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# RECONSTRUCTION OF CLIMATE DYNAMICS, VEGETATION HISTORY AND HUMAN IMPACT IN NORTHERN ROMANIA DURING THE HOLOCENE

**PhD Thesis Summary**

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**Keywords:** palynology, charcoal, testate amoebae, forest dynamics, climate oscillations, palaeoecology, palaeoclimate, pollen, macroremains, magnetic properties, organic content, geochemical analysis, treeline, timberline, human impact, Holocene.

**INTRODUCTION**

All over the world there is now concern about the climate changes (IPCC, 2014). To understand the current and future global climate changes it is important to look back, at past changes, their driving forces and their consequences on past ecosystems.

The best way to gain insight into the composition shifts of the current vegetation and its relationship with the environment and also with human societies is to look at historical patterns through palaeoecological records (Tanţău 2006, Tanţău et al., 2003, 2010, 2011a,b, 2014; Feurdean et al., 2010; 2013b).

Vegetation reconstructions are an important research tool for the more recent geological times. Climate parameters cannot be directly measured in sedimentary deposits and thus the need for a more direct recording of the response to climate change, or a climate proxy.

For Holocene sequences, there is a large pool of climate proxies that are relatively easy to constrain, because the species composition have not vary much in the last 2 million years. These proxies include $\delta^{18}$ O - a proxy for ice volume, eolian dust - a proxy for aridity and wind intensity, and pollen and spores – a proxy for paleoecology, paleotemperature, and paleoprecipitation (Gornitz, 2009).

The main method used for this study is **Palynology**- the study of fossil pollen. Pollen and spores are very resistant to decay and can be found in almost all kinds of sediments, which allows for the reconstruction of more or less complete sequences of palaeoclimate changes (Maslin, 2009).

Yet palaeoecological studies on vegetation based only on fossil pollen are not enough; these need to be combined with other proxies (plant macrofossils, stomata, charcoalized plant remains, tree rings, magnetic properties, geochemistry etc.) to create a more complete picture of past changes and their scale, of the drivers and consequences of vegetation changes. The use of multiple, often complementary proxies is a way of increasing the reliability of paleoclimate reconstructions (Gornitz, 2009). This kind of multiproxy approach can provide more detailed informations on climatic oscillations, on the sensitivity of different ecosystems, on changes in the treeline and timberline location and composition but also on the human impact on vegetation.

Beside climate changes, human activities are also influencing the natural environments with increased impact towards the present days. Humans are impacting directly and indirectly the environment through agriculture, forest cutting, and technology. Feurdean et al. (2013b) showed that anthropogenic indicators became widespread in Romania due to land-use changes (animal husbandry, mowing, agricultural farming, burning activity, forest clearance), especially in the late Holocene.

Fire too is an important element in the evolution of vegetation through time. It acts as a distress factor and therefore it is important to understand the extent of its impact on the ecosystems, be it natural or human-induced fires. In many sites the vegetation changes were associated with peaks in charcoal, indicating the use of fire to increase the grazing area (Feurdean et al. 2013a, Haliuc et al. 2016).

High altitude environments are amongst the most sensitive to climate and land use changes. In Romania, the history of vegetation is relatively well-known due to the fossil pollen analyzes performed since the beginning of the 20-th century by a number of researchers, and starting with 1999 the Romanian Palynology has benefitted from the $^{14}C$ absolute ages to support its findings.

The temporal and spatial pattern of the reconstructed history of tree taxa is rather homogenous over the country during the Late Glacial Maximum and the postglacial period. The chronological differences and the variation in the pollen spectra are due to altitude and the different geographical settings of the studied sites (Tanţău, 2006).

Still, new and well dated sequences from other regions and elevations of the Carpathians are needed to better understand the vegetation dynamics and its drivers of change.

The **SPECIFIC AIM** of this thesis is **evaluating the impact of climate, fire and human interferences on vegetation dynamics, with focus on the treeline and timberline, as well as on the anthropogenic disturbance on these landscapes during the Holocene.**

This thesis' **contribution** to palaeoenvironmental research in Romania stems from:

**1) its highly relevant research subject in environmental studies i.e., documenting the sensitivity of high mountain vegetation to various drivers of changes and**

**2) the methological approach i.e., multi-proxy investigation aiming to disentangle the relative contribution of these various drivers of change.**

## STUDY AREA AND REGIONAL SETTING

Rodna Mountains, located in the north of Romania, belong to the Northern group of the Eastern Romanian Carpathians and are the highest mountains of the range, dominating the neighboring depressions in the historic regions of Maramures and Bucovina with Pietrosul Peak, 2303 m; Inău Peak, 2279 m, Buhăiescu Mare Peak– 2257 m (Coldea, 1990). They are mostly metamorphic in terms of geology, sitting in a larger crystalline-Mesozoic area and stretching over an area of more than 1000 km² (Balintoni, 2005) (Fig. 1).

**Fig. 1.** Location of Rodna Mountains on the physical map of Romania (source: Google Maps).

The geology of this region comprises metamorphic rocks belonging to the Bretila, Rebra and Repedea groups. The Rebra Group is represented mainly by the Rodna Nappe (with gneisses, schists, amphibolites, dolomites, crystalline limestones, quartzites after Mutihac, 2004) to which Kräutner and Bindea (2002) assigned a Precambrian age. The studied area has an epimetamorphic (sericite-chlorite) schist and mica schist base, yet patches of flysch-like deposits are present in Rotunda and Prislop Passes.

Through their location, Rodna Mountains are at the contact between two major areas of influence, baltic and oceanic. These influences are added to a moderate temperate - continental climate. Data from the nearest meteorological station, Iezer (1785 m), show that the area presently has a subalpine climate, characterized by low mean annual temperatures (1,3ºC at the station's altitude, decreasing to –1,5ºC towards the summit and increasing to 6ºC the lower areas with permanent spruce forest) and abundant precipitation (~1200 mm/y), mostly in the form of snow. The orientation of the main ridge from East to West and the 1600 m elevation differences make the climate slightly different between North and South slopes, in terms of temperature and precipitations (MPRMNP, 2013).

Romania sits today at a crossroad between the subcontinental, mediterranean şi steppic vegetation regions, having a transition role in the structure of vegetation in South-East Europe. Coldea analyzed in 1990 the Rodna range flora and marked a prevalence of Eurasian elements (36,7%), with insertions in different phytohistorical stages of circumpolar (12,7%/), central-european (8,1%), mediterranean (4,6%) and continental elements (1,4%).

In terms of vegetation developed on altitude, four belts can be distinguished in Romania (Coldea and Cristea, 1998; Cristea, 1993; Feurdean et al., 2007b; Geantă et al., 2014; Toader and Dumitru, 2005):

1. The foothill woodland belt (300–600 m), composed predominantly of deciduous oak species (mainly *Quercus petraea*), *Tilia cordata, Corylus avellana, Carpinus betulus* and *Fagus sylvatica*;
2. The montane belt (600–1800 m), which is subdivided into three sub-belts:
   - 2.1. The lower montane sub-belt with *Fagus sylvatica* (600–800 m);
   - 2.2. The middle montane sub-belt with *Fagus sylvatica, Picea abies* and *Abies alba* (between 800 and 1200 m);
   - 2.3. The upper montane sub-belt: *Picea abies* (dominant) with *Pinus sylvestris*, *Pinus cembra* and *Larix decidua* (1200 to 1800 m).
3. The subalpine belt (1800–2000 m) which is dominated by a mix of *Pinus mugo, Juniperus communis* and *Rhododendron kotschyi*;
4. The alpine belt (above 2000 m) characterised by communities of dwarf shrubs and herbs.

All studied sites are located in the subalpine zone, between 1673 m and 1918 m, within the confines of Rodna Mountains National Park.

A) **Buhăiescu Mare Lake** (also known as Rebra Lake or Buhăiescu IV (Pişota, 1968) is located on the north-eastern slope of Buhăiescu Mare at 1918 m (Fig. 8). It is a remnant glacial lake with a surface of 0.9 ha, maximum depth of 0.5 m and a catchment area of about 15.75 ha (Mindrescu et al., 2006). Buhăiescu Mare Lake is fed by surface inflows as well as precipitations and inwash from the surrounding slopes and it is drained by a single outlet. The lake is situated just above the current treeline, and the vegetation in the catchment comprises *Carex*, Ericaceae, *Juniperus* patches and scattered *Pinus mugo*. Currently, there is a sheepherders' hut in the close vicinity of the lake (established in the last few years) and a road for all-terrain vehicles leading to it, serving the shepherds and park rangers.

B) The second studied site is a peatbog named **Gărgălău** after the neighboring peak and saddle, and is located in a glacial cirque under the Gărgălău Saddle (1810 m altitude). It is fed and traversed by a left tributary of the Bistriţa Aurie Stream and has an area of 4 ha (Fig. 9). The specific subalpine vegetation for this altitude is characterized by the "*Rhododendro myrstifolii–Pinetum mugi*" plant community (Coldea, 1990). The main vegetal taxa present around the site are *Pinus mugo, Juniperus communis* ssp. *nana, Rhododendron myrstifolii, Rhododendron kotschyi*, *Vaccinium myrtillus, V. vitis-idaea, Empetrum nigrum,* and *Carex* sp.

Isolated solitary trees can be found up to 1800 m in this valley.

C) The third site is **Știol Lake** (also known as Izvorul Bistriței Aurii Lake, meaning the source of the Bistrița Aurie stream) is another one of the glacial lakes located in Rodna Mountains (Fig. 10). Although relatively small, it is situated in one of the largest glacial cirques in Romania, the Bistricioara Mare Cirque. It was dammed in 2002 and thus the lake surface and catchment area were enlarged (Mîndrescu et al. 2010).

Being located at a relatively low altitude for a glacial lake, it is close to a number of tourist paths that connect the attractions in the area (e.g. the Horses' Waterfall, the Borşa Ski Resort, Gărgălău Peak). The lake was formed behind a rock bar and moraine dam deposited during the Würm glacial (LGM - Last Glacial Maximum) at an altitude of 1670 m. It is 1 ha in area and has an average depth of 2 m. It sits in the subalpine vegetation belt, at the treeline ecotone and is surrounded by Ericaceae, *Carex*, *Pinus mugo,* and rare *Picea abies* individuals*.*

## METHODOLOGY

The recent tendency in palaeoenvironmental studies is to combine pollen analysis with plant macrofossil analysis for a higher taxonomical resolution of past vegetation and climate changes (Birks and Birks 2000; Feurdean 2004).

A scientific study in Palynology implies complex activities first in the field, and even more so in the laboratories. To reach the final results of a pollen analysis, there is a succession of steps that need to be pursued: prospecting the field and identifying the most suited coring site, extraction of sediment samples, subsampling of the cores in the laboratory, chemical treatment of the subsamples in the laboratory, microscopic study (counting and identifying pollen grains and other chosen palynomorphs), plotting the pollen diagrams, statistical analysis and interpreting the results.

### Field sampling

The cores were collected with a gravity corer for the upper unconsolidated part of the sediments and with a Russian corer (1 m length, 7 cm diameter) for the deeper sediments (Fig. 11). Multiple cores were taken in order to obtain enough material for all biotic and abiotic analyses.

The gravity cores were subsampled on site at 0.5-1 cm intervals and placed in sealed plastic bags. The Russian cores were described, wrapped in plastic film and then transported at the Department of Geology at Babes-Bolyai University, Cluj-Napoca.

**Subsampling in the laboratory**

In the laboratory the cores were carefully cleaned to avoid contamination and described in detail from a lithostratigraphical point of view (sediment type, consistency, and color). They were correlated in the case of multiple cores, evaluated for any possible lack of stratigraphic continuity, and then sub-sampled at different intervals for biotic and abiotic analyses, depending on the desired resolution. Subsamples were placed in sealable plastic bags or recipients.

**Biotic analyses**

**1. Pollen, spores and microcharcoal**

The study of fossil pollen (**Palynology**) aims to reconstruct past changes in vegetation composition and diversity at local to regional scales.

For Buhăiescu Mare, samples of 1 $cm^3$ were taken at an interval of about 2 cm, and for Gărgălău and Știol at intervals of 2-5 cm.

The samples were then chemically treated, mounted in glycerine and used for pollen, spores, coprophilous fungi, stomata and microcharcoal analysis under a light microscope. Lycopodium tablets containing a known number of spores were added to the samples prior to their chemical treatment to estimate microcharcoal concentrations (with the exception of the Gărgălău site). Non-pollen palynomorphs (mainly coprophilous fungi) were also determined for the two lake sequences and used as an indicator for the presence of herbivorous animals in the area (Cugny et al., 2010). Microscopic charcoal particles (10–150 µm) were counted on the pollen slides, then used to reconstruct regional fire history (Whitlock and Larsen, 2001). The frequencies of all taxa were calculated as percentages of the terrestrial sum (composed of arboreal and non-arboreal pollen and spores) and plotted using the Tilia software (Grimm, 1991, 2004). Conifer stomata were identified with the key of Sweeney (2004), and appear in the arboreal pollen diagrams.

**Charcoal**

The study of charred plant remains in Quaternary sedimentary sequences (mainly lakes) is used to gain an insight on the fire history in the proximity of the site, and the relationships between vegetation fires on one side, and climate and human influences on the other side.

There are two approaches in studying charcoal: the study of macroscopic particles (or macrocharcoal – larger than 150 micrometers) and the study of miscroscopic particles (or microcharcoal, between 10-150 micrometers) (Carcaillet et al., 2001; Whitlock and Larsen, 2001). The macrocharcoal study gives information about local fires, usually 1-2 km around the site. The microcharcoal study gives information about the history of fires at a regional level, since the smaller size makes it easier for them to be transported by wind and/or water.

**Plant macrofossils**

The identification of plant macrofossils (seeds, leaves, etc.) can validate the presence of a specific taxon near the site, allowing for the identification of plants at the species level thus adding more accuracy to the reconstruction of vegetation patterns through time (Birks, 2001).

At Gărgălău, plant macrofossils were analyzed at 1 cm intervals in samples of approximately 20 $cm^3$. At Buhăiescu Mare and Știol, samples were analyzed at 2 cm intervals in contiguous samples of approximately 15-20 $cm^3$. The samples were washed and sieved under a warm water current over a 0.20-mm mesh screen, then analysed with the use of a stereomicroscope. For plant macrofossils zonation I used the local pollen assemblage zones (LPAZ).

**Abiotic analyses**

**Chronology**

Information from palaeontological proxies is of limited value until an absolute chronology can be established. Radiometric dating techniques are based on a comparison between the abundance of a naturally occurring radioactive isotope and its isotopes, using the accepted decay rates. The most common method is $^{14}C$ dating of macrofossils or of organic-rich layers (using AMS, accelerator mass spectrometry). Additional methods include $^{210}Pb$, $^{137}Cs$ and the identification of volcanic ash layers of known age.

To determine the age of the sediment samples, radiocarbon measurements were performed on plant macrofossil material and bulk peat using the AMS facilities at Chrono Center in Queen’s University, Belfast, UK. For lakes Buhăiescu Mare and Știol, additional dating of the top sediment via measurements of $^{210}$Pb and $^{137}$Cs radioisotope concentrations was performed at the Laboratory for Gamma Spectrometry, Faculty of Environmental Science, Babes-Bolyai University Cluj-Napoca, Romania, using an ORTEC DigiDart spectrometer with a HpGE detector, Gamma-X (GMX) type (Hutchinson et al., 2015).

Sediment accumulation rate (SAR) was also calculated based on the age-depth model, as it is an important parameter for the characterization of catchment area and lake processes.

**Loss on ignition**

Loss on ignition (LOI) is a widely used method of determining the organic and carbonates content of sediments and usually implies two phases.

After drying the sediments first overnight at 105 °C in a 8.2 l Snol oven, organic matter was oxidized (combusted) for 5 hours at 550 °C to carbon dioxide and ash to measure the organic content. In a second reaction, samples were combusted for 2 more hours at 950 °C. This second phase shows the carbonate content of the sediments, only the oxides remaining. The percentage loss of the dry weight of samples during the reactions was calculated by weighing the samples before and after heating (Heiri et al., 2001).

Loss on ignition (LOI) was measured on the same samples on which we performed mineral magnetic analyses. LOI was also used as a tool for correlating different, partially overlapping sediment cores.

**Magnetic properties**

The magnetic properties of the sediments are given by the presence of ferrous mineral particles and can characterize the sediment in relationship with climate and erosion. Magnetic susceptibility measurements became part of paleoclimate studies since 1970. Scientists use this method to highlight processes such as erosion, sedimentation, modifications induced by fires and land use changes, and climate variations in time. It is a simple, quick and non-destructive method, besides having the advantage to be available on a wide range of materials, from lake sediments to loess deposits.

The magnetic measurements were performed in two phases. First, a continuous measurement of volume magnetic susceptibility (κ) was done with a Bartington MS2 device using a C sensor in order to facilitate core correlation. Saturated Isothermal Remanent Magnetisation (SIRM) was then selected to assess the input of minerogenic material and to reflect episodes of erosion associated with climate changes, land clearance, grazing and fire. The sequences were continuously sub-sampled (2 $cm^3$) and dried over night at 40 ºC prior to mineral magnetic analyses. Magnetic susceptibility was measured in a low magnetic field of

0.1 mT using a balanced alternating current bridge circuit. Mass specific units were calculated and expressed as $(\mu m)^3\ kg^{-1}$. SIRM was induced in a strong magnetic field of 1 Tesla by a Redcliff BSM 700 Puls Magnetic Charger. The resulting remanent magnetization was measured with a Molspin Spinner Magnetometer. Mass specific units were calculated as $mAm^2\ kg^{-1}$ (Akinyemi, 2003).

### Geochemistry

Sedimentary sequences in lakes and oligotrophic peatbogs are strongly influenced by physical modifications in their catchment area.

The geochemical characterization of the sediments requires chemical analysis of geological samples. Since it is not possible to directly measure past climates and environments, geochemical proxies are employed as indirect measures of the main processes. When studying paleovegetation, these proxies may reveal details about paleotemperature, vegetation history, nutrient cycles and availability. Simultaneous use of multiple geochemical proxies helps compensate for the effects of diagenetic alteration and enhances their interpretation for a more complete paleoenvironmental reconstruction (Gornitz, 2009).

Geochemical analyses were made for the Buhăiescu Mare site using a Niton XL3t 900 XRF analyzer.

### Particle size analysis

Particle size analysis (PSA) or granulometric analysis is used for over a century to obtain information about depositional settings, ways of transporting the sediment and the distance the particles travel. Variations of the size of the particles can also be caused by changes in the catchment. Due to the many possible interpretations of this parameter, it is important to use it in an interdisciplinary context.

PSA was undertaken using a Horiba Laser Particle Size Analyser (Partica LA-950). Median size was employed as a key characteristic of the particle size distribution and was used to reflect erosion inputs to the profile.

### Numerical analysis

To facilitate the interpretation of the pollen diagrams, Local Pollen Assemblage Zones (LPAZ) were established (Birks, 1986). The LPAZ were statistically defined using optimal splitting based on an information content technique for Buhăiescu Mare site (Bennett, 2007) and Coniss software, a stratigraphically-constrained cluster analysis for numerical zonation included in the Tilia software, for Gărgălău and Lake Știol (Grimm, 1987), to pinpoint significant changes in the vegetation composition.

Palynological richness for Buhăiescu Mare site was calculated using rarefaction analysis (Birks and Line, 1992) in order to determine changes in landscape diversity through time. The lowest pollen count (T337) was used to standardise the size of the pollen counts (Geantă et al., 2014).

Principal Components Analysis (PCA) was carried out on the covariance matrix of the square root pollen percentage of selected taxa with Canoco software v. 4.5 (Geantă et al., 2014).

## RESULTS

### BUHĂIESCU MARE LAKE

Five cores were extracted in a number of field trips and then correlated. The core correlation was made using information derived from mineral magnetic properties, visible changes in lithology, changes in organic carbon content and the pollen data, and a composite sedimentary record with a total depth of 125 cm was created.

Eight radiocarbon ages together with 210Pb and 137Cs radioisotopes ages indicate that the top 81 cm of the composite profile covers approximately the last 4000 years (Figure 15). Between 81 and 82 cm there is an extended hiatus, identified also on the basis of a sharp lithological transition and in the pollen record. Based on all the data, the lower part of the profile (82–125 cm) belongs to the early Holocene.

**Pollen, spores, stomata**

**LPAZ BM 1 (125–82 cm; 11 000–9800 cal. yrs BP)**

The pollen assemblage during this time was dominated by montane trees and subalpine shrubs (Fig. 18). The abundant occurrence of *Pinus diploxylon* pollen (*Pinus sylvestris/Pinus mugo*; 60–70%) and *Pinus haploxylon* (5%; *Pinus cembra*, 2%) throughout this period, together with the occurrence of a *Pinus* stomata at 96 cm (ca. 10 200 cal yrs BP), indicate the presence in the region of dense forests dominated by *Pinus*. *Picea abies* pollen percentages were almost absent in the beginning of the record, yet they rapidly increased to 10% around 10 900 cal yrs BP up to 40% at 9800 cal yrs BP (Fig. 18). Pollen of subalpine shrubs such as *Alnus viridis* was present with 2% at the beginning of the record, then increased to 5% at the end of this zone, while other shrubs, like *Ericaceae, Juniperus* and *Salix*, did not exceed 2% (Fig. 18).

Other montane tree pollen types present with lower values during this period were *Larix decidua* and *Betula*, whereas submontane and lowland tree pollen types included *Ulmus, Tilia, Fraxinus, Carpinus betulus* and *Corylus avellana*. The occurrence of pollen grains of *Fagus sylvatica* and *Carpinus betulus* in this zone is likely because of sediment that has been reworked from the upper parts of the profile.

Herbaceous pollen taxa were mainly represented by *Artemisia* (up to 5%), Poaceae (<5%), Ranunculaceae, Scrophulariaceae and Chenopodiaceae (<3%; Fig. 19).

Fungal spores are present mainly through *Sordaria* and *Delitschia* but with low values, probably due to the presence of wild herbivores in the area.

**LPAZ BM 2 (82–12 cm; 4 000–300 cal. yrs BP)**

Upper montane tree pollen percentages declined from about 4000 cal. yrs BP, as compared with pre-hiatus values (i.e. prior to 9800 cal. yrs BP), and there was also a marked change in the composition of the forest from the dominant *Pinus* to *Picea abies* (up to 40%) and *Abies alba* (up to 10%). The frequency of submontane and lowland tree pollen types increased, with *Fagus sylvatica* (up to 10%), *Alnus glutinosa/incana, Betula, Carpinus betulus, Corylus avellana, Quercus, Ulmus, Fraxinus* and *Acer* (below 2%). The stomata record included a single *Pinus* stomata at c. 3800 cal. yrs BP. Subalpine shrubs were represented by *Alnus viridis* (up to 8%), which probably occurred locally together with *Salix* and *Juniperus* (Fig. 18).

Herbaceous pollen percentages oscillated around 20–30% and were represented mostly by alpine herbaceous communities (Poaceae, Cyperaceae, Apiaceae, Asteroideae, Cichorioideae) and continental steppe/ruderal taxa (*Artemisia, Rumex*, Chenopodiaceae; Fig. 19).

The fungal spores' presence and diversity slightly increases as *Podospora* and *Sporormiella* are also present besides *Sordaria*.

**LPAZ BM 3 (12–0 cm; 300–0 cal. yrs BP)**

Pollen percentages of montane and submontane tree taxa declined, most notably *Picea abies*, *Abies alba, Pinus diploxylon* and *Pinus haploxylon*-types, *Fagus sylvatica* and *Corylus avellana,* a trend that might be connected to a descent of the timberline. An increase in abundance and diversity of herbaceous taxa, in particular for meadow and pasture indicators (Poaceae, Asteroideae, Cichorioideae, Apiaceae, Ranunculaceae, Scrophulariaceae, Caryophilaceae, *Plantago lanceolata*, *Rumex, Urtica* and Chenopodiaceae) is recorded during this period (Fig. 19).

The coprophilous spores *Podospora* and *Sordaria* are present with values higher than in previous zones.

**Plant macrofossils**

**LPAZ BM 1 (125–82 cm; 11 000–9800 cal. yrs BP)**

This zone features the singular occurrence of a *Picea abies* bud scale in the record. The macro-fossil assemblage also included unidentified wood remains (Fig. 20). The plant macro-remains also included alpine and subalpine meadow plants (Brassicaceae, Caryophilaceae, Poaceae, *Alchemilla* sp., *Potentilla palustris, Carex* sp.), while *Selaginella selaginoides* was the most common among the terrestrial plants. The aquatic macro-flora was composed of *Potamogeton pusilus, Batrachium* sp. and *Chara* sp. Moss types included *Sphagnum* sec. *acutifolia* and *Calliergon* sp. and could indicate the expansion of peat into the paleo-lake (Fig. 20).

**LPAZ BM 2 (82–12 cm; 4000–300 cal. yrs BP)**

The macrofossil record included an unidentified wood fragment around 2750 cal yrs BP and two *Betula* sec. *alba* fruits at 1600 and 600 cal yrs BP (Fig. 20). The next period showed a slight decrease in the abundance of alpine and subalpine herbs (mainly Poaceae and *Carex* sp.). The aquatic and hydrophilous macro-flora was composed of *Batrachium* sp. and *Typha* cf. *minima*. There was an increase in the diversity of moss types that included *Sphagnum* sp. and *Calliergon* sp., which together with the increase in the organic matter content indicates an advance of the bryophytes into the lake. This fact could have acted as a filter for the mineral particles' input (Figures 20 and 22).

**LPAZ BM 3 (12–0 cm; 300–0 cal. yrs BP)**

Plant macro-fossils were mostly herbaceous and less diverse in this zone: Orchidiaceae, *Saxifraga* and Poaceae, with some *Selaginella sellaginoides* also present (Fig. 20).

### Charcoal

The micro- and macrocharcoal records show variations throughout the profile and sometimes a divergent pattern, which could be explained by different sources of the two types of charcoal fragments, that is, microcharcoal primarily regional, whereas macrocharcoal primarily of local origin.

### Magnetic properties, loss on ignition, particle size analysis and geochemistry

The lower part of the profile (units 1 and 2, 125–82 cm; 11 000–9800 cal. yrs BP) is characterized by high values of SIRM and Ti (a lithogenic indicator, showing periods of intense erosion), a low organic content and particle size values indicating a low lake productivity and the input of minerogenic material displaced from the catchment through erosion in the early Holocene.

The SIRM and Ti concentrations become sensibly lower in unit 3, and there is a significant increase in organic content, while the median particle size values are slightly higher and intermittently variable over the past 4000 years. This trend suggests that the supply of magnetic minerals from catchment erosion is relatively insignificant during this period. In addition, the change in lithology with a higher organic matter content suggests the beginning of basin infill by organic matter and soil (Fig.22).

The fire event between 2200 and 1800 cal yr. BP was synchronous with an increase in the median PSA values, which may indicate intense biomass burning leading to topsoil erosion and particle transport. There is a correlation between the fire event around 750 cal yr. BP, and high values in median PSA.

The increase in magnetic concentrations and Ti, together with the decline in organic content and median size particles' frequency during the past 300 years could indicate either intensifying of erosion and transport of mineral particles into the lake, both related to tree cutting, or an alteration in water depth. At the very top of the profile, changes in the mineral magnetic properties may also reflect an input of atmospheric origin, possibly related also to mining activities in the area (Akinyemi et al., 2013).

**GĂRGĂLĂU PEATBOG**

The sequence (150 cm long) is made of fairly decomposed, dark brown Carex peat and is formed on top of a bluish-gray clay with angular clasts of metamorphic rocks. The top 10 cm are made by soil with roots from the living plants and decomposing dead plants.

For the Gărgălău site, seven (AMS) $^{14}C$ measurements performed at the Poznan Radiocarbon Laboratory (Poland) on bulk peat samples were used to constrain the temporal phases of the pollen record (Table 4). The age-depth model was derived based on a smoothing spline model and shows that the peat deposition started at about 11 200 cal yrs BP and was continuous, without any hiatus or important deviations from an overall uniform accumulation rate until close to present times.

**Pollen, spores and stomata**

**LPAZ Ga1 (150-120 cm; 11 260 - 9750 cal yrs BP)**

In the beginning of the early Holocene, in the Preboreal phase, *Pinus diploxylon* type pollen, comprising *P. Sylvestris* and *P. mugo*, increased from 35% to a maximum of 65%, followed by a decrease to 10% starting with the Boreal phase, around 10 000 yrs BP. *Picea abies* pollen percentages increase from 10 to a maximum of 60% around 9750 cal yrs BP (Figs.

26, 27). *Pinus haploxylon/cembra* has its maximum between 10 000 and 10 800 cal yrs BP, while *Larix* only appears sporadically, under 1% throughout the entire diagram.

Deciduous trees such as *Betula, Ulmus,* and *Corylus avellana* are present with less than 5% each. The subalpine and montane shrub taxa *Alnus viridis* and *Betula* occurred with values around 3%. *Ulmus* percentages started to increase around 10 000 yrs BP, while *Betula*, *Alnus viridis* and *Corylus avellana* also showed a slightly increasing trend.

Among herbaceous plants, percentages of Poaceae pollen varied between 5 and 12%, *Artemisia*, Asteraceae and Ranunculaceae are present with ca. 2%, while pollen of other herbaceous plants is only recorded with values under 1%. Cyperaceae pollen and monolete spores are present with values over 10% (Figs. 26, 28).

Towards 10 000 cal yrs BP, pollen percentages of Poaceae and A*rtemisia* slightly declined. Cyperaceae pollen and monolete spores decreased to their minimum values in the diagram (7% and 3%).

**LPAZ Ga2 (120-85 cm; 9750 – 6750 cal yrs BP)**

During this pollen zone, there was a decline in *Picea abies* pollen from its maximum 60 to 25%, synchronous with an increase in the percentages of *Ulmus* to its maximum value of 25% and of *Pinus diploxylon*. The *Picea abies* curve then increases again up to 40% around 9000 cal yrs BP, then varied around 30 %.

This zone was also characterized by a maximum in *Corylus avellana* type pollen (30%) around 8200 cal yrs BP. *Pinus diploxylon* pollen percentages decreased slightly to 10% then remained constant. *Alnus viridis* pollen increased to 7% (Figs. 26, 27).

Cyperaceae and monolete spores were at their maximum values around 9200 and 7300 cal yrs BP respectively, while Poaceae varied around 10%.

There was an increase during this period in the proportion and diversity of herbaceous plants including Chenopodiaceae, Ranunculaceae, Rosaceae, and Scrophulariaceae (Figs. 26, 28).

Two *Picea abies* leaf stomata were found at 101 cm (around 8400 cal yrs BP). This suggests the occasional occurrence of *Picea abies* in a vegetation that was dominated by *Pinus mugo.*

**LPAZ Ga3 (85-42 cm; 6750 – 2600 cal yrs BP)**

During Middle Holocene, *Picea abies* pollen had another peak at 40% around 5300 cal yrs BP then a slight decrease, while *Pinus diploxylon* percentages remained constant around 10%. *Alnus viridis* pollen increased to 15% with centennial-scale variations across the entire zone.

*Tilia*, *Quercus*, and *Betula* were present with values under 3%. *Carpinus betulus* curve begins in this zone, at around 6500 cal yrs BP. *Ulmus* and *Corylus avellana* pollen receeded drastically towards the end of this zone.

*Fagus sylvatica* became established around 5500 cal yrs BP and its frequency started to increase around 5300 cal yrs BP up to 15% (Figs.26, 27).

The diversity of herbaceous plant pollen increased during Middle Holocene yet most of them appear sporadically with low percentages. Herbaceous plants such as Rosaceae, Scrophulariaceae, Urticaceae and *Artemisia* were present with values over 2%, while Poaceae pollen varied up to 12%. The first occurrence of Cereales pollen is around 4500 cal yrs BP. Cyperaceae pollen repeatedly decreased from 10% down to around 3% and back (Figs. 26, 28). Two *Pinus* stomata were found at 71 cm (6000 cal yrs BP) and other two at 61 cm (4500 cal yrs BP), confirming the local presence of *Pinus mugo* (Fig. 27).

**LPAZ Ga4 (42-0 cm; 2600 –0 cal yrs BP)**

The first occurrence of *Abies alba* is recorded in the Late Hoocene, around 2350 cal yrs BP. The continuous pollen curve of *Abies alba* reached a maximum of 15% around 1200 cal yrs BP. *Fagus sylvatica* was well represented throughout the interval, especially between 2500 and 500 cal yrs BP when it reached the maximum of 12%. *Picea abies* decreased to 20% around 2200 and 800 cal yrs BP, then recovered and reached 50% in the top of this zone. *Pinus diploxylon* pollen percentages varied around 10-15%. *Carpinus betulus* decreased from 7 to 3%. Other deciduous trees like *Quercus, Tilia, Ulmus* are also in decline towards the present times (Figs. 26, 27).

Poacea pollen had its optimum around 2000 cal yrs BP, while other herbaceous plants indicative of meadows and pastures (Chenopodiaceae, Ranunculaceae, Scrophulariaceae, *Plantago lanceolata* and *Plantago* sp., Urticaceae and *Cannabis* type) were present with percentages under 3% yet in greater variety than in other pollen zones. Cereales pollen also increased over 1%. Fern spores are present with percentages up to 2%. Monolete spores are at their lowest values here (7%).

**Plant macrofossils**

The plant macrofossil diagram is dominated by Cyperaceae rootlets and moss (mainly *Sphagnum* sp.) remains.

**LPAZ Ga1 (150-120 cm; 11 260 - 9750 cal yrs BP)**

The macro-remain assemblage in this part of the Early Holocene comprises *Pinus mugo* needles, *Alchemilla* sp. seeds, Cyperaceae (with very high percentages, up to 90%), mosses and wood fragments (Fig. 29). The wood fragments only occured in this zone, between 11 000 and 10 500 cal yrs BP.

**LPAZ Ga2 (120-85 cm; 9750 – 6750 cal yrs BP)**

The macrofossil record consists mainly from herb remains, with only two pine needles around 7800 and 7200 cal yrs BP. *Cenococcum geophilum* sclerotia (a fungus that occurs in dry peatbogs) are present starting around 8500 cal yrs BP. Cyperaceae percentages remain constantly elevated.

**LPAZ Ga3 (85-42 cm; 6750 – 2600 cal yrs BP)**

*Pinus mugo* needles were present from the beginning of the zone but declined from about 4500 cal yrs BP (Fig. 29), indicating a reduction of subalpine wooden vegetation. There is one occurrence of a *Rubus idaeus* seed around 3200 cal yrs BP. Mosses and Cyperaceae presence and diversity increase.

**LPAZ Ga4 (42-0 cm; 2600 –0 cal yrs BP)**

A single pine needle was found around 2500 cal yrs BP. Mosses diversity decreases but there are high percentages of *Sphagnum girgensohnii* leaves that gradually replace the receding Cyperaceae rootlets after 300 cal yrs BP. Unidentified herb rootlet fragment occur in the top 10 cm of the profile with percentages that go up to 60% towards the surface. *Selaginella* spores are also present with a continuous curve of 10-15% after 2000 cal yrs BP.

**Charcoal**

For the Gărgălău peatbog site, only microcharcoal was counted for the 2014 samples when present in the pollen slides, as a record of regional past fire activity. Macrocharcoal was not detected in sufficient quantities for counting, probably because of the high altitude and remoteness of the site. Microcharcoal also is barely present, compared to the Buhăiescu Mare site at a slightly higher altitude. The microcharcoal graph shows higher values in the Early Holocene/Boreal phase, when temperatures increased, reflecting more frequent vegetation fires in the region (Fig. 30).

There is another increase in the Middle Holocene, around 4700 cal yrs BP, during the Holocene Climatic Optimum (in the Atlantic phase according to the Blytt-Sernander chronology), and in the Late Holocene, during the last 500 years.

**Geochemical analysis**

Ti peaks show increased erosion and transport around 8400, 7500-6500, 2400 and 400 cal yrs BP.

The correlation between the Ti and Pb peaks around 8400 cal yrs BP could indicate a time with increased reworking and transport of the sediments.

Pb values have some minor peaks in the Early Holocene, then are close to 0 between 8300 and 1900 cal yrs BP. A major increase is seen after 1000 cal yrs BP up to the present.

**ȘTIOL LAKE**

Lake Știol's sedimentary record covers the last ~2500 years.

**Pollen, spores, stomata**

**LPAZ LS 1 (85-77 cm; 2500-1900 cal yrs BP)**

The pollen percentages of upper montane and subalpine trees and shrubs were relatively constant (*Picea abies* and *Alnus viridis* around 20%, *Fagus sylvatica* 10%, *Pinus diploxylon* and *Juniperus* around 5%) and suggest a rather stable vegetation composition (figs. 34, 35).

Poaceae were the most frequent among herbs (10%), followed by Cyperaceae (5%).

**LPAZ LS 2 (77-48 cm; 1900-700 cal yrs BP)**

During this time zone *Alnus viridis* pollen percentages varied around 30% and started to increase around 680 cal yrs BP, while *Picea abies* values decrease constantly towards 7% around 700 cal yrs BP. *Pinus diploxylon* and *Juniperus* also decreased slightly, along with *Betula*, *Fagus sylvatica* and *Corylus avellana*. Herbaceous pollen increases in diversity and percentages, with Poaceae and Asteraceae having the higher values (up to 10%).

**LPAZ LS 3 (48-17 cm; 700-150 cal yrs BP)**

Subalpine shrubs such as *Alnus viridis* and *Juniperus* are on an increasing trend between 500 and 150 cal yrs BP. There is also an overall increase and diversification in upper montane and subalpine vegetation.

**LPAZ LS 4 (17-0 cm; 150 cal yrs BP-present)**

The pollen record suggests there is a major change in vegetation composition, with the replacement of subalpine trees by subalpine and alpine herbs. Over the last 50 years *Alnus* *viridis* and *Juniperus* percentages decrease, while other high altitude trees and shrubs like *P. Abies alba, P. cembra, and P. mugo* and herbs i.e., Poaceae, Asteraceae, *Artemisia* and *P. lanceolata* increased.

**Plant macrofossils**

The plant macrofossil record shows the abundant occurrence of coniferous tree macroremains, especially *Pinus mugo* and *Juniperus* needles, over the last 2500 years.

**Charcoal**

Both the macrocharcoal and the microcharcoal records at Lake Știol show moderate, but highly oscillating values. The correlation between the two records is partial, and in some cases there is a lag between local and regional fire events (fig.38).

The highest charcoal accumulation rate (CHAC) is around 450 cal yrs BP and over the past 250 years. The intensity and extent of the fires could determine the subsequent erosion episodes.

**Mineral magnetic properties, geochemical analysis, particle size distribution and LOI**

An oscillating pattern shown by mineral magnetic parameters (SIRM) and Rb, a lithophile element, indicate a higher content in mineral magnetic particles and soil erosion in connection with fire events. This link between burning and erosion is especially visible around 2300, 1500 and 1000 cal yrs BP.

The loss on ignition diagram indicates a higher organic content of the sediment between 1400 and 700 cal yrs BP, and after 250 cal yrs BP.

The major peak in medium size particles around 650 cal yrs BP could indicate a major erosional event with increased transport into the lake.

A period of stability in the lake catchment between 600 and 200 cal yrs BP is portrayed by lesser fluctuations in the values of macrocharcoal, the geochemical element Rb as well as mineral magnetic parameters, and also in decreasing values of medium size particles' frequency.

## DISCUSSIONS

Among the drivers of environmental change, it is important to disentangle natural factors from human-induced factors. A multi-proxy approach is the most suited tool to achieve such goal, given its multiple constraints and perspectives.

The high-altitude environments represent a valuable archive of these changes, due to their remoteness from intensely inhabited areas and as such, the existence of good sedimentary records.

### Vegetation history and climate dynamics

#### 1. Early Holocene (11.7-8.2 ka)

Both Buhăiescu Mare and Gărgălău pollen and macrofossil records, which cover the beginning of the Holocene, recorded increased percentages of *Pinus diploxylon*-type pollen (*Pinus sylvestris* and *Pinus mugo*) between 11 000 and 10 000 cal yrs BP, which indicates regional *Pinus* forests. The low percentages of *Pinus haploxylon*-type *(Pinus cembra)* and the altitude of the sites (1810 m and 1918 m), indicates that the timberline ecotone below the sites was primarily composed of *Pinus sylvestris*, while local, high altitude pine communities consisted of the subalpine species *Pinus mugo*.

The regional forests also included *Picea abies Abies alba, Larix decidua* and *Betula*.

After 9800 cal yrs BP *Picea abies* replaced *Pinus sylvestris/cembra* in both sites (Geantă et al., 2014, Tanțău et al., 2014) and remained the dominant component of the timberline until ca. 200–300 years ago, when pollen percentages of *Picea abies* started to decline. The presence of submontane and lowland trees and shrubs pollen indicates the establishment of thermophilous forests at lower elevations in Rodna Mountains, with *Ulmus*, *Corylus avellana*, *Tilia* and *Fraxinus* present in higher percentages at Gărgălău than at Buhăiescu Mare.

#### 2. Middle Holocene (8.2-4.2 ka)

The proportion of subalpine and montane trees slightly decreased after 8000 cal yrs BP both in Buhăiescu Mare and in Gărgălău sites. Together with the increase in subalpine shrubs percentages, this probably indicates a lowering of the timberline during this time.

The first occurrence of cereal pollen and the increased values of ruderal plants (Chenopodiaceae, Urticaceae and *Cannabis* type) after 4500 cal yr BP reflects agricultural activities at lower altitudes and grazing taking place in the vicinity of the site.

There are important changes in the submontane and lowland timber composition during this time, with *Ulmus* and *Corylus avellana* in decline. *Fagus sylvatica* expansion starts later in Gărgălău (ca. 3500 cal yrs BP) than in Buhăiescu Mare (ca. 4000 cal yrs BP), possibly due to the different exposure and dominant winds.

### 3. Late Holocene (4.2-0 ka)

After 2500 cal yrs BP, the expansion of *Fagus sylvatica* and *Abies alba* in all three sites, as well as in other alpine areas in the Carpathians, was associated with the decline in *Picea abies* and the increase in *Alnus viridis* (Björkman et al., 2003; Fărcaş et al., 2013; Geantă et al., 2014; Tanţău et al., 2011, 2014a, 2014b).

The Late Holocene *Fagus sylvatica* expansion is related to human activities, as *Fagus sylvatica* replaces other trees from the mixed Oak forests: *Ulmus, Fraxinus, Tilia* and *Corylus avellana*. Today, it is the main forest constituent at elevations between 400 and 1200 m. *Carpinus betulus* maintains its presence constant then decreases around 300 cal yrs BP in Gărgălău and 400 cal yrs BP in Buhăiescu Mare, while in Știol at lower altitudes it slightly increases.

At Știol Lake, the pollen and plant macrofossils records over the last few hundred years shows an increased abundance of subalpine shrubs i.e., *Alnus viridis* and *Juniperus* sp. between 500 and 100 cal yrs BP (Fig. 38). Since there is no correlation with pollen of anthropogenic indicators during this interval, we consider this change in vegetation to indicate a change in climate. Evidence from several fossil records in the area show that the Little Ice Age (LIA) was characterized by dry conditions, burning intensification and increased soil erosion (Feurdean et al., 2012; Geantă et al., 2012; Onac et al., 2015).

## Fire history in Rodna Mountains region over the Holocene

| Period | Local fire activity | Regional fire activity |
|---|---|---|
| **Early Holocene** | The macrocharcoal record from Buhăiescu Mare Lake shows an average increasing trend in local fire activity between 11 000 and 9700 cal yrs BP. The elevated Ti concentrations point towards a period where main events were soil erosion and slope activity. | Around 10 600 cal yrs BP, the increase in regional fire activity in Buhăiescu Mare Lake catchment was associated with moderate particle inputs and magnetic enrichment (SIRM).<br><br>The microcharcoal graph for Gărgălău shows higher values, reflecting more frequent vegetation fires in the region. |
| **Mid Holocene** | Peaks in macrocharcoal accumulation rates in Buhăiescu Mare Lake occured between 4000 and 3500 cal yrs BP, and around 3000. The correlations between the 4000 and 3500 cal yrs BP, both in the local and regional records, indicate important fire episodes that affected the whole area. | At Buhăiescu Mare, periods of high microcharcoal accumulation rates were recorded between 4000, 3500 and 3000 cal yrs BP. At Gărgălău, an increase around 4500-4700 cal yrs BP, during the Holocene Climatic Optimum, points to increased frequency of regional fires. |
| **Late Holocene** | Local peaks in fire activity occurred at Buhăiescu Mare Lake around 2500, 1400, 1100, and around 750 cal yrs BP.<br><br>At Știol Lake, the beginning of the macrocharcoal record (between 2500-2000 cal yrs BP) has less variation in fire activity, with a peak around 1750 cal yrs BP. After 1500 cal yrs BP the trend in the macrocharcoal record suggests a period of enhanced fire activity, with peaks around 1000, 650 and between 350-450 cal yrs BP, as well as over the past 250 years.<br><br>Some of the peaks in macrocharcoal correlate with high values in mineral magnetic parameters, loss on ignition, Rb content and/or median particle size, indicating periods of erosion following vegetation fires. | The Gărgălău record reflects an increase in regional fire activity during the last 500 years.<br><br>At Știol Lake, peaks in microcharcoal, indicating regional fire events, were identified around 2500, 300, 220 cal yrs BP, and in recent times. Some of these events correlate with increases in pollen percentages herbs, shrubs and ferns, indicating low intensity fires leading to a faster regenerating of shrubs, pasture herbs and wetland ferns, as compared to tree taxa. |

**Treeline and timberline dynamics**

In Romania, the timberline varies with local and current climatic conditions. In Rodna Mountains the treeline is around the altitude of 1650-1700 m, while the closed forest, or timberline is considered to be around 1500 m, even higher (1600-1650 m) on the northern slopes (MPRMNP, 2013).

The changes in species relative contribution and distribution observed over time show that the timberline and treeline responded to both climate and human impact.

a) Buhăiescu Mare Lake site (1918 m) was most probably situated above the treeline for the entire Holocene, yet the krummholz area with *Pinus mugo* individuals might have been reached the vicinity of the lake for periods from the early and middle Holocene;
b) Gărgălau peatbog site (1810 m) records reflect a treeline dominated by *Pinus mugo* until at least 3000 years ago. The site was situated above the timberline, in the treeline ecotone dominated by *Pinus mugo*, for most of the Holocene, with a possible higher position of the treeline around 8500 cal yrs BP. A decrease in the *Pinus mugo* presence in modern times;
c) Știol Lake site was located close to the timberline made by *Picea abies* for the last 2500 years;
d) Tree- and timberline movements have been influenced by climate, fires and human activities.

**Human impact**

Positive peaks in charcoal values and abiotic parameters such as mineral magnetic values, medium size particles and lithophile elements indicate periods of erosion following either natural or human induced fires.

The pollen of cultivated plants (Cerealia, *Secale*) first appeared around 10 000 cal yrs BP at Buhăiescu Mare Lake and around 6 000 cal yrs BP at Gărgălău, together with low percentages of herbs associated with grazing and ruderal fields (*Artemisia*, Asteraceae, *Rumex*, *Urtica*, Chenopodiaceae). This may imply that people were already impacting subalpine landscapes through livestock grazing during the Neolithic. Yet the low values of coprophilous fungi suggests that grazing was not intense or consistent, or could simply point to the presence of wild herbivores in the area.

A more consistent presence of anthropogenic indicators (pollen of cultivated plants, grazing indicators and ruderals) was noted at both these sites starting with 3500 cal yrs BP.

This was simultaneous with a reduction in the pollen percentages of *Picea abies* and *Pinus mugo*. Changes in forest structure were confirmed by fluctuations in the proportion of shrub taxa.

An increase in the proportion and diversity of anthropogenic indicators and coprophilous fungi (at Buhăiescu Mare only) over the last centuries correlates with increased values in charcoal, suggesting that anthropogenic activities (cutting, grazing and burning) led to the modification of the mountain forest ecotone.

The abiotic analyzes at Știol and Buhăiescu Mare Lakes also show an increase in SIRM and elevated values in LOI that occurred in recent decades. Știol Lake was dammed in 2002 and riparian erosion may be the cause of these values (Hutchinson et al., 2015). This is another way human activities are impacting the environment in general and vegetation in particular.

Moreover, XRF analyzes show elevated values of Pb in recent times (last 500 years for Gărgălău and Buhăiescu Mare, and last 1800 years for Știol Lake), pointing to mining (prior to 1850) and industrial activities (after 1850) in the region (Fig. 49). According to the Baia Mare Museum of History and Archaeology, mining activities are documented in the area since the 14-th century.

The peaks in the Early Holocene could indicate increased transport due to precipitations.

## CONCLUSIONS

- All profiles show that climate was a driving factor of change in the montane and subalpine vegetation of Northern Romania since the last deglaciation. It is expected this impact will be visible also in the future and therefore mitigation is necessary.
- The treeline and timberline visibly responded to changes in climate and to human impact over the studied period. The early Holocene was characterized by a higher position of the treeline and timberline. A descent of the timberline and treeline was noted during the last 1200 years, and more so over the past 200 years, with replacement by sub-alpine shrubs (*Alnus viridis*) and alpine herbaceous communities. These recent vegetation changes were associated with an increased frequency of pollen based-anthropogenic indicators, charcoal particles, and abiotic proxies for erosion, therefore implying human-induced fires and clearance and resultant erosion inputs in the catchment of the lakes and the peatbog.
- Fires occurred naturally in the study area, but were enhanced by anthropogenic activities especially in the last 200 years.

- ➦ The results highlight the impact of anthropogenic activities even in relatively remote mountain areas.
- ➦ Effects of current warming on the altitude range of the treeline are not yet visible, probably because land use in the Rodna Mountains (grazing and burning) has more strongly contributed to changes in land cover than the climate fluctuations of the last centuries.
- ➦ Although, outside Romania, uncontrolled deforestation in the Carpathians decreased after year 2000 and forest expanded, in Romania this trend is not visible, as legal and illegal deforestation is ongoing even in high-altitude protected areas.
- ➦ Multiproxy studies bring a more complete perspective on paleoclimate evolution and can help us predict future climate changes.
- ➦ Future studies are needed for a better time resolution and to better discern the role of each driver of climate change.

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