Research paper

The Holocene
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DOI: 10.1177/0959683614534747
hol.sagepub.com
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High mountain region of the Northern Romanian Carpathians responded sensitively to Holocene climate and land use changes: A multi-proxy analysis

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Abstract

A high-altitude lake sediment sequence (Buhăiescu Mare, 1918 m a.s.l.) in the subalpine zone of the Rodna Mountains was analysed through a multi-proxy approach to determine the sensitivity of high mountain habitats to climate, fire and land use changes. The early Holocene regional forests were dominated by *Pinus* (*sylvestris* and *mugo*) and replaced by *Picea abies* from 9800 cal. yr BP. After an extended hiatus in the profile (*c.* 9800–4200 cal. yr BP), probably because of the physical removal of sediments through avalanche or high-flow events, *P. abies, Abies alba* and *Fagus sylvatica* forests developed after 4200 cal. yr BP. The timberline and treeline reacted sensitively to past changes in climate and human impact. The site was probably situated above the treeline throughout most of the investigated period. However, a treeline ecotone or krummholz zone may have sporadically reached the lake's elevation in the early Holocene. A decline in timberline and treeline elevation was noted during the last 1200 years, and more evidently over the past 200 years, with replacement by subalpine shrubs (*Alnus viridis*) and alpine herbaceous communities. Because these vegetation changes were associated with an increased prevalence of pollen-based anthropogenic indicators, charcoal particles and abiotic indicators, human-induced fires and clearance and resultant erosion inputs to the lake are implied. Effects of current warming on the altitude range of trees are not yet visible, probably because land use has more strongly contributed to changes in land cover than the climate fluctuations of the last millennium in the Rodna Mountains.

Keywords

charcoal, climate, land use changes, plant macro-remains, pollen, Rodna Mountains, treeline

Received 18 February 2014; revised manuscript accepted 7 April 2014

Introduction

High-altitude environments (treeline and alpine communities) are particularly sensitive to climate changes, disturbances and land use changes because of their narrow tolerance capabilities, habitat fragmentation and habitat restriction (Pauli et al., 2012; Theurillat and Guisan, 2001). Treelines or treeline ecotones are transitional zones between closed forests (timberline limit) and alpine communities and are composed of a mixture of trees, shrubs and herbaceous species, many of them endemics (Tinner and Theurillat, 2003; Van der Maarel, 1976). The position of the treeline is climatically sensitive, although topography, soil type and snow and wind regimes can also be influential (Körner, 2003; Tinner, 2013; Tinner and Kaltenrieder, 2005; Tinner and Theurillat, 2003; Wick and Tinner, 1997). Palaeoecological and palaeoclimatological records have documented that the rapid climatic warming at the onset of the Holocene (11,700 years ago) appeared to drastically restrict the habitat for alpine/arctic species at the expense of trees and shrubs (Birks and Bjune, 2010; Birks and Willis, 2008). Long-term multidisciplinary studies on Holocene treeline and timberline shifts have mainly been conducted in the Alps and in Scandinavia. These studies have recorded oscillations of up to 350 m in their vertical extent during the course of the Holocene (Barnekow and Sandgren, 2001; Berthel et al., 2012; Bjune, 2005; Reasoner and Tinner, 2008; Tinner and Ammann, 2005; Tinner and Kaltenrieder, 2005; Wick and Tinner, 1997). This sensitivity in alpine and subalpine environments is expected to lead to an elevation of the treeline with a significant proportion of species loss under future climate changes (Schwörer et al., 2013). In fact, an upward slope movement of trees and shrubs as a response to

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climate warming has already been noted in many montane and subalpine regions (Körner, 2012 – global; Martazinova et al., 2011 – Ukraine; Theurillat and Guisan, 2001; Tinner and Ammann, 2005 – Alps). Cold demanding alpine herbs are also expanding up slope around the globe (Pauli et al., 2012).

In Romania, existing Holocene palaeovegetation records (mainly pollen records) from high elevation sites have documented dynamic changes in montane and subalpine vegetation composition and structure (Björkman et al., 2003; Bodnariuc et al., 2002; Fărcaş et al., 1999, 2007, 2013; Feurdean and Willis, 2008; Feurdean et al., 2009, 2010; Magyari et al., 2012; Tanţău, 2006; Tanţău et al., 2003, 2011, 2014a, 2014b). Nevertheless, multi-proxy studies in these high-altitude environments are scarce (Feurdean et al., 2009; Magyari et al., 2012), and there have been no attempts to investigate Holocene timberline and treeline response to climate change and human impacts despite the significant extent of the Carpathian Mountains in this country. Although fossil pollen analysis is one of the most common tools for the reconstruction of past vegetation composition and dynamics, its spatial resolution (metres to hundreds of kilometres) is too broad to provide fine-scale estimations of fluctuations in the treeline, which normally occur over short distances of *c.* 100–200 m (Berthel et al., 2012; Birks, 2001; Tinner and Theurillat, 2003). Efforts to reconstruct treeline fluctuations therefore need to be based on a combination of fossil pollen analysis with other methods that offer a smaller scale spatial record such as plant macro-fossils, megafossils, stomata, charcoalised plant remains and tree rings (Birks and Birks, 2000; Magyari et al., 2012; Reasoner and Tinner, 2008; Tinner, 2013). When these biotic proxies are combined with abiotic parameters, that is, mineral magnetic properties, geochemical analyses and particle size analysis, they offer additional information on past environmental conditions such as episodes of erosion associated with climate changes, land clearance grazing and fires. Therefore, while a multi-proxy approach is more challenging through the amount of work and skills required, it offers essential information on past environmental modifications as well as the vegetation response to these changes.

In this context, a multi-proxy analysis (pollen, spores, stomata, plant macro-fossil, micro- and macro-charcoal, loss on ignition (LOI), mineral magnetic properties, geochemical and particle size characteristics and dating evidence via AMS ^{14}C and ^{210}Pb dating) of a 125-cm-long lacustrine sequence from the Rodna Mountains (Northern Romanian Carpathians) was employed to determine the sensitivity of high mountain vegetation to climate and disturbance through fire and land use change in this understudied region.

Specifically, we aimed to:

1. Reconstruct shifts in timberline and treeline ecotones in response to climate, fire and land use changes;
2. Explore the sensitivity of alpine communities in the Rodna Mountains to natural and anthropogenic forcing.

Study area

The Rodna Mountains, located in the north of Romania, are the highest in the eastern sector of the Carpathians (Pietrosul Peak, 2303 m; Coldea, 1990). The range was heavily glaciated during the last glacial maximum and holds a series of 48 glacial cirques and 42 lakes and peatbogs of glacial origin (Mîndrescu et al., 2014; Urdea, 2004). Dating of the glacial erratics and bedrock samples suggest that final ice retreat in the Rodna Mountains took place at 12.5–11.2 cal. yr BP (Gheorghiu, 2012). The geology of this region comprises crystalline rocks such as epimetamorphic schist and mica schist, and the lake sits in an area of sericite-chlorite schist. The area has a moderate temperate climate with Atlantic and Baltic influences. Present mean annual temperature is 1.2–0°C, while mean annual precipitation is 1300 mm (Dragotă and Kucsicsa, 2011). Meteorological observations made locally (Iezer Weather Station) show an increase in the mean annual air temperature of 0.7°C, while annual precipitation decreased by 100 mm from 1961 to 2007 (Dragotă and Kucsicsa, 2011).

In terms of vegetation, four belts can be distinguished in Romania (Coldea and Cristea, 1998; Cristea, 1993; Feurdean et al., 2012; 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. Lower montane with *Fagus sylvatica* (600–800 m);
   2.2. Middle montane with *Fagus sylvatica, Picea abies* and *Abies alba* (between 800 and 1200 m);
   2.3. Upper montane: *P. 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.

The elevation distribution of vegetation belts in the Northern Romanian Carpathians, including the Rodna Mountains, is known to be up to 200 m lower than in the southern part of the Carpathians (Cristea, 1993). The timberline (the limit of the closed forest) in the Rodna Mountains is around 1500 m. This is closer to the timberline position in the northern part of the whole Carpathian range, that is, the Tatra Mountains (Kozak et al., 2007; Obidowicz, 1996; Planul de Management al Parcului Naţional Munţii Rodnei (Management Plan of Rodna Mountains National Park and Biosphere Reserve) (MPRMNP), 2014) than in the southern Carpathians. The current treeline in the Rodna Mountains is composed of *Picea abies* and its elevation ranges from 1600 to 1700 m, but can be influenced locally by slope characteristics (MPRMNP, 2014). The treeline ecotone is characterised by mixed occurrence of shrubs such as *Pinus mugo, Juniperus nana, Alnus viridis* and dwarf shrubs such as Ericaceae and *Betula nana* (MPRMNP, 2014).

Lake Buhăiescu Mare (1918 m a.s.l.; 7.34.25°N, 23.38.36°E) also known as Lake Rebra or Buhăiescu IV (Pişota, 1968) is located on the north-eastern slope of Buhăiescu Mare Peak, in the Rodna National Park and Biosphere Reserve (Figure 1). It is a small, remnant glacial lake with a surface of 0.9 ha, 0.5 m maximum water depth and a catchment area of about 15.75 ha. Lake Buhăiescu Mare is fed by surface inflows as well as precipitation and in-wash from the surrounding slopes and is drained by a single outlet. This lake is situated above the current treeline, and the vegetation of the catchment consists of *Carex*, Ericaceae, *Juniperus* patches and scattered *Pinus mugo*. Currently, there is a sheepherders' summer hut in the vicinity of the lake (established in the last few years) and a road for all-terrain vehicles into the catchment serving the shepherds and park rangers. The sheep graze over a larger area, yet they descend to the lake daily for water. Sheep grazing and transhumance are documented in Romania starting with the 13th century (Popa, 2010), yet they go back even further based on oral history.

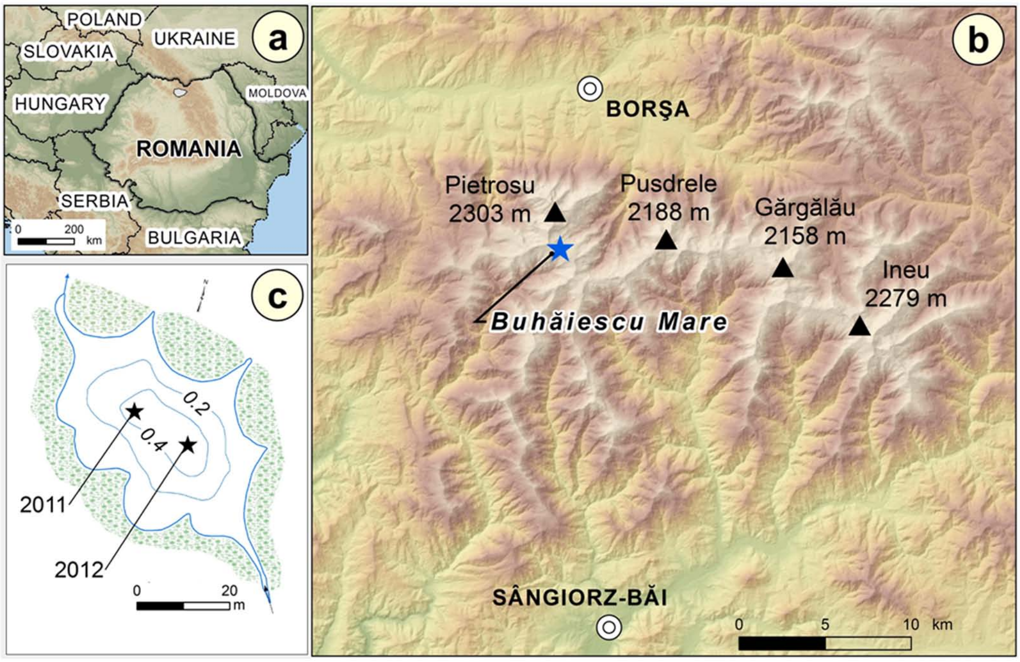

Figure 1. Site location: (a) Rodna Mountains within Romania, (b) Lake Buhăiescu Mare within the Rodna Mountains and (c) Plan and bathymetry of Lake Buhăiescu Mare with coring sites.

Table 1. Radiocarbon and selected ^{210}Pb dates used for the age–depth model.

Isotope	Lab. code	Depth (cm)	Material	AMS ^{14}C age/BP	Age (cal. yr BP, 2σ range)	Age (cal. yr BP)[a]	Included in the model
^{210}Pb		0	Bulk sediment			−72	Yes
^{210}Pb		2.5	Bulk sediment			−23	Yes
^{210}Pb		5.5	Bulk sediment			−32	Yes
^{210}Pb		14	Bulk sediment			86	Yes
^{14}C	UBA-20370	19.5	Peat and *Sphagnum*	1442 ± 27	1298–1380	1339	Yes
^{14}C	UBA-20369	33.5	Sphagnum	2259 ± 30	2159–2262	2210	Yes
^{14}C	UBA-20368	46.5	Herbaceous seeds	963 ± 37	906–1012	959	Yes, outlier
^{14}C	BM1-21563	51.5	Plant macro-fossil	3328 ± 31	3474–3638	3556	Yes
^{14}C	UBA-19170	81	Bulk sediment	3731 ± 33	3980–4157	4068	Yes
^{14}C	UBA-21560	86	Wood	8830 ± 53	9698–10,158	9928	Yes
^{14}C	UBA-21553	99.5	Bulk sediment	22,524 ± 112	26,729–27,788	27,258	Rejected
^{14}C	UBA-21572	112–115	Herbaceous seeds and brown mosses	5916 ± 48	6642–6860	6751	Rejected

[a]Present considered AD 1950.

Methods

Coring and chronology

Sediment cores were taken with a Russian corer in 2011 and 2012 (Figure 1c). In addition, the surface sediment (~22 cm) was retrieved in 2012 with a gravity corer and sliced at 0.5 cm intervals in the field. A lithostratigraphic description was made both on site and in the laboratory according to changes in texture, colour and grain size. The cores were screened using magnetic susceptibility measurements (Bartington Instruments Ltd MS2 meter and C sensor; Walden et al., 1999). The core correlation and composite sedimentary record totalling 125 cm was created using information derived from mineral magnetic properties, lithostratigraphy, changes in organic carbon content and the pollen data (for details, see Supplementary Figure S1, available online).

A total of eight samples containing both bulk and plant macrofossil material were sent to the Chrono Center in Queen's University, Belfast, for ^{14}C AMS ages (Table 1). The top 12.5 cm of sediment (25 samples) obtained from the gravity core was dated via ^{210}Pb and ^{137}Cs isotopes in the Laboratory for Gamma Spectrometry, Babeş-Bolyai University Cluj-Napoca, Romania (Table 1; for a fully dated profile see Hutchinson et al., submitted).

Magnetic properties, geochemical analysis, LOI and particle size analysis

In addition to the use of volume magnetic susceptibility (κ) to facilitate core correlation, Saturated Isothermal Remanent Magnetisation (SIRM) was selected to reflect episodes of erosion associated with climate changes, land clearance, grazing and fire (Higgitt et al., 1991; Hu et al., 2002; Yu and Oldfield, 1993). SIRM measurements were performed every 2 cm using a Molspin pulse discharge magnetiser. The resultant magnetic remanences were measured using a Molspin Minispin fluxgate magnetometer (Akinyemi et al., 2013; Hutchinson, 1995; Walden et al., 1999). Geochemical analyses were made using a Niton XL3t 900 XRF analyser. Samples were packed into sample holders, the bases of which comprise 6-µm polyester films as a sample window. The instrument and sample are held in a shielded laboratory support stand. NCS DC73308 was employed as a Certified Reference Material (CRM). Only Ti, a known lithophilous element, is shown and was selected to indicate erosion periods.

Particle size analysis (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.

For LOI, samples were dried at 105°C over night, combusted for 5 h at 550°C and expressed as percentage loss of the dry weight. The results were used to estimate the organic content of the sediments (Heiri et al., 2001).

Pollen, spores, charcoal, stomata and plant macro-fossil

Samples of 1 cm^3 were retrieved every 2 cm, chemically treated (HCl, NaOH, HF, $ZnCl_2$, acetic acid), mounted in glycerine and used for pollen, spores, coprophilous fungi, stomata and micro-charcoal under a light microscope. *Lycopodium* tablets were added to the samples prior to their chemical treatment to estimate micro-charcoal concentrations. Pollen grains were determined using the atlases of Reille (1995, 1999), and the taxa were confirmed via the Romanian Flora (Ciocârlan, 2000). The minimum number of pollen grains counted was 400 per sample, and 85 different pollen and spores types were identified. Non-pollen palynomorphs (mainly coprophilous fungi) were determined alongside the pollen and used as an indicator of herbivorous presence in the area (Cugny et al., 2010). They were identified using the keys of Van Geel et al. (1980, 1983) and Cugny et al. (2010). Microscopic charcoal particles (10–150 µm) were counted on the pollen slides and used to reconstruct regional fire history (Whitlock and Larsen, 2001). The frequencies of each taxon were calculated as percentages of the terrestrial sum (AP + NAP) and plotted using Tilia and TGView software (Grimm, 1991, 2004). Because of over-representation in the pollen record, monolete spores and Cyperaceae pollen were excluded from the pollen sum. Conifer stomata were identified with the key of Sweeney (2004). Contiguous 2-cm^3 sub-samples were retrieved at 1-cm intervals for macroscopic charcoal analysis. Samples were gently wet sieved through a 160-µm mesh. The total number of macro-charcoal particles was counted using a stereomicroscope in order to estimate past changes in fire activity at a local scale (Feurdean et al., 2013a).

Plant macro-fossils were analysed 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 0.20-mm mesh screens and were analysed with the use of a stereoscopic microscope. Fossil carpological remains, vegetative fragments (leaves, rootlets, epidermis) and mosses were recognised using the available identification keys (Bojnanský and Fargašová, 2007; Smith, 2004; Tobolski, 2000; Velichkevich and Zastawniak, 2006) and are presented as concentrations.

Numerical analysis

The Local Pollen Assemblage Zones (LPAZs) were statistically defined using optimal splitting based on an information content technique (Bennett, 2007) and define significant changes in the vegetation composition. Principal Components Analysis (PCA) was applied on pollen data to determine the compositional changes throughout the sequence. PCA was carried out on the covariance matrix of the square root pollen percentage of selected taxa with Canoco software v. 4.5 (Ter Braak and Smilauer, 2002).

Palynological richness 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.

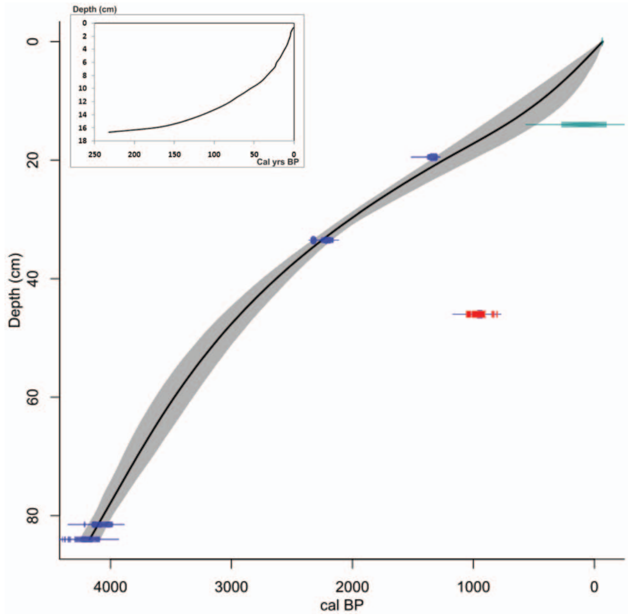

Figure 2. Age–depth model for the Buhăiescu Mare profile, upper 82 cm. Inset shows the top 18 cm dated by ^{210}Pb.

Results and interpretation

Chronology

Results from the radiocarbon age estimates indicate that the top 81 cm of the core spans approximately the past 4000 years (Figure 2). There is an extended hiatus at 81–82 cm, which was identified on the basis of a sharp lithological transition, the pollen record and the radiocarbon ages, so that the lower part of the profile (82–125 cm) belongs to the early Holocene (Table 1). This hiatus in the sedimentary record may reflect the exposed position of the site close to the outer edge of the glaciated basin, where geomorphic events such as avalanches or high-flow events may have removed evidence of the period 4000–9800 cal. yr BP. The mire surrounding the lake indicates that the current water body was more extended in the past. The event/events that removed the sediments may also have opened up the basin and displaced the rock/glacial deposits that were damming the lake. This would have lowered the lake level changing the nature of the depositional environment. In addition, the age yielded by radiocarbon dating (22,524 ± 112 yr BP) performed at 99.5 cm on a bulk sediment with very little organic material (0.06%) was later contradicted by the ages obtained on plant macro-fossil material from 112–115 cm (5916 ± 48 yr BP) and at 86 cm (8830 ± 53 yr BP). In order to constrain the chronology for the lower part of the sequence (82–125 cm) and this radiocarbon age reversal, we used pollen stratigraphic markers obtained from Poiana Ştiol, a well-dated pollen profile located in our study area, covering the last 11,000 cal. yr BP (Tanţău et al., 2011). We associated an age to our vegetation events as follows: high percentages of *Artemisia* and *Pinus* between 90 and 125 cm were taken as indicators of the early Holocene, the marked decline of *Pinus* and the beginning of *P. abies* expansion at 115 cm was assigned to 10,900 cal. yr BP, whereas the strong *Picea abies* expansion starting with 86 cm at 9900 cal. yr BP (Figure 3).

The age–depth model of the upper section of the profile (top 81 cm) was constructed using the smooth spline method as implemented by CLAM software (Blaauw, 2010). In this model, the ^{14}C AMS age estimates were converted into calendar years BP using the IntCal3 data set of Reimer et al. (2013), whereas the ^{210}Pb age estimates for the top 14 cm were previously calculated using Constant Rate of Supply (CRS) model (Hutchinson et al., submitted). One too young radiocarbon age was rejected (963 ± 37) as it led to a large number of age–depth reversals (Figure 2). This age–depth model also gave a high number of age–depth reversals for the top 20 cm, including the junction of ^{14}C AMS and ^{210}Pb dates. A new (conjoined) model was created using the reliable ^{14}C AMS age estimates and the age assignment for topmost sample taken from the ^{210}Pb date, with the age–depth model for the top 14 cm established based on ^{210}Pb (CRS) age estimates, by assuming a constant sedimentation rate between the two periods (Figure 2).

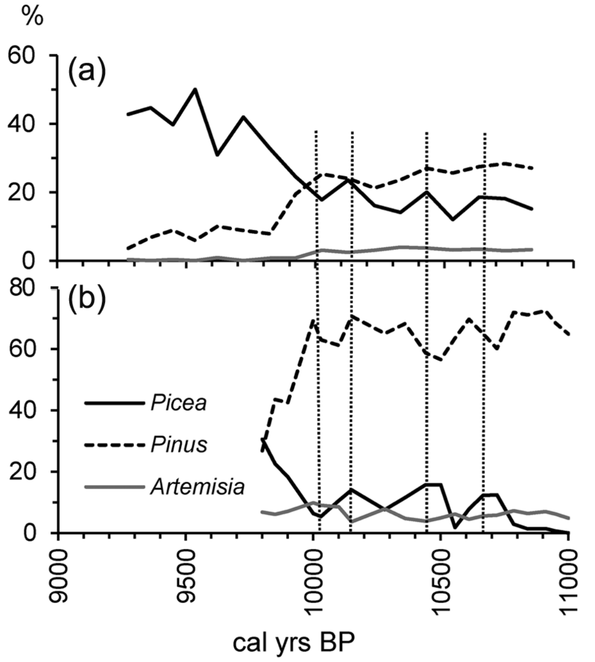

Figure 3. Pollen-based stratigraphic correlation between selected pollen curves in (a) Poiana Ştiol (1540 m a.s.l.) and (b) Buhăiescu Mare (1918 m a.s.l.) sites. Dashed lines connect similar peaks in the *Picea* curve.

Lithostratigraphy, mineral magnetic properties, geochemical analysis, particle size distribution and LOI

The lower part of the profile (unit 1 and 2, 125–82 cm; 11,000–9800 cal. yr BP) is highly minerogenic in composition with fine sediment derived from the surrounding schists that underlie the basin (Figures 4, 5 and 6). Between 125 and 105 cm (unit 1, ~11,000–10,700 cal. yr BP), the profile consists of light grey, silty clay, followed by petrol grey, clayey silt between 105 and 82 cm (unit 2, 10,700–9800 cal. yr BP). This unit is characterised by high values of SIRM and Ti (a lithogenic indicator), a low organic content and a particle size indicative of low lake productivity and the input of catchment-derived material through erosion in early Holocene. Unit 3 (above the hiatus) is composed of dark grey, clayey/silty gyttja (82–25 cm; 4000–1500 cal. yr BP), whereas the top 25 cm (unit 4, the last 1500 cal. yr BP) consists of a less compact black gyttja (Figures 4 and 5). The SIRM and Ti concentrations become markedly lower in unit 3, and there is a significant increase in organic content, whereas the median particle size is slightly higher and intermittently variable over the past 4000 years. This pattern suggests that the supply of magnetic minerals via catchment erosion is relatively insignificant throughout this period. In addition, the change in lithology with a higher organic matter content suggests the initiation of basin infill. Thereafter, the increase in magnetic concentrations and Ti with a decline in organic content and particle size during the past 300 years could indicate intensification of clearance-related erosion and transport of mineral particles into the lake, 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 (Akinyemi et al., 2013).

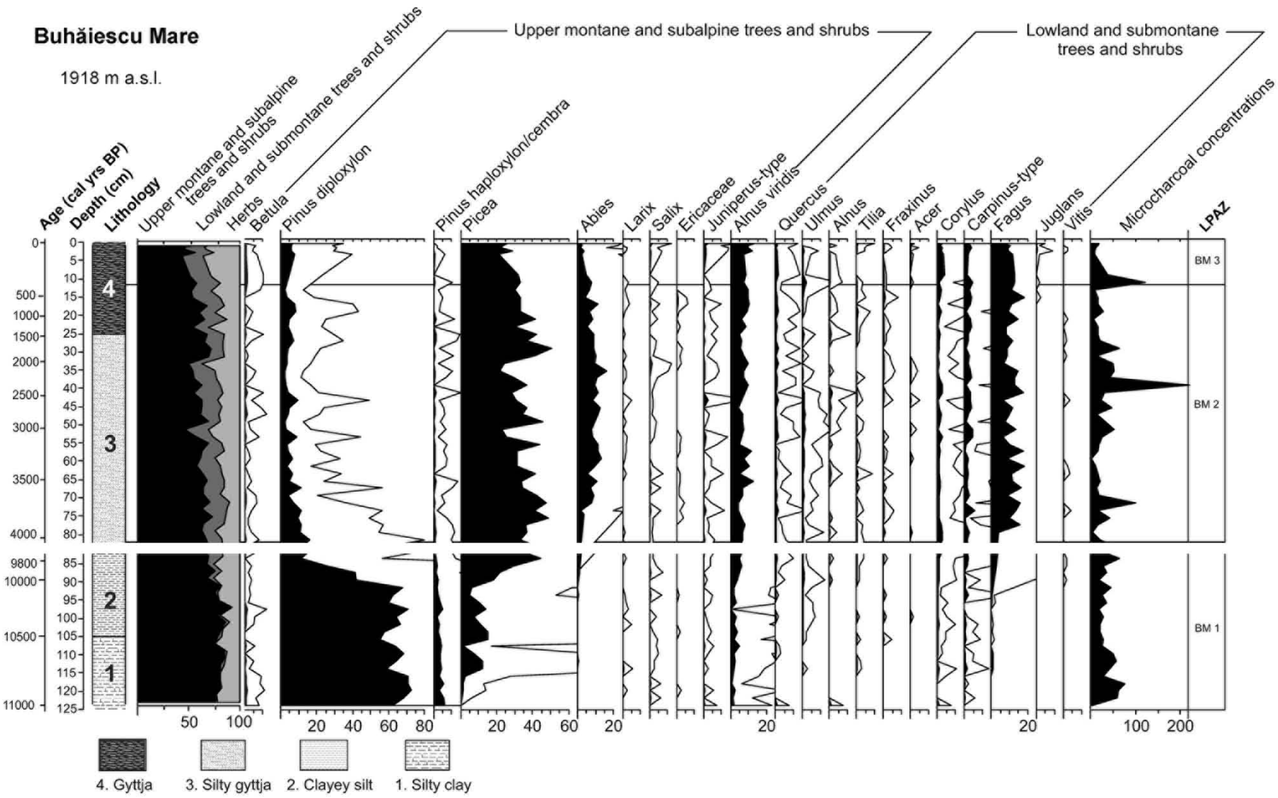

Figure 4. Pollen percentages of arboreal pollen types and micro-charcoal concentration diagram. Empty curves show 10× exaggeration.

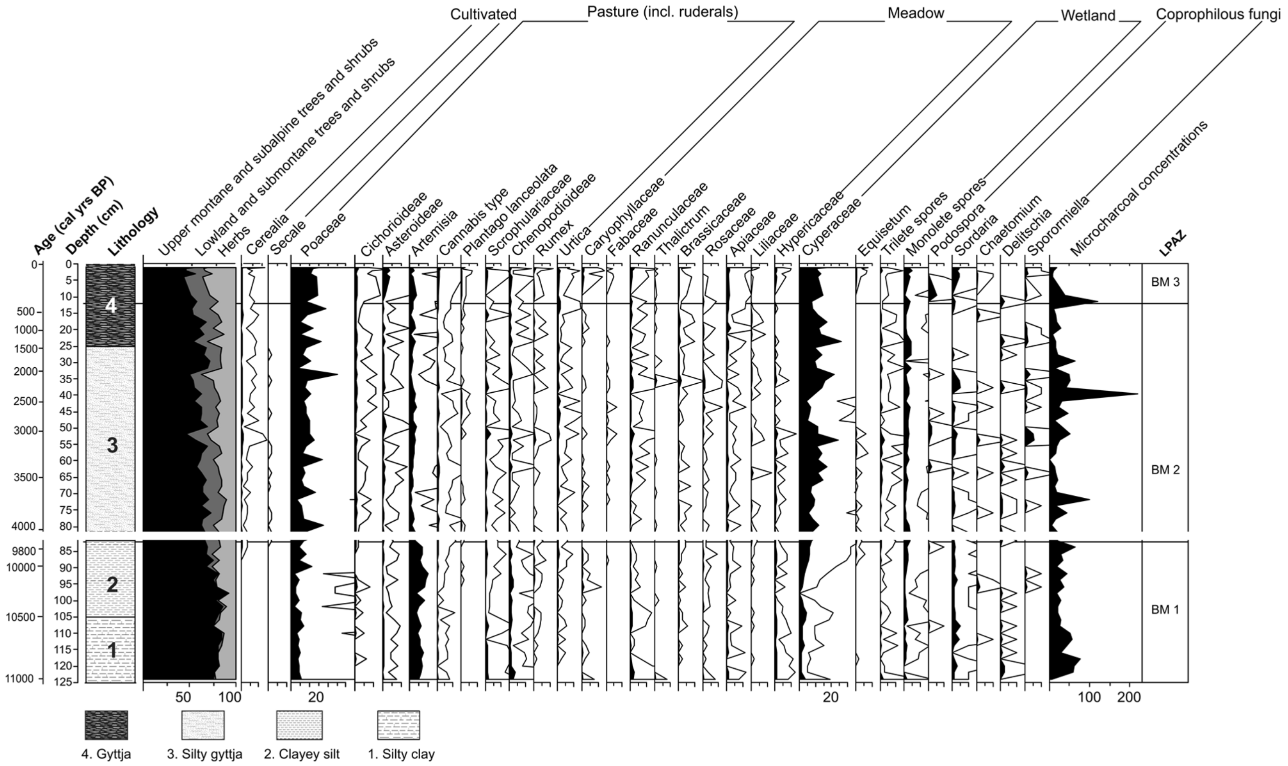

Figure 5. Pollen and spores percentages diagram for herbs, ferns and fungi. Empty curves show 10× exaggeration. Cyperaceae, water plants and ferns are excluded from the pollen sum.

Biotic proxies: pollen, stomata and plant macro fossil-based vegetation reconstruction

The pollen and macrofossils records were subdivided into three statistically significant Local Pollen Assemblages Zones: BM 1, BM 2 and BM 3 (Figures 4–6). Results from the PCA indicate that samples covering the first part of the early Holocene (11,000–9800 cal. yr BP) are markedly different from those of the late Holocene, that is, the last 4000 cal. yr BP (Figure 7), and there is also a small compositional shift over the past 50 years.

LPAZ BM 1 (125–82 cm; 11,000–9800 cal. yr BP). The tree pollen assemblage was dominated by montane trees and subalpine shrubs (Figure 4). The abundant occurrence of *Pinus diploxylon*-type pollen (*Pinus sylvestris/Pinus mugo*; 60–70%) and *Pinus haploxylon* type (5%; *Pinus cembra*, 2%) throughout this period, together with the occurrence of a *Pinus* stomata at 96 cm, indicate a timber dominated by *Pinus. Picea abies* pollen percentages were almost absent at the beginning of the record, but increased rapidly to 10% at 10,900 cal. yr BP and then to 40% at 9800 cal. yr BP (Figure 4). The only occurrence of a *Picea abies* bud scale in the record also belongs to this zone. Other mountain tree pollen types scarcely present during this period were *Larix decidua* and *Betula*, whereas submontane and lowland tree pollen types included *Ulmus, Tilia, Fraxinus, Carpinus* and *Corylus*. The occurrence of pollen grains of *Fagus sylvatica* and *Carpinus betulus* in this zone is likely because of reworked sediment. The macro-fossil assemblage also included unidentified wood remains (Figure 6). Pollen of subalpine shrubs such as *Alnus viridis* was present at 2% at the beginning of the record, increasing to 5% at the end of this zone, while other shrubs, that is, Ericaceae, *Juniperus* and *Salix*, did not exceed 2% (Figure 4).

Herbaceous pollen taxa were mainly represented by *Artemisia* (up to 5%), Poaceae (<5%), Ranunculaceae, Scrophulariaceae and Chenopodiaceae (<3%; Figure 5). The plant macro-fossil assemblage contained 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 palaeolake (Figure 6).

LPAZ BM 2 (82–12 cm; 4000–300 cal. yr BP). Upper montane tree pollen percentages declined from about 4000 cal. yr BP, as compared with pre-hiatus values (i.e. prior to 9800 cal. yr 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 and is represented by *Fagus sylvatica* (up to 10%), *Alnus glutinosa/incana, Betula, Carpinus betulus, Corylus avellana, Quercus, Ulmus, Fraxinus* and *Acer* (below 2%). The stomata and plant macro-fossil records included a single *Pinus* stomata at *c.* 3800 cal. yr BP, an unidentified wood fragment at *c.* 2750 cal. yr BP and two *Betula sec. Alba* fruits at 1600 and 600 cal. yr BP (Figure 6). Subalpine shrubs percentages were dominated by *Alnus viridis* (up to 8%), which probably occurred locally together with *Salix* and *Juniperus* (Figure 4).

Herbaceous pollen percentages fluctuated around 20–30% and were represented by alpine herbaceous communities (Poaceae, Cyperaceae, Apiaceae, Asteroideae, Cichorioideae) and continental steppe/ruderal taxa (*Artemisia, Rumex*, Chenopodiaceae; Figure 5). The macro-fossil record showed a slight decrease in the abundance of alpine and subalpine herbs (mainly Poaceae and *Carex* sp.). The aquatic macro-flora were composed of *Batrachium* sp. and *Typha* cf. *minima*. The diversity of moss types increased and included *Sphagnum* sp. and *Calliergon* sp., which together with the rise in organic matter indicates an advance of the bryophytes into the lake. This could have acted as a filtering for mineral particles input (Figures 6 and 7).

LPAZ BM 3 (12–0 cm; 300–0 cal. yr BP). Pollen of both montane and submontane tree taxa declined, most notably *Picea*

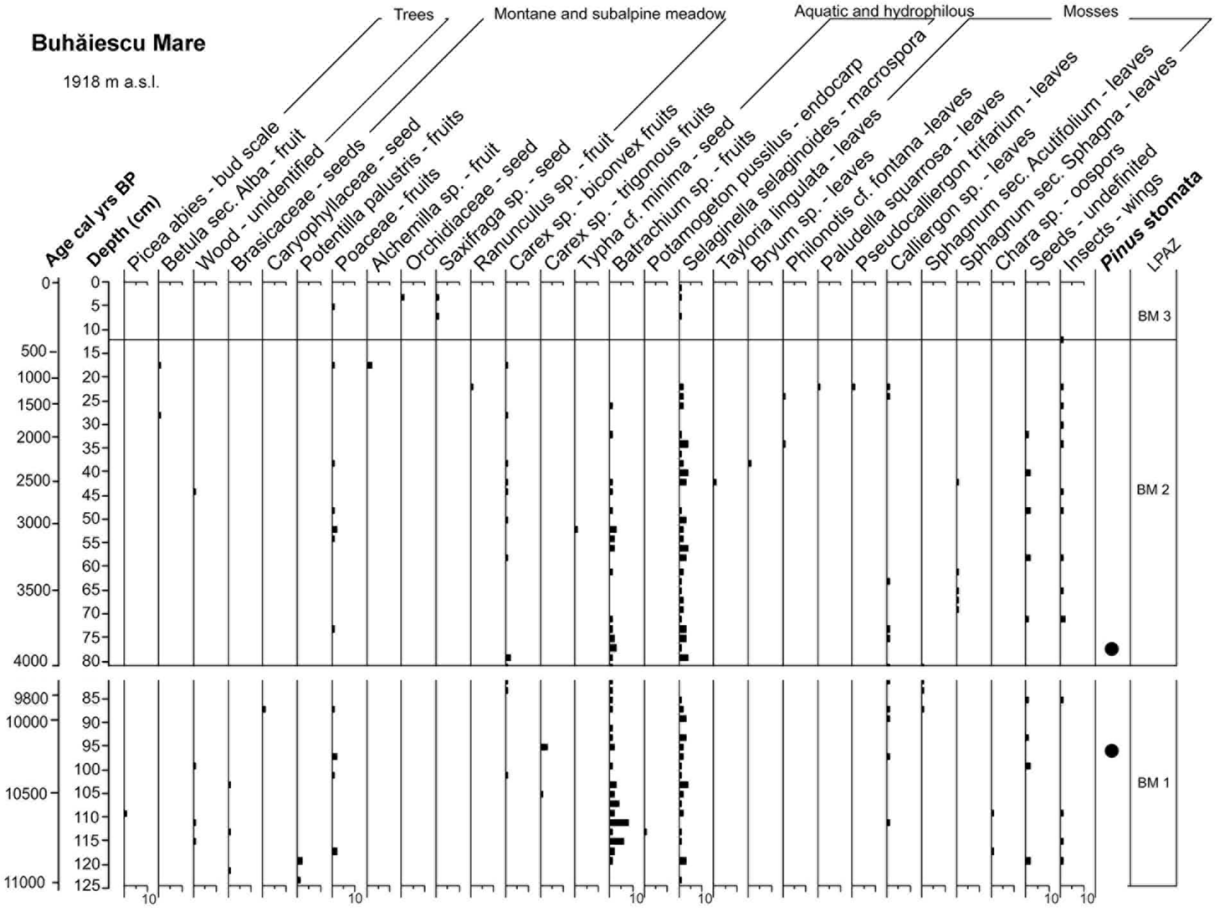

Figure 6. Plant macro-fossil concentrations per 15–20 cm³.

abies, Pinus diploxylon and *Pinus haploxylon*-types, *Abies alba, Fagus sylvatica* and *Corylus avellana*, which might be connected to the descent of the timberline. The relative 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) increased during this period (Figures 5 and 7). Plant macro-fossils were exclusively herbaceous and less diverse in this zone: Orchidiaceae, *Saxifraga* and Poaceae (Figure 6).

Micro- and macro-charcoal records of past fire activity

The micro- and macro-charcoal 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, micro-charcoal primarily regional, whereas macro-charcoal primarily of local origin.

For the early Holocene, where only concentration data are available because of the lack of a well-constrained chronology, micro-charcoal concentrations were the highest in the profile between 11,000 and 10,000 cal. yr BP, whereas macro-charcoal concentrations peaked between 10,000 and 9800 cal. yr BP. This indicates the occurrence of predominantly regional fires in the first part of the early Holocene, with local fires occurring after 10,000 cal. yr BP (Figure 7).

For the late Holocene, with a better constrained chronology, periods of high micro-charcoal accumulation rates were recorded between 4000 and 3500 cal. yr BP; 3000 and 1800 cal. yr BP; and more recently around 200 cal. yr BP, indicating intensified regional fire activity. Intervals of elevated macro-charcoal accumulation rates that partially overlap with micro-charcoal accumulation rates were noted between 4000 and 3500 cal. yr BP and around 1800 cal. yr BP, and suggest that most of the micro-charcoal particles during this period originated from local fires, but may also reflect a synchronicity between local fires and those in the region. However, intervals of solely elevated macro-charcoal accumulation rates were noted around 3000 and 2500 cal. yr BP, between 1400 and 1100 cal. yr BP and at 750 cal. yr BP, suggestive of episodic local fire activity.

Discussion

Our multi-proxy study in the Rodna Mountains, northern Romania, is the first to investigate Holocene treeline variability in the Carpathians. Although sediment deposition at the study site was not continuous and has been affected by a sedimentary hiatus spanning the last part of the early Holocene and the whole mid-Holocene (9800 and 4000 cal. yr BP), and possibly by sediment mixing, our results bring a valuable perspective on the impact of climate and land use changes on higher altitude vegetation.

General vegetation development: timberline composition and elevation limits

The abundant occurrence of *Pinus diploxylon*-type pollen (*Pinus sylvestris* and *Pinus mugo*), and *Pinus haploxylon* type (*Pinus cembra* – Swiss pine) between *c.* 11,000 and 10,000 cal. yr BP indicate a regional forest dominated by *Pinus* (Figure 4). Based on the dominance of *P. diploxylon* pollen (up to 70%), and given the altitude of the site (1918 m), is it probable that the timber below the site was primarily composed of *P. sylvestris* and secondarily *P. cembra*, while local pine communities consisted of the subalpine species *P. mugo*. The upper montane forests in the region also included *Picea abies, Betula* and *Larix decidua.* In

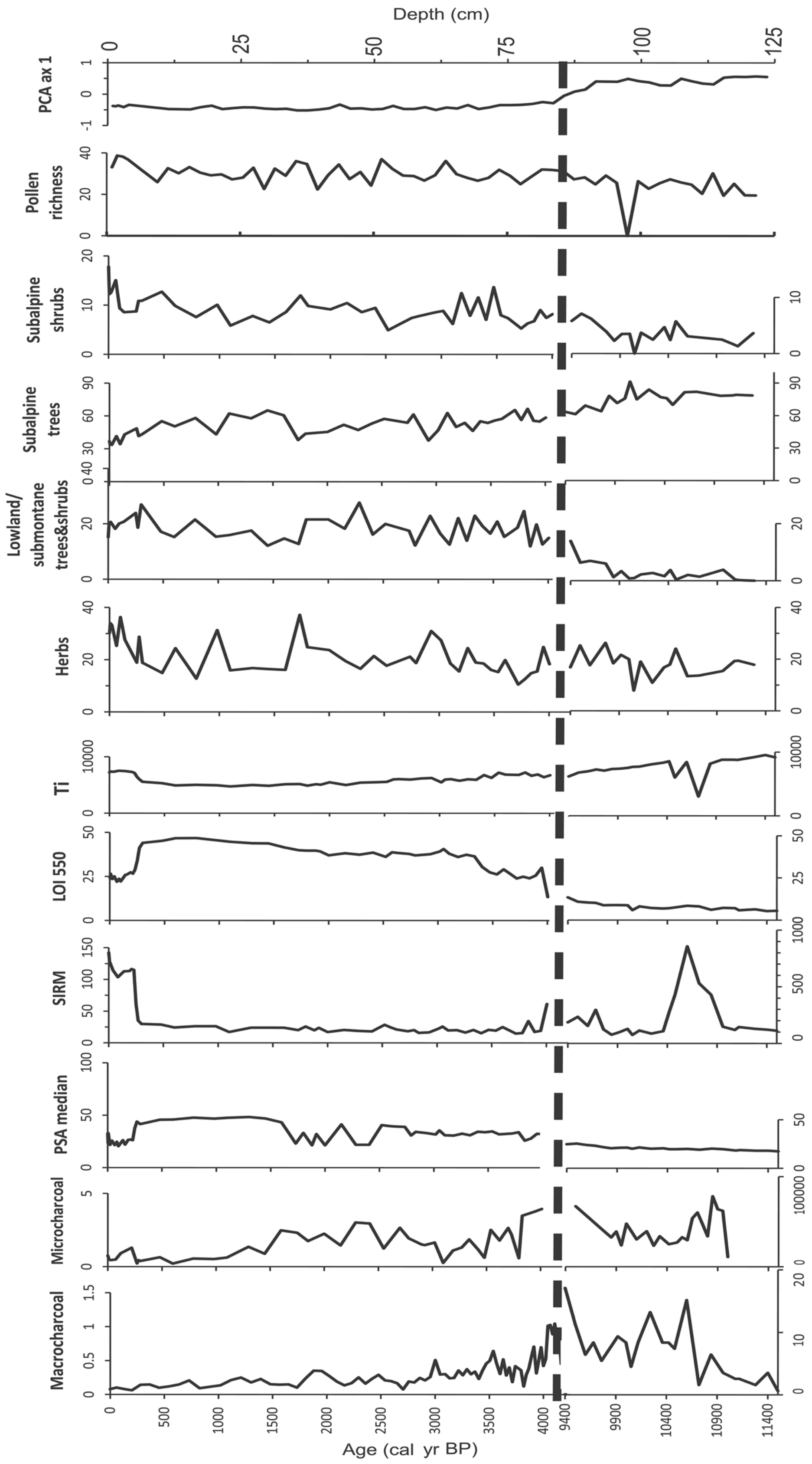

Figure 7. Multi-proxy results for Buhăiescu Mare Lake. Macro-charcoal: above hiatus – accumulation rate (cm^2/yr); below hiatus – concentration ($/cm^3$); micro-charcoal: above hiatus – accumulation rate (cm^2/yr); below hiatus – concentration ($/cm^3$); median particle size (μm); Saturated Isothermal Remanent Magnetisation (SIRM; 10^5 Am^2/kg); organic matter content at 550°C (%); Ti content (mg/kg); percentages for summed vegetation groups; pollen richness (E(T337)) and principal components analysis (PCA; axis 1 explains 85% of the variance). Dashed line marks the depositional hiatus.

the Swiss Alps, where most treeline studies in the closest settings to the Carpathians have been conducted, pollen percentages of 70–80% for subalpine tree taxa are considered to reflect regional timberline conditions, while herbaceous pollen percentages higher than 30% are interpreted as a treeless alpine environment (Berthel et al., 2012; Tinner and Theurillat, 2003). In Lake

Buhăiescu Mare's profile, the upper montane arboreal percentages are around 80% in the early Holocene, which indicates the proximity of the timberline limit (Figure 4). Yet, the lack of significant macro-fossils and the broad range of wind transport in *Pinus* pollen in high-altitude environments (Pellatt et al., 1998; Sugita et al., 1999; Tonkov et al., 2001) place this site above the timberline and treeline (Birks and Birks, 2000). A high proportion of *Pinus* is typical for many early Holocene sequences in the Carpathians, demonstrating the ubiquitous presence of *Pinus* across a wide elevation range (Fărcaş et al., 1999; Feurdean et al., 2011, 2012a; Magyari et al., 2012; Tanţău et al., 2011, 2014b).

After 9800 cal. yr BP, the arboreal pollen (AP) percentages remained constant, but there was an important shift in the upper montane species composition with *Picea abies* replacing *Pinus sylvestris/cembra* as the dominant component of the timberline ecotone (Figures 4 and 7). The pollen percentages for *Picea abies* from Lake Buhăiescu Mare show that spruce has persisted abundantly in the profile with little changes until 200–300 years ago, when it started to decline. The dominance of *Picea abies* in the timberline from about 11,000–10,000 cal yr BP fits with previous inferences of its long-lasting persistence and abundance at high elevations in the Carpathians throughout the Holocene (Fărcaş et al., 1999, 2013; Feurdean et al., 2011; Tanţău et al., 2011). Studies on the response of timberline and treeline to climate and human impact in the Alps suggest a stronger sensitivity of the timberline than the treeline. For instance, while the treeline moved 100–200 m throughout the Holocene, Tinner (2007, 2013) found that the timberline ascended from 2250 m at 11,000 cal. yr BP to 2500 m at 9000 cal. yr BP.

At our site, following an extended hiatus, the proportion of upper mountain trees (mainly *Picea*) decreased to *c.* 65% from about 4000 cal. yr BP, and *Abies alba* (10%) developed as a significant timber component (Figures 4 and 7). This paralleled an increase in the pollen percentages of subalpine shrubs (*Alnus viridis, Juniperus, Salix*), which probably indicates a lower timberline limit at this time (Figure 3). However, at the same time, the pollen of lowland and lower montane trees increased markedly with the beginning of the dominance of *Fagus sylvatica*. Today, beech is a significant forest constituent at elevations stretching between 400 and 1200 m, explaining its abundance in the Lake Buhăiescu Mare pollen record. Pollen of lowland montane and submontane trees such as *Fagus, Quercus, Carpinus, Corylus, Alnus* and *Betula* have been shown to be well represented in the modern pollen rain in montane and subalpine areas, where coniferous forests dominate (Tonkov et al., 2001, 2009). The expansion of *Fagus sylvatica* and *Abies alba* in the northern Carpathians appeared to be closely associated with the decline in *Picea abies* and increase in *Alnus viridis* (Björkman et al., 2003; Fărcaş et al., 2013; Tanţău et al., 2011, 2014a, 2014b). However, although the expansion of *F. sylvatica* occurred more or less simultaneous at these sites, the development of *Abies alba* is very heterogeneous, and there is a temporal difference of about 2000 years between sites (Fărcaş et al., 2013; Tanţău et al., 2011, 2014a, 2014b). *A. alba* has a low pollen productivity, heavy pollen grains that are deposited locally, and therefore, *A. alba* pollen percentages are a good indicator of local fir presence (Poska and Pidek, 2010). This distinctive pattern in the pollen representation of *A. alba* among sites in the northern Carpathians could reflect the past heterogeneous distribution of fir forests in the region. Outside the Carpathians, in the Alps, a marked timberline descent from 2400 m before 4500 cal. yr BP to ~2000–2100 m thereafter was primarily attributed to anthropogenic impact (Tinner, 2007, 2013). In the Rila Mountains, Bulgaria, a lowering of the timberline connected to human impact took place after 2800 cal BP (Tonkov and Marinova, 2005). We can therefore also imply some connection between human impact and the timberline descent in Rodna Mountains during the late Holocene (see section 'Human impact').

Treeline characteristics and position

Results from stomata, plant macro-fossil and wood remains suggest that Lake Buhăiescu Mare was probably situated above the treeline throughout most of the investigated period. There was, however, an occurrence of isolated fragments of tree macro-fossil (*Picea abies*) and stomata (*Pinus sylvestris*) during the early Holocene (11,000–9800 cal. yr BP), which suggest the presence of isolated pine and spruce trees close to the lake, and therefore possibly a higher position of the treeline during the early Holocene. It is also possible that the lake was located in a Krummholz zone, characterised by the presence of low-growing, prostrate individuals, just above the treeline. Added to the presence of unidentified wood macro-remains, this suggests the occurrence of woody vegetation in the form of trees and/or shrubs (*Pinus mugo, Alnus viridis, Juniperus, Salix*) in the lake's vicinity. Isolated macro-fossil and stomata findings, on the other hand, could also be wind transported from trees growing at elevations below the site as this mode of input has been previously documented in the Alps and in Norway (Berthel et al., 2012; Birks and Bjune, 2010; Lotter and Burks, 2003).

The position of the treeline is climatically sensitive and is influenced mainly by summer temperatures (Körner, 2012). Early Holocene climate reconstruction and simulation studies show that the climate of the region was characterised by warmer and drier-than-today summers (Feurdean and Willis, 2008; Feurdean et al., 2013a; Tóth et al., 2012) because of high summer insolation (Kutzbach and Webb, 1993). Our palaeobotanical results may suggest that the treeline responded sensitively to the warmer conditions of the early Holocene and was probably higher than the current treeline. A compositionally diverse and comparatively elevated early Holocene treeline (2000 m a.s.l.) has also been documented in the southern Carpathians (Magyari et al., 2012). In the Alps, the reconstructed position of the treeline during the interval 10,000–6000 cal. yr BP was around 2550 m, therefore up to 180 m higher than its present elevation (Tinner, 2007). The problems of the stratigraphic hiatus and good chronological control in the Buhăiescu Mare sediment profile do not allow for any precise timing of the sequence of vegetation changes during the early and mid-Holocene.

Over the last 4000 years, a single *Pinus* stomata (~3800 cal. yr BP), and two *B.* sec. *alba* fruits at 1600 and 600 cal. yr BP, in conjunction with herbaceous pollen percentages greater than 30%, may indicate the temporary occurrence of isolated, possibly krummholz-like individuals, growing in the lake area in an otherwise open landscape. Climatically, low June insolation at mid-latitude in the Northern Hemisphere during the late Holocene (Berger and Loutre, 1991) led to a decline in reconstructed and simulated summer temperatures in the region (Feurdean et al., 2008, 2013b). In the Alps, the treeline dropped around 4000 cal. yr BP from 2550 to 2400 m and showed a further gradual decline to reach 2350 m at the present as a result of a cooler climate and human disturbance (Tinner, 2007; Tinner and Theurillat, 2003). In the Rila Mountains, Bulgaria, treeline depression occurred after 2800 cal yr BP and is connected to anthropogenic disturbance (Tonkov and Marinova, 2005). Interestingly, however, recent (i.e. the last 100–150 years) rises in the treeline have been documented in northern areas of the Carpathians such as Ukraine (Martazinova et al., 2011), Poland, Slovakia and Hungary (Kozak et al., 2007), and attributed to changes in land use such as land abandonment and the regeneration of abandoned land in the mountain zone (Weisberg, 2011).

Human impact

To obtain information about the nature of human activities and their impact on vegetation, we used several pollen types such as pollen from cultivated plants, or so-called primary anthropogenic indicators (*Cerealia*-type, *Secale*), and pollen of herbaceous plants associated with pastures/meadows or ruderals, that is, secondary anthropogenic indicators (*Plantago media/major, P. lanceolata,* *Artemisia*, Asteraceae, *Cannabis, Urtica, Rumex*; Behre, 1988; Brun et al., 2007; Feurdean et al., 2013b). In addition, spores of coprophilous fungi may indicate an increased presence of grazing herbivores in the area. There are no significant palaeoecological indicators of human impact in the lower part of the profile (i.e. the early Holocene), and therefore, we imply that natural vegetation and fire dynamics predominated (Figures 4 and 5). After the hiatus in our sediment profile, and from about 4200 cal. yr BP, Cerealia and *Secale* pollen types are present at low values signalling agricultural activities at lower altitudes (Figure 5). However, pollen of primary (Cerealia) and of secondary anthropogenic indicators, mostly pasture indicators (*Plantago lanceolata, Urtica Rumex*, Asteroideae and Cichorioideae), increased from about 3200 cal. yr BP onwards and show the presence of grazing activities in upland areas and possibly in the lake vicinity. Indications of the first human impact in other mountain sites from this region range from *c.* 8000 years ago, that is, Neolithic (Fărcaş et al., 2013; Feurdean and Astalos, 2005), to 3200 cal. yr BP, that is, Iron Age (Tanţău et al., 2011). However, most pollen sequences from the Carpathians concur in showing a clearer human impact from the Bronze Age, that is, from 4000 cal. yr BP onwards (Fărcaş et al., 2003; Feurdean et al., 2013b; Tanţău et al., 2011). North of our study area, the first indication of human impact was about 4000 years ago in the Tatra Mountains, Slovakia (Obidowicz, 1996) and about 3600 cal. yr BP in SE Poland (Kołaczek, 2007).

Anthropogenic impacts on local and regional vegetation increased after 1200 cal. yr BP. This is manifested as a further local expansion of alpine herbaceous communities, ruderal species (Poaceae, *Artemisia, Ambrosia, Rumex*, Chenopodiaceae, Asteroideae, Cichorioideae, Apiaceae, *Urtica*) and coprophilous fungi (*Sporormiella*), suggesting the enlargement of local grazed areas (Figures 5 and 7). Since this episode coincides with 'Mediaeval Warm Period' (AD 800–1300), it is possible that warmer climate conditions increased the length of the high-altitude pastoral season and resulted in a more visible modification of the vegetation around the study site, similarly to observations of this effect in the Apuseni Mountains (Feurdean et al., 2009) and Alps (Tinner et al., 2003).

The enhanced abundance and diversity of primary and secondary anthropogenic indicators, shrubs (*Alnus viridis* and *Corylus avellana*) and of micro-charcoal values over the past ~300 years are synchronous with a decline in the abundance of upper mountain trees (*Abies alba, Picea abies*). Intensification of local grazing activity over the past 300 years is also indicated by the slight increase in coprophilous fungi spores (especially *Podospora, Sporormiella* and *Sordaria*). These may be suggestive of an anthropogenically driven drop in the timberline and treeline connected to intensification of land use (Figures 4, 5 and 7). *Abies alba* and *Pinus cembra* are sensitive to disturbance by fire (Feurdean and Willis, 2008; Tinner et al., 1999), whereas *Alnus viridis* and *Corylus avellana* are favoured by burning (Tinner et al., 1999). Thus, the decline in *Abies alba* and expansion of *Alnus viridis* and *Corylus avellana* around the time of enhanced local and regional fire activity could be related to an intensification in burning to clear and manage the land for grazing. A high sensitivity of mountain trees to fire has also been noted in the Pyrenees (Gil Romera et al., 2014). Evidence for widespread forest clearing and burning over the past ~300 years is common in most palaeoecological records in the Carpathians (Fărcaş et al., 2013; Feurdean et al., 2009, 2012b, 2013a; Tanţău et al., 2003, 2011). Tree cutting in the subalpine area since the early 20th century is documented by Kubijovič (1934). Such records show that forest clearance and burning lead to development of subalpine dwarf-shrub communities (*Rhododendro-Pinetum mugi* and *Bruckenthalio-Piceetum*) in forest clearings (Coldea and Cristea, 1998). On the other hand, clearance and burning of subalpine vegetation to expand pastures has also led to the reduction of *Pinus mugo* at this elevation (Coldea and Cristea, 1998). The peaks in grazing indicators, coprophilous fungi and micro-charcoal during the past 200 years, but in particular over the last 50 years, correspond to higher values of SIRM and Ti in the sediment profile (Figure 7), probably indicating increased soil erosion following periods of more intense land use including burning (Hutchinson, 1995; Oldfield et al., 2003; Yang and Rose, 2005). This, together with a lowering of sediment organic matter, implies a better geomorphological connectivity between the lake and its catchment, that is, the depression was once again responding to catchment changes more like a lake receiving a stream inflow, than a mire.

Conclusion

Our multi-proxy study in the Rodna Mountains and Biosphere Reserve in northern Romania is the first to investigate Holocene treeline variability in the Carpathians and brings a valuable perspective on the impact of climate and land use changes on higher altitude vegetation. Results from stomata, plant macro-fossil and wood remains suggest that Lake Buhăiescu Mare was situated above the treeline throughout most of period investigated. However, isolated trees, or krummholz, have been present sporadically around the lake, especially during the early Holocene, indicating a higher treeline position than today.

Anthropogenic impact has intensified in the last 1200 years and has contributed to the lowering of timberline and increased slope erosion. This feature is even more apparent in the last 200 years, suggesting that human-driven land use has had a stronger contribution to changes in land cover than the climate over the last millennium in the Rodna Mountains. The effects of current global warming, such as an advance of the trees towards higher altitudes, are not yet visible in the pollen and plant macro-fossil records of this site.

The palaeoecological record suggests that alpine meadows have persisted since the early Holocene and throughout the past 4000 years at the elevation of Lake Buhăiescu Mare. However, the area occupied by alpine/snow bed communities has expanded slightly over the past 4000 years, and in the recent past (the last 200 years), in particular. This implies that the current alpine communities around the study site were close to a natural state until 200 years ago, but have been enlarged thereafter by human activities such as summer grazing and tree cutting/burning. In the absence of anthropogenic impacts, in response to the anticipated global warming, these alpine communities would probably face a restriction in their habitats because of the upward movement of subalpine tree species.

Although, outside Romania, uncontrolled deforestation in the Carpathians decreased after the year 2000 and forest expanded; in Romania, this trend is not visible as legal and illegal deforestation is ongoing even in protected areas. According to the 2012 Greenpeace report (www.greenpeace.org/romania/global/romania/paduri/despadueririle%20din%20Romania/forestcover%20change%20in%20Romania%202000-2011.pdf), 3.4% of Romania forest cover was lost or degraded between 2000 and 2011. Therefore, balancing future climate change with land use management remains a considerable challenge.

Acknowledgements

We are very thankful to Daniel Forgaci for fieldwork, Andreea Auer for macro-charcoal counting, Joannes Janssens for help in identification of fossil mosses and Elena Marinova for help in selecting plant material for dating. Two anonymous referees are gratefully acknowledged for their suggestions improving this manuscript.

Funding

AG and AF received support through a grant of the Romanian National Authority for Scientific Research, CNCS – UEFISCDI (project number PN-II-RU-TE-2011-3-0145). AG acknowledges grant POSDRU/159/1.5/S/132400.

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