al.</i> 2017
3	Tăul Muced	Eastern Carpathians-Rodna Mts. 47° 34' 26" N 24° 32' 42" E	Elev. = 1360 m a.s.l. St = 5.6 m Site = 2 h Age = 8850 at 5.15 m	Peat bog	Charcoal, lithostratigraphy, pollen.	Feurdean <i>et al.</i> 2015 Gałka <i>et al.</i> 2016 Diaconu <i>et al.</i> 2017
4	Prelipca	Eastern Carpathians-Gutâi Mts., western slope 47° 48' 83" N 23° 31' 91" E	Elev. = 830 m a.s.l. Site = 2.374 ha CA = 29 St = 10 m (hiatus) Age = 14400 at 9.88 m	Peat bog Located in rock slope failure (sackung)	Charcoal, lithostratigraphy, pollen, plant macrofossil, mineral magnetic analyses (SIRM), organic matter content via LOI, and petrographic analyses (clay mineralogy and grain size measurement).	Feurdean and Beimike 2004 Feurdean 2005 Feurdean and Astalos 2005 Feurdean <i>et al.</i> 2007a, b, 2008
5	Iezerul Sădovei	Eastern Carpathians-Western part of the Feredeș Mts., southern Bucovina 47° 36' 13" N 25° 26' 58" E	Elev. = 930 m a.s.l. Site = 0.70 ha CA = 2 ha St = 4.4 m Age = 1300 at 0.98 m	Lake Landslide-dammed located at the bottom of the valley	Charcoal, lithostratigraphy, pollen, plant macrofossil, mineral magnetic analyses (SIRM), organic matter content via LOI, and petrographic analyses (grain size measurement).	Florescu <i>et al.</i> 2017
6	Turbuța	Transylvanian Basin, northwestern part 47° 15' 26.5" N 23° 18' 42.9" E	Elev. = 275 m a.s.l. Site = 1.5 ha St = 1.9 m (hiatus)	Paleolake landslide dammed	Micro-charcoal, lithostratigraphy, pollen, total carbon analyses.	Feurdean <i>et al.</i> 2007a
7	Știucii	Transylvanian Basin, northern part 46° 58' 044" N 23° 54' 106" E	Elev. = 239 m a.s.l. Site = 38 ha St = 7.27 m	Lake Mixed origin: salt karst and landslide-dammed	Micro and macro-charcoal, lithostratigraphy, pollen, organic matter content via LOI, magnetic susceptibility, elemental geochemistry; sedimentation rates (SR) using ²¹⁰ Pb, ²²⁶ Ra, ¹³⁷ Cs, and ²⁴¹ Am.	Hutchinson <i>et al.</i> 2015 Feurdean <i>et al.</i> 2015
8	Pașii Săndor	Western Carpathians-Apuseni Mts. 46° 35' 44.86" N 22° 44' 00.96" E	Elev. = 1290 m a.s.l. Site = 1 ha St = 0.76 m	Peat bog, infilled sinkhole Located on plateau	Charcoal, lithostratigraphy, pollen.	Feurdean and Willis 2008b Feurdean <i>et al.</i> 2009
9	Pietrele Onacii	Western Carpathians-Apuseni Mts. 46° 38' 33" N 22° 50' 43" E	Elev. = 1055 m a.s.l. Site = 3.5 ha St = 1.85 m	Forested peat bog, infilled sinkhole Located on plateau	Charcoal, lithostratigraphy, pollen.	Feurdean and Willis 2008b

10	Molhașul Mare	Western Carpathians-Apuseni Mts. 46° 35' 24" N 22° 45' 51" E	Elev. = 1360 m a.s.l. Site = 1 ha St = 2.24 m	Peat bog, infilled sink-hole Located on plateau	Charcoal, lithostratigraphy, pollen, magnetic susceptibility, organic matter content via LOI.	Feurdean and Willis 2008b
11	Tăul dintre Brazi	Transylvanian Alps- Retezat Mts., northern slope 45° 23' 49.58" N 22° 54' 11.43" E	Elev. = 1730 m a.s.l. Site = 0.11 ha CA = 5.28 ha Water depth = 1.1 m St = 4.9 m Age = 13620 at 5.78 m	Lake Located on the bottom of a glacial valley	Charcoal, lithostratigraphy, elemental geochemistry, organic matter content via LOI, pollen, macrofossils, conifer stomata, diatoms, ostracode, chironomids, ancient DNA.	Magyari <i>et al.</i> 2009a, b, 2011, 2013 Finsinger <i>et al.</i> 2016
12	Galeș	Transylvanian Alps- Retezat Mts., northern slope 45° 23' 09.69" N 22° 54' 38.51" E	Elev. = 1973 m a.s.l. Site = 3.68 ha CA = 177.5 ha Water depth = 20 m St = 3.28 Age = 13540 at 2.80 m	Lake Located in glacial cirque	Charcoal, pollen, macrofossils, conifer stomata, diatoms, Cladocera, chironomids.	Magyari <i>et al.</i> 2009a, b
13	Lia	Transylvanian Alps- Retezat Mts., southern slope 45° 21' 08.73" N 22° 52' 44.24" E	Elev. = 1910 m a.s.l. Site = 1.3 ha CA = 431.9 Water depth = 4.3 m St = 7.62 Age = 14200 at 7.62	Lake Located in glacial cirque	Charcoal, diatoms (siliceous algae), pollen, macrofossils, cladoceran, and chironomids.	Buczkó <i>et al.</i> 2013 Finsinger <i>et al.</i> 2016
14	Bucura	Transylvanian Alps- Retezat Mts., southern slope 45° 21' 38.58" N 22° 52' 34.15" E	Elev. = 2040 m a.s.l. Site = 10 ha CA = 201.4 ha Water depth = 17.5	Lake Located in a complex glacial cirque	Charcoal, pollen, macrofossils, cladocera, chironomids.	Buczkó <i>et al.</i> 2013 Magyari <i>et al.</i> 2018 Hubay <i>et al.</i> 2018
15	Oltina	Floodplain in Danube River, the lower Danube Plain, in southeastern 44° 09' 16" N 27° 38' 13" E	Elev. = 7 m a.s.l. Site = 33 km ² Age = 6000 at 9.62	Lake Has a major tributary, Canaraua Fetii, and is connected to two smaller lakes, Ceamurlia and Iortmac	Macro-charcoal, lithostratigraphic, LOI, AMS ¹⁴ C, ²¹⁰ Pb and ¹³⁷ Cs, pollen, n-alkanes.	Feurdean <i>et al.</i> 2021

According to the results of these investigations, the most significant short-term climatic events were recorded in lake and peat sedimentary archives on the Romanian territory within the framework of a regional comparison (Fig. 2).

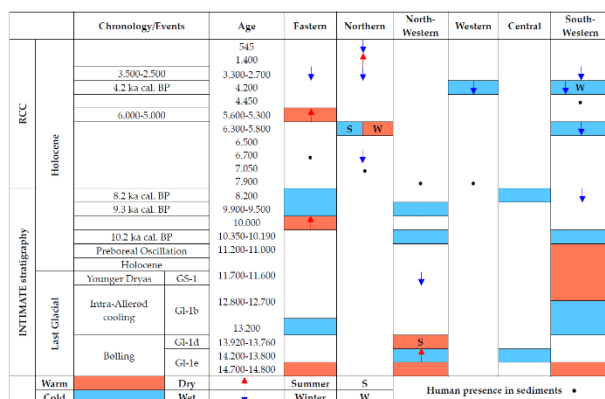


Figure 2. Summary of inferred climatic changes between 14400 and 550 cal. yr BP at reviewed sites from Romania (adapted after Mîndrescu *et al.* 2017)

These climatic events are further related to the Intimate event stratigraphy (Blockley *et al.* 2012) from 14400 to 8000 cal. yr BP, whereas the 8000 cal. yr BP to the present period is roughly related to the regional climatic changes documented by Mayewski *et al.* 2004 and Magny & Haas 2004 cited by Mîndrescu *et al.* 2013. The characteristics of the climatic stages identified in this area based on the multi-proxy analyses carried out at the sites described in Table 1 and presented in Figure 3 are summarized below according to Blockley *et al.* 2012 cited by Mîndrescu *et al.* 2017.

14.4 – 11.7 ka cal. BP. A pollen-based quantitative temperature reconstruction (Feurdean *et al.*, 2008) showed a 2 °C increase in annual temperatures, which reached 4 °C at 14.8 kyr cal. BP. During this period, in the Northern, Eastern, and Southwestern Carpathians, the temperature increase was documented in winter temperatures, whereas summer temperatures remained unchanged. This event is equivalent to the GS-2/GI-le transition in the Greenland ice core isotope record, which shows an increase in temperature amplitude (Blackley *et al.*, 2012).

11.7 – 8 ka cal. BP. In European regions, climate warming at the Holocene transition resulted in enhanced

vegetation competition and diversity. This major and abrupt climate shift triggered a visible response in vegetation at both lowland and upland sites (Fărcaș et al. 1999, 2006; Björkman et al. 2002; Tanțău et al. 2003, 2006; Feurdean, 2005; Feurdean et al. 2007a, b) which demonstrates that all elevations were comparably vulnerable. Biomass burning reached maximum values due to fire conditions and biomass availability. Charcoal records revealed lower fire activity between 12 and 10.7 kyr cal. BP in the lowland of northern Transylvania due to a shortage in fuel availability against the background of arid and strongly seasonal climatic conditions, i.e., higher summer temperature (4 °C above current mean temperature) and lower precipitation (by 33 %) compared to the present (Feurdean et al., 2013b). Between 9900 and 9500 cal. yr BP, higher lake levels accompanied by decreasing productivity and change in sediment geochemistry, and vegetation (Buczkó et al. 2012, 2013; Magyari et al., 2009b, 2011; Soroczki-Pinter et al., 2015), appear to reflect the shift towards drier conditions from ~ 9200 cal. yr BP.

8.2 - 3 ka cal BP. Between 8000 and 3000 cal. yr BP, in the western sector of the Northern Carpathians, coldest month and annual temperatures were lower compared to current conditions, whereas summer temperatures and

precipitation showed increased values, comparable to the present; more stable conditions prevailed compared to the Early Holocene were interrupted by several short-term climate events (Schnitchen et al. 2006; Feurdean et al. 2008). In the SW Carpathians event between 6300 and 5800 cal. yr BP, characterized by summer cooling, a decrease in winter ice-cover season, and an augmenting size of the water body, because of cooler and moister conditions (Buczkó et al., 2013; Magyari et al., 2009a, b). The event is synchronous with a short climatic change recorded in SE Europe and the Northern Mediterranean Region known as 6000-5000 cal. yr BP cold anomaly (Mayewski et al., 2004) characterized by cooler summers and warmer winters (Tanțău et al., 2011a). This anomaly was also identified, albeit with even greater amplitude, in the Eastern Carpathians, at Poiana Știol peatbog (Tanțău and Fărcaș 2004; Tanțău et al., 2011a), in Buzău Subcarpathians (Tanțău et al., 2009) and Southern Transylvania-Făgăraș Depression (Tanțău et al., 2006, 2011b).

3 ka cal. BP to Present. In the Northern Carpathians the last 3000 cal. yr BP was characterized by warm winters (0-1 °C mean temperature of the coldest month) and elevated annual temperatures (7-8 °C), while precipitation decreased by about 100 mm (Mîndrescu et.al., 2017).



Figure 3. Pictures of study sites, upper left corner (Iezerul Sadovei, Molhoșul Mare, Poiana Știol), upper right corner (Tăul dintre Brazi, Lia, Oltina, Gales), bottom left corner (Bucura, Știucii, Tăul Muced, Tăul Negru)

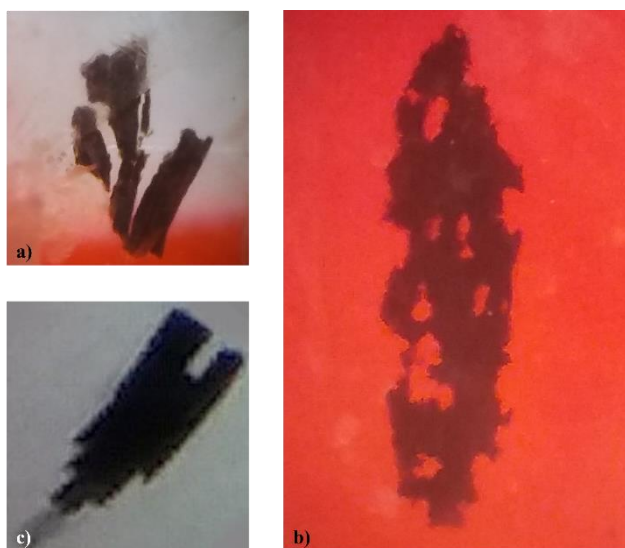


Figure 4. Photographs of representative charcoal morphotypes under a stereomicroscope: a) wood; b) grass (Poaceae) and c) conifer needles

Figure 4 shows the different categories of sedimentary charcoal pieces found in studies. Macroscopic charcoal present in sedimentary records can be classified into these categories. Charcoal morphology can reflect fuel sources with varying degrees of certainty (Scott et al., 2000). As a result, charcoal morphological data can be used to indicate past vegetation assemblages (Mustaphi & Pisaric, 2014) and investigate the different contributions of vegetation types to biomass burning.

Bibliometric analysis on keywords using VOSviewer

The study provides an analysis of recently published literature on paleolimnological studies of wildfires related to ongoing climate change carried out in Romania. The analysis considers papers published from 2004 to 2022 in Web of Science or Scopus (Figure 5).

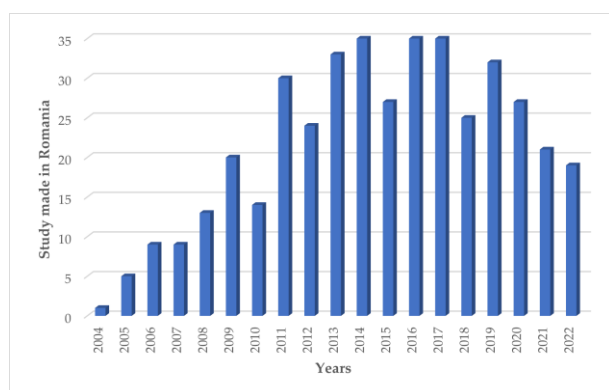


Figure 5. Distribution of review sources from 2004 to 2022 covering studies on paleofires, environmental and climate change carried out in Romania

The study identifies the keywords involved in the selection of the materials, which are necessary for an

understanding of the importance of peatbog fire in climate change and how the change of landscape can be influenced by anthropogenic activities. The study also uses bibliographic data and abstracts from Web of Science and Scopus to construct the map based on the data text. The application creates classes of terms, allowing us to preview the selected items, highlighting the links and where they appear in the database.

Climatic and palaeoenvironmental data

The analysis of sediment records from lakes and peatbogs in Romania suggests that the climate during the late Holocene was predominantly affected by natural factors. However, during the late Holocene, it was impacted by a combination of natural and anthropogenic factors. The deforestation of the Romanian Carpathians took place much later than the rest of Europe during the Holocene, resulting in a different pattern of biomass burning in the lowlands compared to the highlands. In Figure 6, the authors who have studied fire regimes in Romania from 2004 to 2022 are highlighted. The figure focuses on identifying climate changes and their impact on the fire regime over time, as well as reconstructing paleofire history. It shows the most relevant contributors in this field, including Feurdean, Tanțău, Fărcaș, Hutchinson, Peters, Magyari, Mîndrescu, Florescu, and Haliuc. The density of the figure is related to the occurrence. The authors' work on climate change and vegetation fires has evolved in terms of research methods over the period in question.

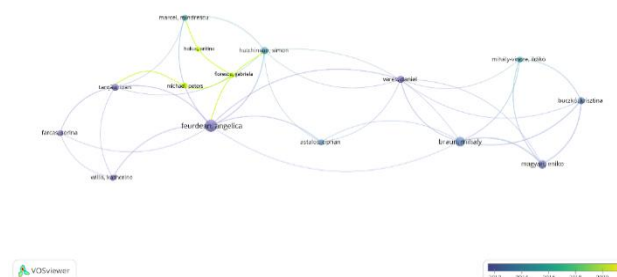


Figure 6. Network visualization map of the main authors who studied wildfires in Romania, showing the evolution from 2004 to 2022

Spatial distribution of wildfires studied in Romania

According to VOSviewer software, the spatial distribution of wildfires studied in Romania is represented by purple dots, which are correlated between articles on the main topic of reconstructing wildfire in the context of climate change using charcoal as the main proxy. Figure 7 illustrates that in 2006, there was a focus on studies related to climate change in Romania, specifically in the Carpathians. The maximum green color in 2014 is followed by a slight decrease in the number of studies, which can be attributed to the studies carried out earlier. Figs. 5 and 7 show that the maximum color, followed by a sharp

decrease in the number of studies, can be observed in the years 2016-2017 and 2019. It seems that the highlighted studies were conducted in Romania, focusing on the Holocene period and forest areas marked with yellow dots. Other relevant topics include climatic change, core and lake sediment analysis, fire activity, macro-charcoal and charcoal particle analysis, land clearance, and studies conducted in the southern Carpathian Mountains, with Lia and Bucura sites, (Finsinger et al. 2018; Pál et al. 2018; Orbán et al. 2018; Buczkó et al. 2013; Magyari et al. 2018; Hubay et al. 2018). In the map with green dots, the smallest items represent the sites in northwest Romania from the Transylvania Basin where studies have been

carried out on paleofire regime reconstruction in the Turbuța and Știucii sites (Feurdean et al. 2007, 2015), in Apuseni National Park, studies have been conducted on the following sites: Padiș Sondori (Feurdean et al. 2008, 2009), Pietrele Onachii and Molhașul Mare sites (Feurdean et al. 2004, 2008), Gutâi Mts., with Preluca Țiganului site (Feurdean et al. 2004, 2005a, b, 2007a, b, 2008), Rodna Mts., with Poiana Știol and Tăul Muced sites (Fărcaș et al. 2004; Tanțău et al. 2006; 2011, Feurdean et al. 2015, 2017), and Lăpuș Mountain with Tăul Negru site (Peters et al. 2018). Blue dots indicate reconstruction and environmental change. Human settlements have impacted the landscape and environment in these areas.

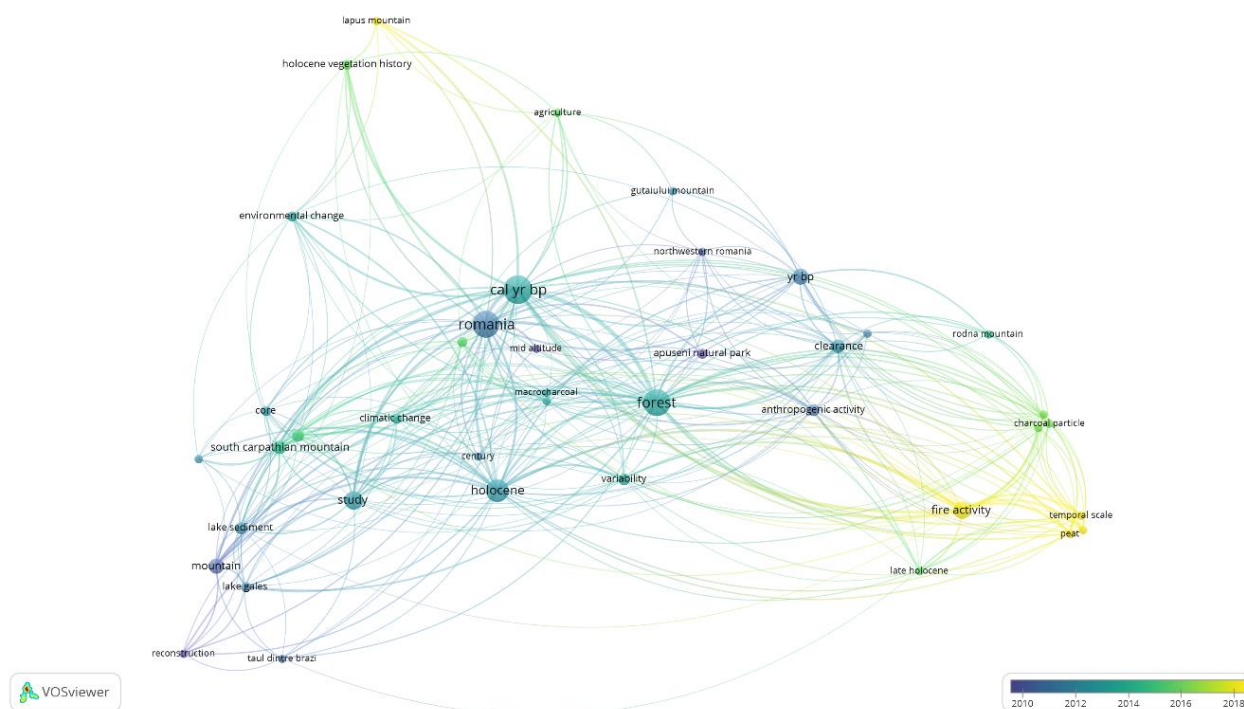


Figure 2. Bibliometric visualization map of studies carried out in Romania from 2004 to 2022

Discussion

In Romania, climate variability has varied by region in the late Holocene. Climate change has led to an increase in extreme weather conditions such as prolonged droughts and wildfires (Beniston et al. 2007, Begović et al. 2020, Vacek et al. 2023). Studies suggest that droughts will become more intense and frequent in central and southern Romania in the foreseeable future. This will affect lakes and peatbogs, which will be more vulnerable to lengthy droughts and frequent wildfires (Vacek et al. 2023). Human activities such as deforestation and mining, as well as landscape changes, will contribute to the occurrence of wildfires. Research conducted over the last two decades should inform the development of sustainable landscape management and environmental protection policies based on scientific evidence.

Studies in low-altitude areas (steppe, forest-steppe)

Feurdean et al. (2021) conducted a study on Lake Oltina, located on the Danube floodplain. The results showed that the lake was formed between 6000 and 2500 cal. yr BP, during a period when there was a vast canopy of xerothermic (*C. orientalis* and *Quercus*) and temperate (*Carpinus betulus*, *Tilia*) tree taxa. Over time, due to agricultural activities, the tree cover started to decline, while the climate remained humid. At around 2500 cal. yr BP, there was an increase in biomass burning, which suggests that fire was used as a management tool. Over the last millennium, there has been a significant decline in the amount of wooded areas. The landscape openness at Lake Știucii (239 m a.s.l.) during the late Holocene was estimated to be about 20% higher than the actual data.

The open coniferous forest was reduced during the late Holocene, likely indicating a transition. This was due to a higher cover of *Poaceae* and *Picea* and lower values for *Pinus* and *Artemisia*. The Bronze Age was characterized by human activities, including extensive forest clearance after 3700 cal. yr BP, indicating that the Transylvanian Plain was more wooded in the past. However, the forests were never completely closed due to dry growing season conditions, recurrent fires, and anthropogenic impacts that favoured the persistence of grasslands throughout the late Holocene, according to Feurdean et al. 2015. At Turbuța palaeolake in the Transylvanian Basin, the presence of *Pinus* and *Betula* open woodlands with small populations of *Picea*, *Ulmus*, and *Alnus* is indicated before 12000 cal. yr BP. The vegetation dynamics at Turbuța, along with other sites in Romania, suggest a response of the vegetation to regional climatic changes, which indicate that the forests in the lowlands of Turbuța were never closed, as reported by Feurdean et al. 2007b.

Studies in mid-altitude areas (deciduous forest, mixed forest)

At paleolake, Preluca Țiganului (730 m a.s.l.) from Gutâi Mts., the current vegetation types in the area include *Picea* and *Pinus*, and the climate has been relatively stable. Small climate oscillations are recorded at mid-altitude sites because these areas are close to the tree-line ecotone. The development of vegetation shows different responses and amplitudes of response to climatic changes, with local factors determined by the altitude and topography of the study site, as described in Feurdean et al. (2007a). According to Florescu et al. (2017), the data collected from lake Iezerul Sadovei provides the first evidence of environmental changes that have taken place in the mountainous region of Southern Bucovina in the past ~ 950 years. The environmental degradation in this area and its surroundings is primarily caused by human activities such as deforestation. However, it is also influenced by climate-related hydrological conditions such as flooding and the evolution of slope processes. At the Tăul Negru peatbog, there has been a continuous increase in indicators of human activity, such as the presence of *Plantago lanceolata* and *Chenopodiaceae*, and an increase in the abundance of *Poaceae*, *Rumex*, and *Urticaceae* (Peters et al. 2019). The increase in charcoal content is particularly significant in this area, indicating further opening of forests and increasing forest exploitation (charcoal burning) and grazing pressure. The first signs of anthropogenic activity were detected around 6000 cal. yr BP. This pressure was observed in the development of a cultural landscape, which progressed during the Middle Ages and became even more pronounced in modern times. Local disturbances increased during periods of mining activity. It is possible that people used fire to clear forests and open access to mining sites or pastures (Petraș et al. 2021).

Feurdean et al. (2008) conducted a study in the Apuseni National Park, NW Romania, to reconstruct the long-term dynamics of *A. alba*. Three sites – Molhașul Mare, Pietrele Onachii, and Padiș Sondori – were selected for this purpose. The study found that the concentrations of micro-charcoal recorded in Molhașul Mare and Padiș Sondori were highest between 6000 and 4200 cal. yr BP, followed by a decrease and overall low values between 4200 and 500 cal. yr BP. Subsequently, the levels steadily increased again during the last 300-500 years. The study reveals that *A. alba* has existed in Romania since at least 5700 cal. yr BP. These stands grew in mixed formations until approximately 300 years ago when they were reduced to their present state.

Studies in high altitude areas (coniferous forests, the ecotone at the upper limit of the forest, subalpine and alpine areas)

Gałka et al. (2016) and Diaconu et al. (2017) have reported that Tăul Muced is an ombrotrophic raised bog located in the Eastern Carpathians in Rodna National Park at an altitude of 1.360 m a.s.l. The bog covers an area of approximately 2 hectares, of which about 0.5 hectares has been designated as a scientific reserve under the IUCN category. The bog's surface is mostly covered by spruce trees with small patches of dwarf pine (*Pinus mugo*) scattered around. The dominant species in the moss communities are *Sphagnum russowii* and *S. magellanicum*, along with *Vaccinium microcarpum*, *Carex pauciflora*, *Vaccinium myrtillus*, *Drosera rotundifolia*, *Listera cordata*, and *Polytrichum strictum* (Diaconu et al. 2017; Feurdean et al. 2015). The pollen sequence indicates that *Sphagnum magellanicum* was the most prominent species in the formation of peat for around 8000 years. However, it also reveals ten stages where *Eriophorum vaginatum* had a higher representation at the following times: 8100, 7550, 6850, 6650, 5900, 4650, 3150, 1950, 1450, 750 cal. yr BP. The cyclical analysis of *Sphagnum magellanicum* and *Eriophorum vaginatum* at Tăul Muced suggests that this could be due to regional changes in climatic conditions or the result of autogenic succession (Gałka et al. 2016). Between 4300 and 3300 years ago, there was low fire activity and *Sphagnum macrofossils* were dominant (Gałka et al. 2016). From 2750 to 1300 years ago, the peatland surface conditions were dry, and the air temperature reconstructions suggest relatively warm summers of approximately 14 °C. Charcoal supports the dry conditions with six centennial-scale temperature changes over the last 6550 years. The summers were relatively cold during the periods 6550-5600, 4500-3150, and 1550-600 years ago. However, warm air temperatures were experienced from 5600-4500, 3150-1550, and 100 years ago to the present (Diaconu et al. 2017). Lake Brazi (Tăul dintre Brazi) is situated on the northern slope of the Retezat Mountains at an altitude of 1.740 m a.s.l in the Galeș valley. On the

other hand, Lake Lia is situated at 1.910 m a.s.l on the southern slope. It is noteworthy that the number of fires on the northern slope was relatively lower compared to the southern slope. In the past, the forests on the northern slope around Lake Brazi were mainly dominated by *Picea abies* and they persisted for a long time. During this time, the intervals between fires were comparatively longer, ranging from 1000 to 4000 years. On the other hand, the forests on the southern slope around Lake Lia had a higher abundance of *Pinus mugo* and their fire-return intervals were significantly shorter, ranging from 80 to 1650 years. Forest clearance through burning to increase pasture was moderate compared to the rest of the region. The frequency of fires differed in various areas due to the different microclimates of the northern and southern slopes, and the location of sites above the tree line ecotone. During the last ~ 2000 cal. yr BP, anthropogenic vegetation changes increased, particularly on the southern slope, and were associated with a moderate rise in biomass burning until ~ 1300 cal. yr BP (Finsinger et al., 2016).

It has been suggested by a palaeolimnological investigation that the glacial lakes of the Southern Carpathians – Lia, Bucura, and Galeș – had oligotrophic and oxygenated waters from the late Holocene to the present. This could indicate that forest clearance through burning to reduce pasture was carried out moderately, according to Buczkó et al. 2013. According to Tanțău et al. (2011), the area was covered by dense woodlands containing various tree species such as *Betula*, *Pinus*, *Picea abies*, and *Alnus*. During this period, *Picea abies* was the dominant species. The peat sequence from Poiana Știol provides a detailed account of the forest dynamics and climate history of the Holocene period. The study suggests that human impact on the area became evident approximately 3200 years ago and was mainly due to deforestation and forest grazing (Tanțău et al. 2011).

Conclusions

Paleoenvironmental studies around the world are increasingly focusing on the long-term dynamics of fire, vegetation, and climate. These studies analyze macro-charcoal to better understand the relationship between vegetation fires, anthropogenic impact, and climate changes during the Holocene. The sediment record-based environmental reconstructions highlight the spatial and temporal manifestation of vegetation fires, which is especially relevant given the current global climate change and catastrophic events. Our study is a focused literature review that examines published literature on paleofire reconstruction in lakes and peatbogs in relation to climate variability, both past and present. The impact of global climate change is a significant challenge for Romania. It is important to take timely and appropriate measures to reduce its impact and to adapt ecosystems to the projected changes in environmental conditions. To

minimize the ongoing susceptibility of forests, it is necessary to establish and change the species composition of trees in the stand and select suitable tree species that are resistant to adverse abiotic factors such as drought and wildfire. It is crucial to conduct further research to enhance the connection between scientific research and action while developing adaptive responses that are specific to the context of climate change and disturbance regimes. The risk of wildfires is anticipated to increase in the coming years, even in areas that were previously unaffected, like the high and mid-altitude mountain ranges of the Carpathians, leading to expensive economic and environmental consequences.

Code availability

The VOSviewer source code is accessible at <https://www.vosviewer.com/>.

Access requests can be made by contacting Nees Jan van Eck (<http://www.neesjanvaneck.nl/>). For this study, we used the model at version 1.6.19.

Author contribution

Conceptualization, A.P., and M.M.; methodology, A.P.; formal analysis, D.I.; investigation, A.F.; writing—original draft preparation, A.P.; writing—review and editing, A.P., D.I., A.F., M.M. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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