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How warm? How wet? Hydroclimate reconstruction of the past 7500 years in northern Carpathians, Romania

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Abstract

As natural and anthropogenic ecosystems are dependent on the local water availability, understanding past changes in hydroclimate represents a priority in research concerning past climate variability. Here, we used testate amoebae (TA) and chironomid analysis on a radiocarbon dated complex of small pond and peat bog sediment profiles from an ombrotrophic bog (Tăul Muced, northern Carpathians, Romania) to quantitatively determine major hydrological changes and July air temperature over the last 7500 years.

Wet mire surface conditions with a pH between 2.3 and 4.5 were inferred for the periods 4500–2700 and 1300–400 cal yr BP by the occurrence of *Archerella flavum*, *Amphitrema wrightianum* and *Hyalosphenia papilio*. Dry phases in mire surface conditions and a pH between

2.5 and 5 were inferred for 7550–4500, 2750–1300 and 0 cal yr BP–present by the dominance of *Nebela militaris*, *Difflugia pulex* and *Phryganella acropodia*. The quantitative reconstruction of mean July temperature based on the chironomid communities suggests low summer temperatures for the periods 6550–5600, 4500–3150 and 1550–600 cal yr BP, while periods of slightly higher summer temperatures were observed for 5600–4500, 3150–1550 and 100 cal yr BP–present. There is a general good agreement between drier phases of the peat surface conditions with higher July temperature, suggesting that temperature may have been a controlling factor for water table fluctuation.

Our quantitative reconstructions, among the first for central eastern Europe, show a relatively good agreement with other palaeohydrological studies from central eastern Europe, but contrast with others estimates from north-west Europe. Another important aspect of our study is that it provides valuable information on changes in local hydrology and the potential effect of the mean summer temperature over these changes.

Keywords: Holocene, climate dynamics, eastern Carpathians, Chironomidae, ombrotrophic peat, testate amoebae, quantitative reconstructions.

1. Introduction

In the past 50 years, global mean air temperatures have showed a warming tendency of approximately 0.6°C (e.g. Bindoff et al., 2013; Ljungqvist et al., 2016). At a European scale, the temperature increase has been particularly pronounced in summer (June–August), with a mean increase in temperature of ~1.3°C. An increase in the severity and frequency of extreme weather events has also been observed (Gagen et al., 2016; Luterbacher et al., 2016). This warming tendency is corroborated by the recorded rise in annual (~0.6°C) and summer mean temperatures (~1.3°C), and the frequency of extreme weather events coupled with a decline in mean annual precipitation (~100 mm) over the last two decades in the northern Carpathians, our study area (Dragotă and Kucsicsa, 2011). With predictions suggesting that the climate will continue to warm and the frequency of extreme climate events will increase, efforts are being made to improve the accuracy of climate predictions (PAGES 2k Consortium, 2013).

While the climate of the recent past (last century) may be estimated from documentary sources and meteorological data, for the earlier periods we rely on indirect inference (proxy data) from a range of natural archives like ice cores, marine and terrestrial sources (lake sediments, bogs, speleothems and tree rings) (Bradley, 1999). The past climate variability has been estimated using different approaches, e.g. plant macrofossils, testate amoebae, plant biomarkers, tree rings, chironomids and pollen (Feurdean et al., 2014; Moreno et al., 2014). However, in comparison with palaeotemperature, past hydrological conditions have rarely been quantified (Christiansen and Ljungqvist, 2012) even though moisture availability is one of the most critical environmental variables for natural vegetation, ecosystem services and societal needs (Cook et al., 2014; D'Odorico and Bhattachan, 2012; Field et al., 2013; Schewe et al., 2014). Ombrotrophic bogs are particularly suitable for reconstructing past hydro-climatic conditions, as they are entirely dependent on water from precipitation and are isolated from other water sources (Chambers et al., 2012; Chambers and Charman, 2004; Charman et al., 2009; Lamentowicz et al., 2008; Nichols et al., 2009). In addition to climate, autogenic processes and human activity can also influence the local peat-development, hydrology and chemistry and therefore the assemblages of macro- and microfossils preserved in the peat (Belyea and Clymo, 2001). However, knowledge of the ecology of peatlands and their response to environmental factors is best known for oceanic bogs, which are different from bogs from more continental areas. In continental bogs, summer temperature is assumed to play a greater role than precipitation in changing mire surface moisture (Kulczyński, 1949; Rydin and Jeglum, 2006). Winter temperatures and snowfall and/or delayed snowmelt can be a source of water supply to these peatlands (Charman, 2007). In addition, the surface moisture can reflect shifts in the strength of atmospheric circulation patterns and position of major regional air masses.

While the Holocene climate was once considered to be relatively warm and stable, high-resolution ice and marine records have since shown that the Holocene climate was quite variable (e.g. Bond et al., 1997; Magny et al., 2003; Mayewski et al., 2004; Wanner et al., 2011). However, our knowledge of the past European Holocene climate comes mainly from central and north-western Europe, with quantitative climate reconstructions in the central-eastern part still being rare (e.g. Feurdean et al., 2015a, 2008; Hájková et al., 2016; Lamentowicz et al., 2015; Tóth et al., 2015). Specifically, for Romania, the available quantitative hydro-climate reconstructions are based on testate amoebae (Feurdean et al., 2015a; Schnitchen et al., 2006) and pollen records (Feurdean et al., 2008), whereas summer temperatures have been inferred either from chironomids (Tóth et al., 2015) or pollen records (Feurdean et al., 2008). Reviews of qualitative and quantitative palaeotemperature and palaeohydroclimate records for this region were also recently published (Kern et al., 2016; Perşoiu, 2017).

Here, we investigate two profiles from Tăul Muced ombrotrophic peatland located in northern Romania, to document the magnitude of climate variability and environmental changes over the past 7500 years. One profile represents a peat sequence extracted from the centre of this peatland and analysed by means of testate amoebae to reconstruct water table depth (DWT: depth to water table) and pH variability. The second profile was extracted from a small pond located in the middle of this mire and was subjected to chironomid analysis to reconstruct mean July air temperature. The specific objectives were:

(1) to determine the main compositional and ecological trends of subfossil communities of testate amoebae and chironomids;

(2) to quantitatively reconstruct water table depth and pH based on testate amoebae, and July air temperature based on chironomids;

(3) to use the July air temperature reconstruction to constrain the potential effect of evapotranspiration on changes in the water table;

(4) to assess how our inferred hydroclimate conditions compare to those at larger, i.e. regional to continental, spatial scales.

Combining the reconstructions of water table depth and pH, based on testate amoebae, with those of mean July air temperature, based on chironomids, makes use of the strengths of these approaches while mitigating their weaknesses and can yield important additional insights into past climate variability. This is also one of the very few climatic studies set in the continental climate area of eastern Europe.

2. Study area

The study site is located in the Rodna National Park and Biosphere Reserve of the Rodna Mountains, Eastern Carpathians (Fig. 1). Climatically, the study area has a moderate, temperate continental climate with Atlantic and Baltic influences (Doniţă, 2005). A mean air annual temperature of 1.2ºC with mean air summer temperature of 9.4°C and a mean of 10.3°C July air temperature, together with a mean annual precipitation of 1240 mm are reported from the Pietrosul Meteorological Station situated at an altitude of 1785 m. Assuming a 0.55°C increase per 100 m altitude (Pop, 1988) results in a 3.4°C mean annual temperature, 11.6°C mean summer temperature and 12.5°C mean July air temperature at the study site (1360 m a.s.l.). The quantity of precipitation is highest in the summer and lowest in winter. From the geological point of view, the surroundings are comprised of crystalline rocks such as mica schists, conglomerates, limestones, black shales and sandstones (Sahy et al., 2008; Tămaş et al., 2011). The regional vegetation is composed of compact spruce (*Picea abies*) forest (Feurdean et al., 2015a). Marked deforestations are ongoing in the region but not in the immediate vicinity of the study site.

The study site, Tăul Muced (47º34'26" N, 24º32'42" E; 1360 m a.s.l.; 2 ha), is an ombrotrophic raised bog and ca. 0.5 ha of the total surface has the status of a scientific reserve IUCN category Ia (Management Plan of Rodna Mountains National Park, 2013). A small pond of ca. 0.2 ha is located in the central part of the bog. Most of the bog surface is covered by spruce, with patches of dwarf pine (*Pinus mugo*). The moss communities are dominated by *Sphagnum* species (*Sphagnum russowii*, *S. magellanicum*, *S. amblyphyllum*, *S. capilifolium*, *S. cuspidatum*) along with *Vaccinium microcarpum*, *Oxycoccus palustris*, *Scheuchzeria palustris*, *Eriophorum vaginatum*, *Carex pauciflora*, *C. goodenowii*, *Vaccinium myrtillus*, *Drosera rotundifolia*, *Listera cordata*, *Homogyne alpina*, *Dicranum scoparium*, *Pleurozium schreberi*, *Polytrichum strictum* and *Bazzania trilobata* (Feurdean et al., 2015).

3. Methods

A peat (0-500 cm) consisting lacustrine sediments in the bottom part (500-560 cm) was extracted from the centre of the peat bog using a combination of Livingstone and Russian coring equipment. A lacustrine sequence of 245 cm was extracted from a small pond located close to the peat bog centre using a combination of gravity and Livingstone coring equipment. A sedimentary gap in the profile occurs approximately between 20 cm and 39 cm, when the equipment was changed between gravity and Livingstone corer due to the prevalence of a very soft material. The cores were wrapped in plastic films, sealed for transportation and stored at 4ºC.

3.1. Chronology

The chronology of the peat sequence has already been described in detail (see Feurdean et al., 2015a). The chronology of the lacustrine sequence was established based on 6 AMS radiocarbon measurements performed on *Picea abies* needles at Chrono Centre in Queen's University Belfast Radiocarbon Laboratory, Northern Ireland (see Table 1).

3.2. Testate amoebae

Sub-samples for testate amoebae were extracted from the peat core at 2–4 cm intervals. The preparation followed standard protocols (Charman et al., 2000; Hendon and Charman, 1997). Samples of 1 cm^3 were boiled for 10 minutes, stirring occasionally to disaggregate the peat, then sieved through 300 μm meshes. The 15 μm mesh suggested in the protocol was omitted to avoid the loss of small taxa (Payne, 2009; Wall et al., 2009). The resulting material was centrifuged at 3000 rpm for 10 minutes, and the residues were stored in vials with glycerol. Each sample was analysed under a microscope at 400× magnification. A minimum of 150 specimens were counted and identification followed the available literature (e.g. Grospietsch, 1958; Mazei and Tsyganov, 2006; Ogden and Hedley, 1980). Along with testate amoebae, the shells of *Habrotrocha angusticollis* (bdelloid rotifer) were also counted.

3.3. Chironomids

For chironomid analysis, 2 cm^3 sub-samples of sediment were prepared at 4 cm intervals from the pond core, except were the material was missing (20-39 cm). Before preparation, the sub-samples were deflocculated in 10% KOH and heated to 60ºC for 20 minutes. After this step, the sediment was sieved with a 100 µm mesh and poured into a Bogorov-counting tray (Gannon, 1971). All of the head capsules of chironomid larvae were handpicked under a stereo microscope at 40x magnification and mounted on microscope slides in Euparal mounting medium for microscopic identification. Since at least 47–50 head capsules were found and identified from each sub-sample, they provided a representative count for quantitative analysis (Heiri and Lotter, 2001). Taxonomical identification followed Brooks et al. (2007), Rieradevall and Brooks (2001) and Wiederholm (1983).

3.4. Loss on ignition (LOI)

To determine the organic matter of the lake profile, a fist order estimation of lake trophycity we used the loss on ignition method (LOI). Sediment samples of known weight and volume were placed in pre-weighed crucibles, dried for 12 hours at 105 °C in order to remove water content, cooled and weighed again. The samples were then heated at 550°C for 4 hours, cooled, and re-weighed in order to estimate the organic matter (OM) and minerogenic content (Heiri et al, 2001).

3.5. Numerical analysis

Testate Amoebae Zones (TAZ) were numerically defined using a classical clustering analysis (unweighted pair-group average; Hammer et al., 2001) in order to determine major temporal changes in assemblage composition. To summarize the main changes in subfossil testate amoebae, we performed detrended correspondence analysis (DCA) on square root transformed percentage data with CANOCO version 4.5 (ter Braak and Šmilauer, 2002). Due to the lack of regional modern databases for testate amoebae, the water table depth (DWT) and pH reconstructions were inferred using a transfer function developed from peatlands in Poland (Lamentowicz et al., 2008; Lamentowicz and Mitchell, 2005).

Stratigraphic boundaries in the chironomid record were determined based on optimal splitting by information content using the program Psimpoll 4.27 (Bennett, 2007). In order to summarize the main changes in subfossil chironomid assemblages, DCA was performed on square root transformed percentage data using CANOCO version 4.5 (ter Braak and Šmilauer, 2002). Chironomid-inferred mean July air temperature (T_{VII}) reconstructions were performed using weighted averaging partial least-squares regression (WA-PLS; ter Braak and Juggins, 1993) based on a merged Norwegian–Swiss chironomid–temperature calibration data-set (Brooks and Birks 2001,2000; Heiri et al., 2011; Heiri and Lotter 2010). The reconstructions were calculated using the C2 software (Juggins, 2007).

4. Results

4.1. Chronology

The chronology of the Tăul Muced peat bog is presented in detail in Feurdean et al. (2015a). The age–depth model of the Tăul Muced pond sequence (Fig. 2) was constructed using the smooth spline method as implemented by the CLAM software (Blaauw, 2010). In this model, the ^{14}C AMS age estimates were converted into calendar years BP using the IntCal13 data set of Reimer et al. (2013). The radiocarbon measurement UBA- 26358 post date the 1950. The radiocarbon measurement of 4008±31 cal. yr BP at 155 cm appears too old compared to the measurement below (3985±33 cal. yr BP at 199 cm) and was rejected from the age–depth model based on the correlation between pollen stratigraphical markers at Tăul Muced pond and peat. We have constrained our chronology for the lower part of the pond profile, using several common pollen stratigraphical markers between the two sequences, as the peat sequence has a better constrained chronology and assuming that the trends in pollen percentages of the main tree taxa should be similar at the two located just a few meters apart (Fig. A1); (see Feurdean et al., 2017 for the pollen record at Tăul Muced peat). The first tie point, approximately at 2600 cal yr BP (130 cm) is indicated by the rise of *Fagus sylvatica* pollen percentages (Fig. A1). The second tie point, approximately at 2900 cal yr BP (140 cm) is represented by a peak of *Picea abies* and low pollen percentages of *Fagus sylvatica*. The third tie point is approximately at 4500 cal yr BP (200 cm) and marked by another peak of *Picea abies* pollen percentages and low pollen values of *Carpinus betulus*. The fourth tie point, at around 4900 cal yr BP (210 cm) is marked by low values of *Picea abies,* a peak in *Carpinus betulus* and increasing abundance of *Fagus sylvatica*. The fifth tie point, approximately at 5500 cal yr BP (225 cm) is marked by high values of *Picea abies,* declining pollen percentages for *Corylus avellana* and the preceded the onset of *Carpinus betulus* increase. According to this correlation, the age–depth model (age 1) which excludes the date 4008±31 cal yr BP at 155 cm gives the best fit between the peat and pond sequences (Fig. A1b). According to the alternative age–depth model (age 2), which excludes the 3985±33 cal yr BP date at 199 cm, the timing of changes in the abundance of these taxa occurred much earlier (5500–6000 cal yr BP) than in the Tăul Muced peat profile (Fig. A1c) and we therefore chose to reject this age–depth relationship.

4.2. Testate amoebae assemblages

Although the peat sequence is older (Feurdean et al., 2015a), due to poor preservation the testate amoebae assemblages were statistically significant starting with 7550 cal yr BP. Altogether, 29 testate amoebae taxa were identified in the Tăul Muced peat profile, the most common being *Archerella flavum*, *Difflugia pulex*, *Hyalosphenia papilio* and *Nebela militaris*. Based on their relative abundance, six testate amoebae zones (TAZ) were established (Fig. 3). The zone limits were mainly associated with changing abundance of the four most dominant taxa. DCA axis 1 scores cover 2.16 SD units and indicate distinct compositional changes in the testate amoebae assemblages (0.8–1.8 SD units) at zone boundaries. The most important shifts occurred at TAZ-2/TAZ-3 (240 cm; ~2750 cal yr BP), TAZ-3/TAZ-4 (166 cm; ~1300 cal yr BP) and TAZ-4/TAZ-5 (62 cm; 400 cal yr BP).

The oldest zone, TAZ-1 (440–295 cm; 7500–4500 cal yr BP) was dominated by *D. pulex* (mean 70%) and *A. flavum* (mean 23%). Other important species were *Assulina muscorum*, *H. papilio* and *N. militaris* with maximum percentages of 5%. Rare species for this period were *Amphitrema wrightianum* and *Nebela tincta*.

In TAZ-2 (295–240 cm; 4500–2750 cal yr BP), *D. pulex* decreased to ca. 60%, while *A. flavum* increased to a mean of 25%. *H. papilio* retained the abundance of the previous zone. Rare taxa included *Arcella discoides*, *Assulina seminulum* and *N. tincta*.

At the onset of TAZ-3 (240–166 cm; 2750–1300 cal yr BP), *D. pulex* dropped to almost 20%, while *A. flavum* increased to 55% and *A. wrightianum* to 22%. In the second part of TAZ-3 (1850–1300 cal yr BP), *D. pulex* regained its dominance (75%), whilst *A. flavum* decreased to 10–22%. Another important taxon of this period was *H. papilio* (15%). Rare taxa were

Bulinularia indica, *Heleopera sylvatica*, *Hyalosphenia subflava, Nebela parvula*, *N. minor* and *Trinema lineare*. The rotifer *Habrotrocha angusticollis* occurred at a low, but relatively stable, relative abundance in this zone.

TAZ-4 (166–62 cm; 1300–400 cal yr BP) was characterized by the highest diversity with ca. 18 species. The dominant taxa were *A. flavum* (mean of 45%), *H. papilio* (20%) and *A. wrightianum* (15%). At the same time, *D. pulex* percentages dropped to almost zero. Rare taxa for this period were *Heleopera rosea*, *H. sphagni*, *H. subflava* and *Trigonopyxis arcula*.

TAZ-5 (62–8 cm; 400–(-30) cal yr BP) was dominated by *A. flavum* (mean 30%), *H. papilio* (15%) and *N. militaris* (13–37%). *Phryganella acropodia* showed a rapid increase in abundance (74%). Rare taxa were *Assulina scandinavica*, *Centropyxis aculeata*, *H. sphagni*, *H. subflava*, *N. parvula* and *T. arcula*.

TAZ-6 (8–0 cm; -30–present) was dominated by *Euglypha cristata* (40%), taxon that appear only in this period, along with *N. militaris*, *D. pulex* and *N. tincta* all with a mean of 15% and *Corythion dubium* with 13%. Rare taxa for this period were *H. subflava* and *Physochilla griseola*.

4.3. Depth to water table and pH reconstruction

On the basis of the subfossil testate amoebae record of Tăul Muced (Fig. 3), the reconstruction of depth to water table (DWT) ranged from 5 to 28 cm, while for pH, reconstructed values ranged from 2.3 to 5. Between 7500 and 4500 cal yr BP, the DWT was low and fluctuated strongly from 15 to 24 cm, whilst the pH ranged from 2.4 to 4. This was followed by a period (4500–2750 cal yr BP) of increased DWT to values between 7 and 16 cm, and less acidic conditions, i.e. pH 2.7–4.8. The third period (2750–1300 cal yr BP) was characterized by lower DWT (14 and 24 cm) and more acidic conditions, pH 2.6–3.8. In the next interval, 1300–400 cal yr BP, the inferred DWT increased to values between 5 and 18 cm and the pH to between 3.5 and 5, followed (400–100 cal yr BP) by a new decline in DWT to 25–28 cm and a pH of 3.5. During the last century of the sequence (between 100 and -30 cal yr BP), DWT reached 9 cm and pH was 4.4. The values dropped to 26 cm and 4.4, respectively, during the last 30 years.

4.4. Chironomid assemblages and organic matter content

Altogether, 20 Chironomidae taxa (Diptera) were identified from the sediment, the dominant taxa being *Chironomus anthracinus*-type, *Cladopelma lateralis*-type, *Endochironomus impar*-type, *Limnophyes*, *Procladius* and *Psectrocladius sordidellus*-type (Fig. 4). Remains of one other dipteran family, Ceratopogonidae, were found continuously throughout the profile. Based on changes in chironomid assemblages, seven zones (CZ: chironomid zones) were distinguished (Fig. 4). The DCA axis 1 scores (1.44 SD units) show important changes in the chironomid assemblages (0.5–1.2 SD units) at the zone boundaries. The most marked shifts (>0.5 SD units) occurred at CZ-1/CZ-2 (188 cm; ~4100 cal yr BP), CZ-2/CZ-3 (160 cm; ~3150 cal yr BP) and CZ-3/CZ-4 (141 cm; ~2650 cal yr BP) boundaries.

CZ-1 (246–188 cm; 6550–4100 cal yr BP) was dominated by *C. anthracinus*-type (30%), whilst *E. impar*-type, *C. lateralis*-type, *P. sordidellus*-type, *Corynoneura lobata*-type, *Limnophyes* and *Procladius* also reached relatively high abundances (≥10%). Remains of Ceratopogonidae occurred in the largest number in this sediment section. Chironomid concentration fluctuated strongly (between 30 and 120 head capsules/cm^3). At the beginning of the period the OM values dropped from 88% to 75%, and then returned to 84%.

In CZ-2 (188–160 cm; 4100–3300 cal yr BP), the previously dominant *C. anthracinus*-type decreased distinctly (25%), whilst *P. sordidellus*-type became the dominant chironomid group (40%) and *C. lateralis*-type, *C. lobata*-type, *E. impar*-type, *Limnophyes* and *Procladius* increased in abundance. The number of Ceratopogonidae remains slowly decreased. The OM values were stable around 88%.

At the onset of CZ-3 (160–141 cm; 3300–2850 cal yr BP), the proportion of the two dominant taxa switched again. *C. anthracinus*-type reached its maximum abundance (≥50%), while *P. sordidellus*-type together with *C. lateralis*-type and *C. lobata*-type disappeared. Additionally, chironomid concentrations and numbers of Ceratopogonidae decreased considerably. The OM abruptly dropped to 75%.

CZ-4 (141–121 cm; 2850–2350 cal yr BP) was characterized by slightly decreasing relative abundance of *C. anthracinus*-type, and the re-appearance of *P. sordidellus*-type, *C. lateralis*-type and *C. lobata*-type. Chironomidae concentration as well as the number of Ceratopogonidae remains (10 head capsules/cm^3) increased. In this period, the OM reached 85%.

In CZ-5 (121–54 cm; 2200–1000 cal yr BP), *P. sordidellus*-type and *C. lateralis*-type dominated (20%) but the earlier dominant taxa, *C. anthracinus*-type, *E. impar*-type and *Limnophyes*, also reached high relative abundances (10–20%). At the beginning of this period, the OM reached 95%, followed by a decreasing trend and stabilization around 88%.

CZ-6 (54–39 cm; 1000–550 cal yr BP) started with a further increase of *P. sordidellus*-type until ca. 850 cal yr BP. From ca. 850 cal yr BP, the abundance of *P. sordidellus*-type decreased, *C. lobata*-type and *Monopelopia* disappeared, whilst *C. anthracinus*-type increased again. Chironomid concentrations and numbers of Ceratopogonidae remains showed a short-term decline at ca. 850 cal yr BP. The OM was about 85%.

CZ-7 (20–1.5 cm; 100 cal yr BP–present) was dominated by *P. sordidellus*-type and *C. lobata*-type; however, *C. anthracinus* and *E. impar*-type also occurred with high relative abundances. Chironomid concentration and the number of Ceratopogonidae remains decreased. The OM was at 87% with fluctuating values.

4.5. July air temperature reconstruction

On the basis of the subfossil chironomid record of Tăul Muced (Fig. 4), the reconstructed mean July air temperatures (T_{VII}) based on the merged Norway–Swiss transfer function (NS-TF) ranged from 13.0 to 14.7°C. Between 6550–4800 cal yr BP, the chironomid-inferred temperatures fluctuated between 13.3 and 14.3°C, with an overall rising trend. This was followed by a short period (4800–4300 cal yr BP) where the temperatures reached 14.7°C. In the next period (4300–3200 cal yr BP) the July temperatures decreased from 14.1°C to 13.5°C. After a short-term increase of almost 1°C at around 3200 cal yr BP, the temperature decreased gradually to 13.2°C until 985 cal yr BP. Notable short-term fluctuations appeared after this period. Between 1000 and 600 cal yr BP, the temperatures dropped to almost 13°C. No samples were available between 600 and 100 cal yr BP (20–39 cm). Finally, from ca. 100 cal yr BP to the present, the July temperature increased to 14.3°C, temperatures that are higher than the present mean July air temperature of 12.5°C register at the nearby meteorological station.

5. Discussion

5.1. Ecological interpretation of changes in the subfossil testate amoebae assemblages and of the main trends in water table and pH

In the basal part of the peat sequence (ca. 7500–4500 cal yr BP), the dominant taxon was *Difflugia pulex*, which reached a relative abundance of 50–95% (Fig. 3). This species is generally widespread and abundant in fossil communities. In modern ecological studies, *D. pulex* is described with contradictory optima for water table depth, which raises a problem for palaeohydrological reconstructions. For example, Amesbury et al. (2013) describes *D. pulex* as a relatively high water table indicator, while in other studies it is regarded as an indicator for intermediate conditions (Booth, 2008; Charman et al., 2007) or even of low water table depth (Schnitchen et al., 2006; Turner et al., 2013). The differences in ecological status are underlined by Amesbury et al. (2013) and mainly explained by the poor representation of the species in the available modern data-sets that could lead to overestimates for the palaeohydrological reconstructions. However, *D. pulex* modern analogues were improved by Lammarre et al. (2013) who placed the species as an indicator of dry to intermediate moist conditions. The next abundant taxon during this period is *Archerella flavum*, which indicates wet conditions (e.g. Amesbury et al., 2013; Lamentowicz and Mitchell, 2005; Schnitchen et al., 2006). At Fenyves-tető bog, close to our study region (40 km aerial distance), Schnitchen et al. (2006) found *A. flavum* at a water table depth of 5–13 cm. *D. pulex* and *A. flavum*, the most common and abundant species in the Tăul Muced profile, have contrasting hydrological requirements, which results in the reconstruction of marked fluctuations in the mire surface conditions.

From ca. 4500 to 2750 cal yr BP, the percentages of *D. pulex* decreased slightly, whereas those of *A. flavum* and *Hyalosphenia papilio* increased (Fig. 3). Our DTW reconstruction points to a relatively wet mire surface environment for this interval. *Hyalosphenia papilio* was found at a water table depth of 10–15 cm at Fenyves-tető bog (Schnitchen et al., 2006) and also associated with a high water table elsewhere in Europe (e.g. Booth et al., 2008; Charman et al., 2007; Lamentowicz et al., 2008).

Between 2750 and 1750 cal yr BP, an increase in mire surface wetness is suggested by the expansion of *A. flavum*, the corresponding decline of *D. pulex*, and the high proportion of *Amphitrema wrightianum* (Fig. 3). In the northern Romanian peatlands, *A. wrightianum* was found at 0–8 cm water table depth (Schnitchen et al., 2006) and is generally an indicator of wet conditions representing floating *Sphagnum* (e.g. Payne and Mitchell, 2007; Lamentowicz et al., 2008).

By 1750 cal yr BP, the percentages of *D. pulex*, an indicator of dry mire surface conditions, had reached high values, whilst *A. flavum*, a wet indicator, had decreased (Fig. 3). This, and the declining percentages of the very wet indicator *A. wrightianum*, indicate a pronounced drying of the mire surface. This ecohydrological status was maintained until 1300 cal yr BP.

Between 1300 and 400 cal yr BP, the dominant taxon in the assemblages was *A. flavum* along with *A. wrightianum*, a wet mire surface indicator. However, a spike in the abundance of *D. pulex* towards the end of this period (660–570 cal yr BP) indicates a short-term period of dry peat surface conditions (Fig. 3).

Between 400 and 250 cal yr BP, the dominant taxon was *Nebela militaris* (14–23 cm water depth; Schnitchen et al., 2006), a species associated with dry to very dry peat surface conditions (Lamentowicz et al., 2008). During this period, all other species, especially *A. flavum*, showed declining trends and this suggests a marked drying of the mire surface. Later on, between 250 and 25 cal yr BP, *A. flavum* and *A. wrightianum* regained their dominance, this indicating a shift towards wet mire surface conditions. However, at the end of this period, *Phryganella acropodia* became the most abundant taxon (75%). The abundance of this species, together with the abrupt decline of *A. flavum* and *H. papilio*, indicate dry mire surface conditions. The mire surface dryness became accentuated over the last 25 years of the sequence, as demonstrated by the further increased abundance of *N. militaris*, *D. pulex* and *Nebela tincta* species with water table depth optima between 18 and 26 cm, and *Corythion dubium* with water table depth optima between 22 and 29 cm (Lamentowicz and Mitchell, 2005; Schnitchen et al., 2006).

5.2. Ecological interpretation of changes in the subfossil chironomid assemblages and of trends in inferred summer temperature

Generally, two chironomid assemblages alternated along the investigated time period at Tăul Muced (Fig. 4). The first was dominated by *Chironomus anthracinus*-type, with *Endochironomus impar*-type and *Limnophyes* often being the subdominant chironomid taxa in these samples. In the second, *Psectrocladius sordidellus*-type dominated and was usually associated with *Cladopelma lateralis*-type, *Corynoneura lobata*-type and *Monopelopia*. Most of these taxa occur often in the littoral of meso- to eutrophic shallow lakes and sometimes (especially *E. impar*-, *P. sordidellus*-, *C. lateralis*- and *C. lobata*-type) associated with macrophytes (e.g. Brodersen et al., 2001; Brooks et al., 2007; Luoto, 2010). Another important characteristic of the dominant taxa is the ability to tolerate more-or-less acidic lake conditions (e.g. Brodin, 1990; Brooks et al., 2007; Fittkau and Roback, 1983). Acidic conditions were reconstructed from testate amoebae (pH between 2.3 and 5) and could also explain the relatively low taxon richness of chironomids along the core (Brooks et al., 2007).

Between ca. 6550 and 4100 cal yr BP, the chironomid assemblages were dominated by *C. anthracinus*-type, *E. impar*-type and *C. lateralis*-type (Fig. 4), which would be consistent with slightly warmer temperatures and meso- to eutrophic lake conditions (e.g. Hájková et al., 2016; Larocque et al., 2001; Velle et al., 2005). *Limnophyes* also reached its maximum abundance during this period (Fig. 4), which may be a useful indicator of water level changes because this taxon sometimes occurs in semi-terrestrial environments and therefore might indicate decreasing water level (Brooks et al., 2007; Massafero and Brooks, 2002).

Between ca. 4100 and 3300 cal yr BP, *P. sordidellus*-type dominated the chironomid assemblages. This taxon is characterized by lower temperature optima than the earlier dominant Chironomini, although it can also survive in relatively warm climates (e.g. Heiri et al., 2011; Velle et al., 2005). In addition, it is tolerant of more acidic conditions (Brooks et al., 2007; Tátosová et al., 2006; Velle et al., 2005). *E. Impar*-type, *C. lateralis*-type and *Monopelopia* also reached fairly high relative abundances. Around 3300 cal BP, the organic matter (OM) content decreased abruptly, suggesting a drop in lake eutrophy that can explain changes in the chironomid assemblages. In summary, the chironomid assemblage suggests decreasing, but still warm summer temperatures at Tăul Muced between ca. 4100 and 3300 cal yr BP.

Between ca. 3300 and 2800 cal yr BP, the previously dominant taxa disappeared suddenly from the record, while *C. anthracinus*-type re-gained dominance (Fig. 4). This change is reflected as a slight increase in reconstructed summer air temperatures. However, compared to the prominent assemblage change, the increase in the reconstructed temperature is moderate. The associated decrease in OM content may have reinforced the effects of climate, leading to the observed changes in the chironomid assemblages.

Between ca. 2800 and 1000 cal yr BP, there were several changes in the chironomid assemblages, i.e. an increased abundance of *P. sordidellus*-, *C. lateralis*- and *C. lobata*-type and *Monopelopia* (Fig. 4). However, the inferred summer air temperatures changed little. On the other hand, OM increased strongly, suggesting a rise in lake eutrophy that may have affected the chironomid assemblages.

On the whole, the most important compositional assemblage changes could not be explained only by past air temperature changes and this indicates that factors other than air temperature, e.g. water level, pH and trophic state changes, could have significantly influenced the chironomid assemblage of Tăul Muced.

5.3 Disentangling the potential effect of summer temperature on the changes in the water table: a regional comparison

The reconstructed water table and July air temperature from Tăul Muced show a series of changes over the entire record (Fig. 5). The following discussion aims to: i) obtain a better understanding of past local hydroclimate fluctuations by combining the summer air temperature record inferred from chironomids with the water table variations inferred from the testate amoebae; and ii) compare the palaeoenvironmental changes at Tăul Muced with other records from the immediate region as well as other more distant records in Europe, for a local to regional perspective of palaeoenvironmental / hydroclimate changes.

The initiation of the peat development started around 9000 cal yr BP, but the poor preservation of the testate amoebae in the basal part of the sequence means that the DTW reconstruction only starts at 7550 cal BP (Fig. 4). A long-term period of generally dry mire surface conditions (DWT of 15–24 cm) was evident from 7550 to 4500 cal BP, but more accentuated between 7000 and 6500 cal yr BP (Fig. 5), whereas the chironomid inferred July air temperatures was of ca. 13.3°C between 6550 and 5500 cal yr BP. Evidence from the two proxy suggest the prevalence of generally dry conditions between 7500 and 6500 cal yr BP and of cool and slightly dry condition between 6500-5500 cal yr BP. After 5500 cal BP, the DWT points to a slight increase of the mire surface moisture, accompanied by a temperature increase to ca. 14.3°C from 5500 to 4800 cal yr BP. The two combined reconstructions indicate that between 5500 and 4800 cal yr BP, warmer July air temperatures and higher evapotranspiration may have resulted in dry hydrological conditions on the peat. A period of dry conditions between 5500 and 4800 cal yr BP was also reconstructed based on $\delta^{13}C$ *Sphagnum* and a greater biomass burning at the same site (Feurdean et al., 2017; Panait et al., 2017). On the other hand, the plant macrofossil record at Tăul Muced shows an alternation of *Sphagnum* and *Eriophorum* dominance, with a higher proportion of *Eriophorum* around 7000, 5800 and 4800–4200 cal yr BP, associated with dry conditions (Gałka et al., 2016).

The quantitative wetness reconstruction based on testate amoebae at Tăul Muced resembles the palaeohydrological reconstruction of Schnitchen et al. (2006) for the northern Carpathians that shows drier peat surface conditions from 8000 to 4800 cal yr BP. In the case of July air temperature, our values are in partial contrast with the Lake Brazi reconstruction from southern Romania (Tóth et al., 2015), which shows a cooler period between 5500 and 4800 cal yr BP. However, Lake Brazi is located in the south-western Carpathians, more sheltered from the influence of Atlantic air masses than Tăul Muced (Tóth et al., 2015). Similarly, increasing summer temperatures in north-west Romania were recorded by Feurdean et al. (2008) at Preluca Ţiganului between 6800 and 5000 cal yr BP and at Steregoiu between 5500 and 3200 cal yr BP. Our hydroclimate reconstruction agree with the low lake level and simulated high growing season temperature and evapotranspiration for Transylvania before 6500 cal yr BP, but contrasts with the simulated increase in soil moisture conditions, and a decline in growing season temperature and evapotranspiration thereafter (Feurdean et al., 2015b).

On a larger regional scale, a pattern of dry mire conditions was also observed in north-west England and northern Poland between 7150 and 6800 cal yr BP (Langdon et al., 2004; Lamentowicz et al., 2008), but these inferences do not agree with records in eastern (Żurek and Pazdur, 2000; Żurek et al., 2002) and northern Poland (Gałka et al., 2013). Low lake levels were also reconstructed for central Europe between 7000 and 4800 cal yr BP (Magny et al., 2013). The chironomid-based summer temperature reconstructions for central and southern Europe show warmer than today mid-Holocene temperature (9000-5000 cal yr BP), which contrast to the cool pollen-based temperature reconstructions for the same region (Mauri et al., 2015; Samartin et al., 2017).

From ca. 4500 to 2750 cal yr BP, our testate amoebae record shows a wet period with the water table fluctuating between 7 and 18 cm, while the chironomid-based reconstruction shows a moderate decline in July air temperature to ca. 13.5°C between 4800 and 3000 cal yr BP (Fig. 5). Collectively, the two records may suggest that cooler summer temperatures could have reduced the evapotranspiration effect, contributing to wetter growing season conditions. A low fire activity (Feurdean et al., 2017), low $\delta^{13}C$ values in *Sphagnum* (Panait et al., 2017) and the dominance of macrofossils of *Sphagnum* between 4300 and 3300 cal yr BP (Gałka et al., 2016) corroborates the inference of local moist mire conditions. At a neighbouring site, Fenyves-tető bog, the testate amoebae reconstruction of Schnitchen et al. (2006) indicates gradual wetter conditions from 4800 to 3400 cal yr BP, with several minor wet phases peaking at 4700 and 3570 cal yr BP. The deline in July air temperatures at Tăul Muced is partly detectable in the southern Carpathians (Tóth et al., 2015) at ca. 3300 cal BP. A wet interval characterized by a rise in lake level was identified at Lake Ştiucii, Transylvania, between 4300 and 2800 cal yr BP (Feurdean et al., 2013) and at Lake Sfânta Ana, Eastern Carpathians, between 4330 and 3800 cal yr BP (Magyari et al., 2009). A pattern of cooler summer temperature / higher precipitation is partially supported by pollen-based reconstructions (Feurdean et al., 2008).

On a wider geographical scale, wet mire surface conditions were also reconstructed between 4000 and 3200 cal yr BP over a large area in Europe including Poland, Estonia and the UK (Charman et al., 2006; Gałka et al., 2013; Lamentowicz et al., 2015; Sillasoo et al., 2007). A broader regional tendency of high lake stands throughout the mid latitudes in Europe was recorded after 4800 cal yr BP (Magny et al., 2013). Taken together these data suggest a stronger influence of westerlies and consecutively moister air masses brought into the study area.

From 2750 to 1300 cal yr BP, the inferred peatland surface conditions at Tăul Muced were dry (DWT of 14 and 28 cm), while the chironomid-based July air temperature reconstruction indicates relatively warm summers of ca. 14°C (Fig. 5). Dry local conditions are support by charcoal and δ^{13}C isotopic record at the same site (Feurdean et al., 2017; Panait et al., 2017). Our reconstructions match a dry mire phase at Fenyves-tető bog between 2250 and 600 cal yr BP (Schnitchen et al., 2006), whereas warmer July air temperature at Lake Brazi were recorded somehow later, i.e. between 2200 and 1300 cal yr BP (Tóth et al., 2015). Our hydro-climate inference is supported by the reconstructions of low lake water level at Lake Ştiucii (Feurdean et al., 2013), and generally low lake levels recorded in central Europe (Magny, 2004), but contrasts with higher water levels at Lake Sfânta Ana (Magyari et al., 2009) and simulated slightly increase in growing season precipitation (Feurdean et al., 2015b). The DWT partly correlates with reconstructions from northern Poland that inferred a dry phase between 2250–

2100 cal yr BP and wet shifts around 2750–2400 and 2000 cal yr BP (Lamentowicz et al., 2008).

Results from the testate-amoebae-based reconstruction of mire wetness and correlation to the major climatic excursions of the last millennium were presented in detail in Feurdean et al. (2015a). Generally, the Tăul Muced peatland surface was wet (DWT from 5 to 18 cm) between 1300 and 400 cal yr BP and the driest (DWT values of 25 to 28 cm) between 400 and 170 cal yr BP and in the past 40 years (Fig. 5). The July air temperatures show cooler temperatures of ca. 13°C until 600 cal yr BP, which corresponds well to the wet surface conditions determined from testate amoebae. Then the increase in July temperatures (14°C) over the past 100 years is also reflected in dry surface conditions of the mire (Fig. 5). The other Romanian chironomid reconstruction from Lake Brazi shows a temperature increase between 2000-700 cal yr BP, which was interpreted as an artefact of human impact influencing lake trophic state and therefore the temperature reconstruction (Tóth et al., 2015). The pollen record from the Tăul Muced peat profile also shows a distinct decline in the extent of tree cover that started around 1000 cal yr BP and that has intensified over the last 100 years (Fig. 5) associated with increasing human impact (Feurdean et al., 2015a). The large variability and heterogeneity in the proxy reconstructions during the last millennium may suggest an additional imprint of anthropogenic impact (Florescu et al., 2017) on terrestrial and aquatic records i.e., deforestation, drainage, eutrophication, changes in pH.

6. Conclusions

Our climate reconstruction from the Tăul Muced ombrotrophic peat bog sequences provides the first multimillennial quantitative reconstruction of water table depth, pH and July air temperature based on two sets of biotic proxies, i.e. testate amoebae and chironomids, in the

Carpathians. It offers detailed insights into the hydro-climate variability and the potential influence of temperature on these changes during the past 7500 years.

The quantitative reconstruction of the water table depth and pH based on the testate amoebae shows six main hydroclimate phases of the mire surface conditions. Wet phases of the mire surface conditions were inferred in the periods 4500–2750 and 1300–400 cal yr BP. Dry mire surface conditions were inferred for 7550–4500, 2750–1300 and 0 cal yr BP–present. The quantitative reconstruction of the July air temperature based on the chironomid communities shows relatively small changes. However, it records six centennial-scale changes in temperature over the past 6550 years: relatively cold summer temperatures were inferred in the periods 6550–5600, 4500–3150 and 1550–600 cal yr BP; and warmer July air temperatures were inferred for 5600–4500, 3150–1550 and 100 cal yr BP–present.

In general, the results show a good agreement between drier phases of the peat surface conditions and higher summer temperature, suggesting that temperature may be an important factor controlling water table fluctuations on the mire in this region. However, in some sections, the two reconstructions disagree, suggesting that changing precipitation may have masked or overridden the effects of temperature changes on the humidity status of the mire during some phases of the Holocene.

The findings of our study, one of the few from CE Europe, are relatively consistent with those from other palaeoclimate reconstructions from central eastern Europe. However, they show contrasting conditions to other estimates from north-west Europe. One of the most important aspects of the study is that is provides valuable information on changes in the local hydrology and the potential effect of the mean summer temperature over these changes in an understudied region.

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Appendix A. Supplementary files

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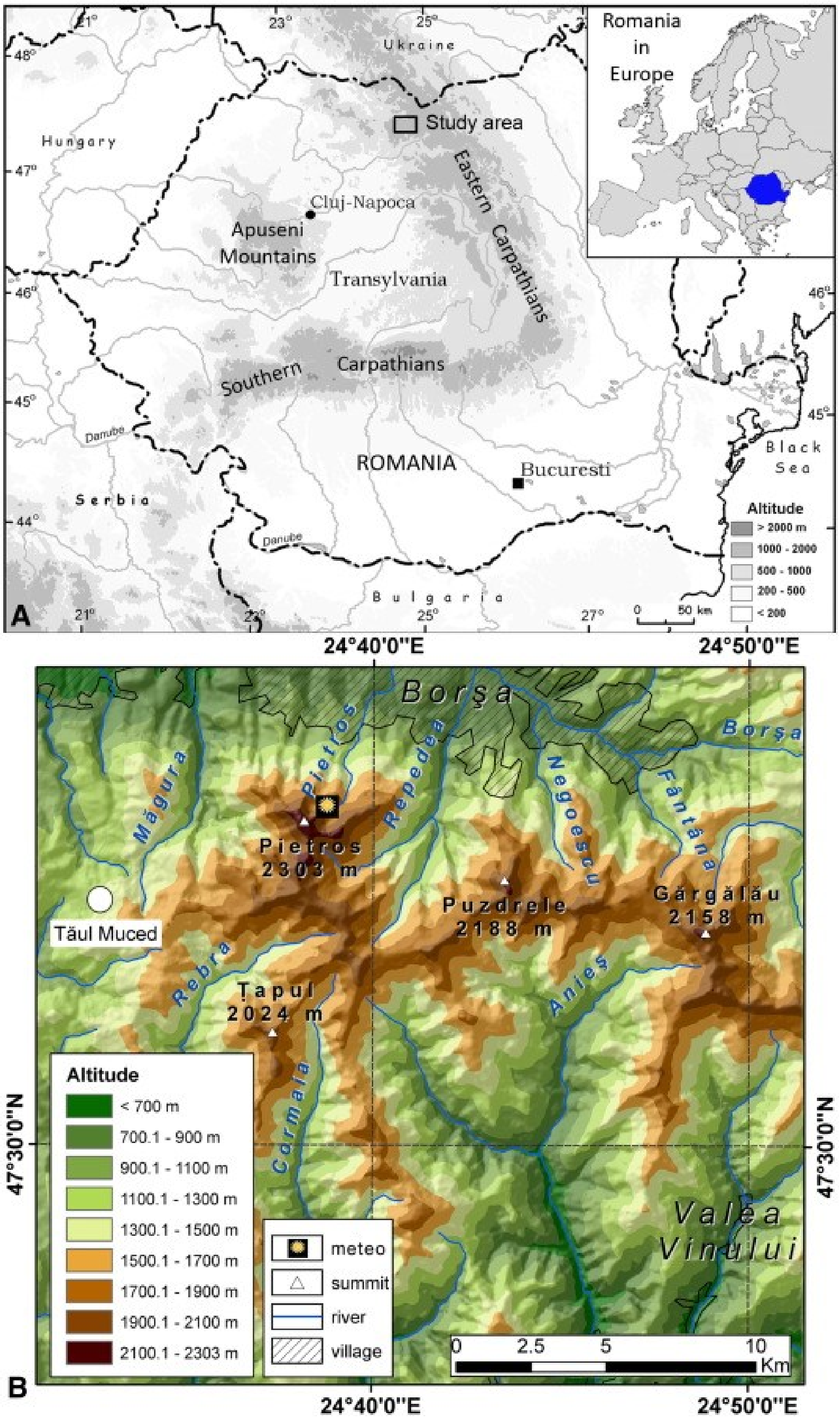


Figure 1. Location of the study area in Romania (A) and of the study site in the western part of the Rodna Mountains (B).

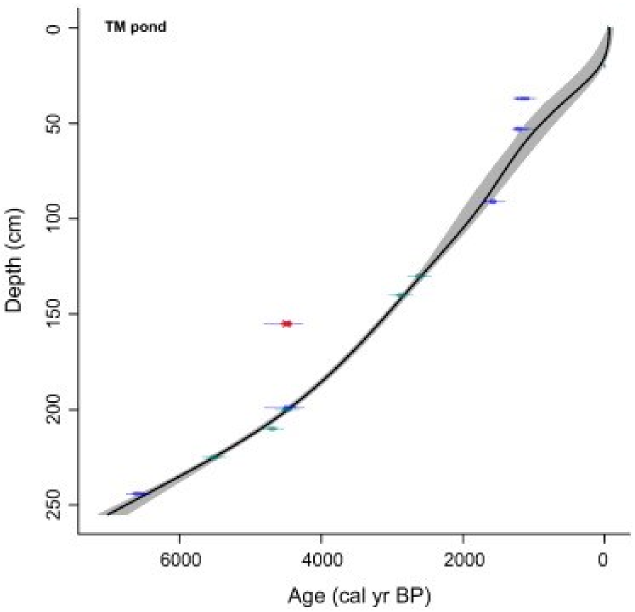


Figure 2. Age–depth model for Tăul Muced pond sequence. Data points used for the construction of the age–depth model are shown in blue, data points rejected from the model are shown in red and pollen stratigraphical markers are shown in green. The zero value of the X axis represent 1950 A.D.

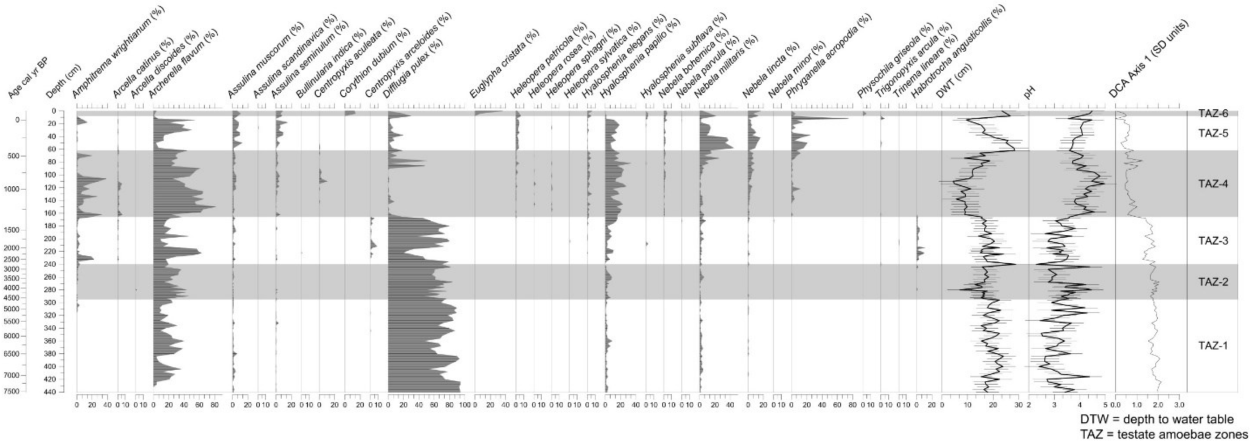


Figure 3. Relative abundance of testate amoebae (TA) in the Tăul Muced peat sequence, with the TA-inferred depth to water table (DWT) and pH reconstruction, and the first (longest) DCA axis scores.

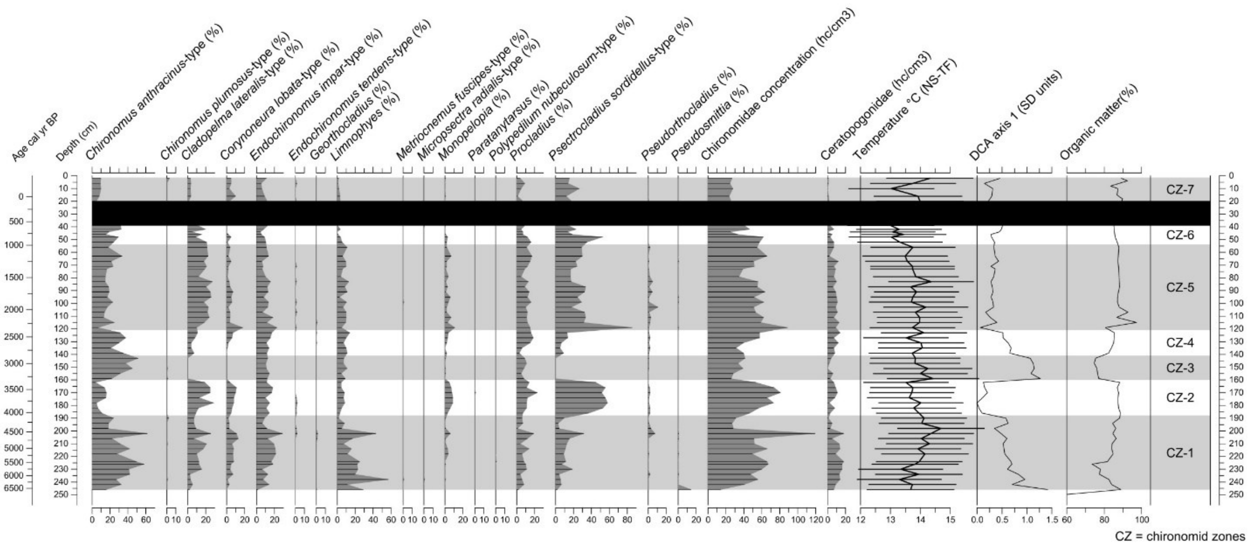


Figure 4. Relative abundance of Chironomidae in the Tăul Muced pond sequence (including all of the taxa recorded), with the chironomid-inferred July air temperature reconstruction, the organic matter content (in terms of loss-on-ignition) from the sequence and the first (longest) DCA axis scores. Missing data represent the 20-39 cm gap from the pond sedimentary profile.

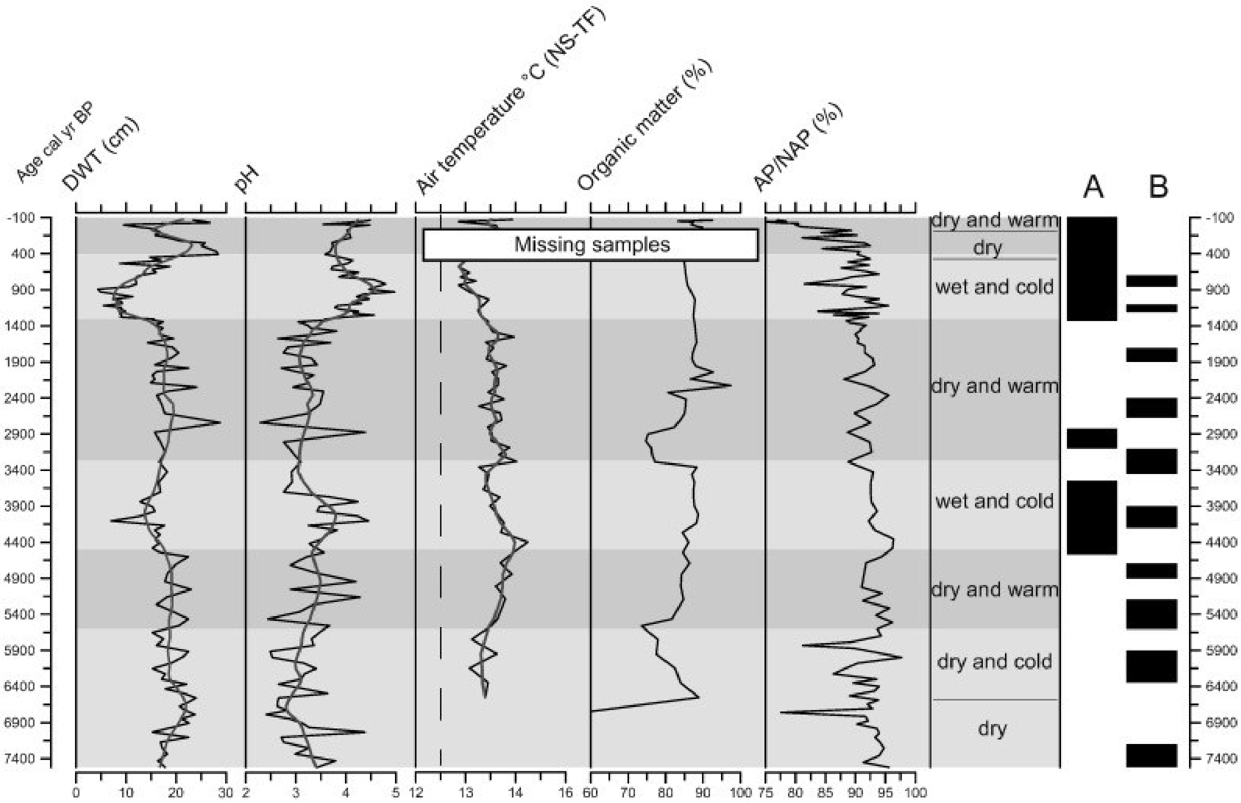
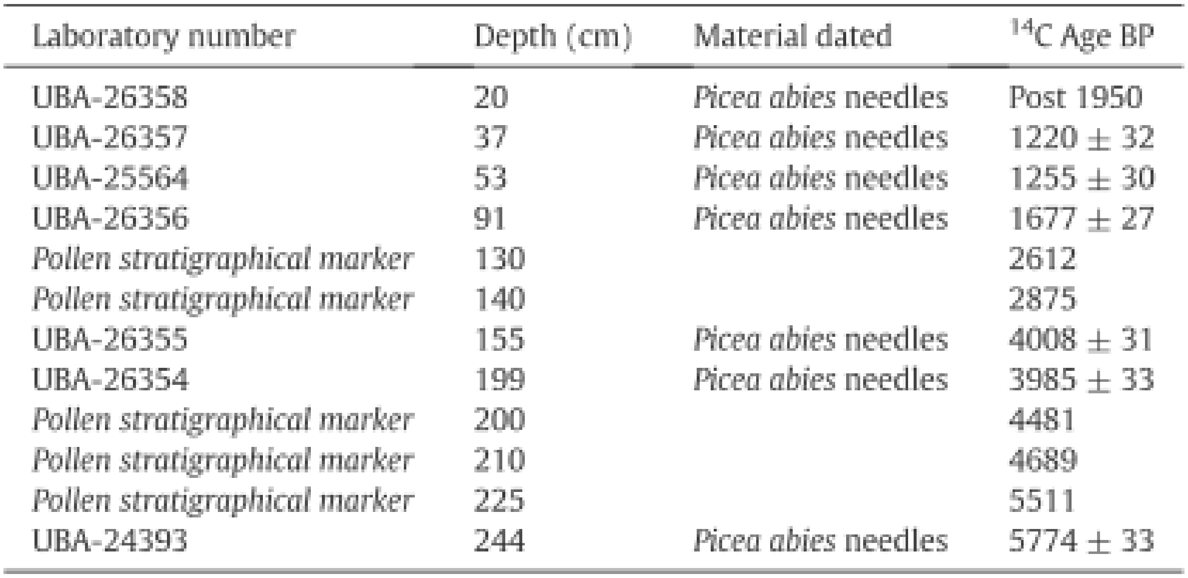


Figure 5. Comparison of the inferred variables: depth to water table (DWT), pH and July air temperature (red lines represent smooth spline) with percentage of organic matter content and arboreal /non-arboreal pollen (AP/NAP) ratio after Feurdean et al. (2017). A) Regional high lake levels after Feurdean et al. (2013). B) Mid-European high lake levels after Magny (2004).

Table 1. AMS ^{14}C dates and pollen stratigraphical markers in the Tăul Muced pond sequence.



Laboratory number	Depth (cm)	Material dated	^{14}C Age BP
UBA-26358	20	*Picea abies* needles	Post 1950
UBA-26357	37	*Picea abies* needles	1220 ± 32
UBA-25564	53	*Picea abies* needles	1255 ± 30
UBA-26356	91	*Picea abies* needles	1677 ± 27
Pollen stratigraphical marker	130		2612
Pollen stratigraphical marker	140		2875
UBA-26355	155	*Picea abies* needles	4008 ± 31
UBA-26354	199	*Picea abies* needles	3985 ± 33
Pollen stratigraphical marker	200		4481
Pollen stratigraphical marker	210		4689
Pollen stratigraphical marker	225		5511
UBA-24393	244	*Picea abies* needles	5774 ± 33

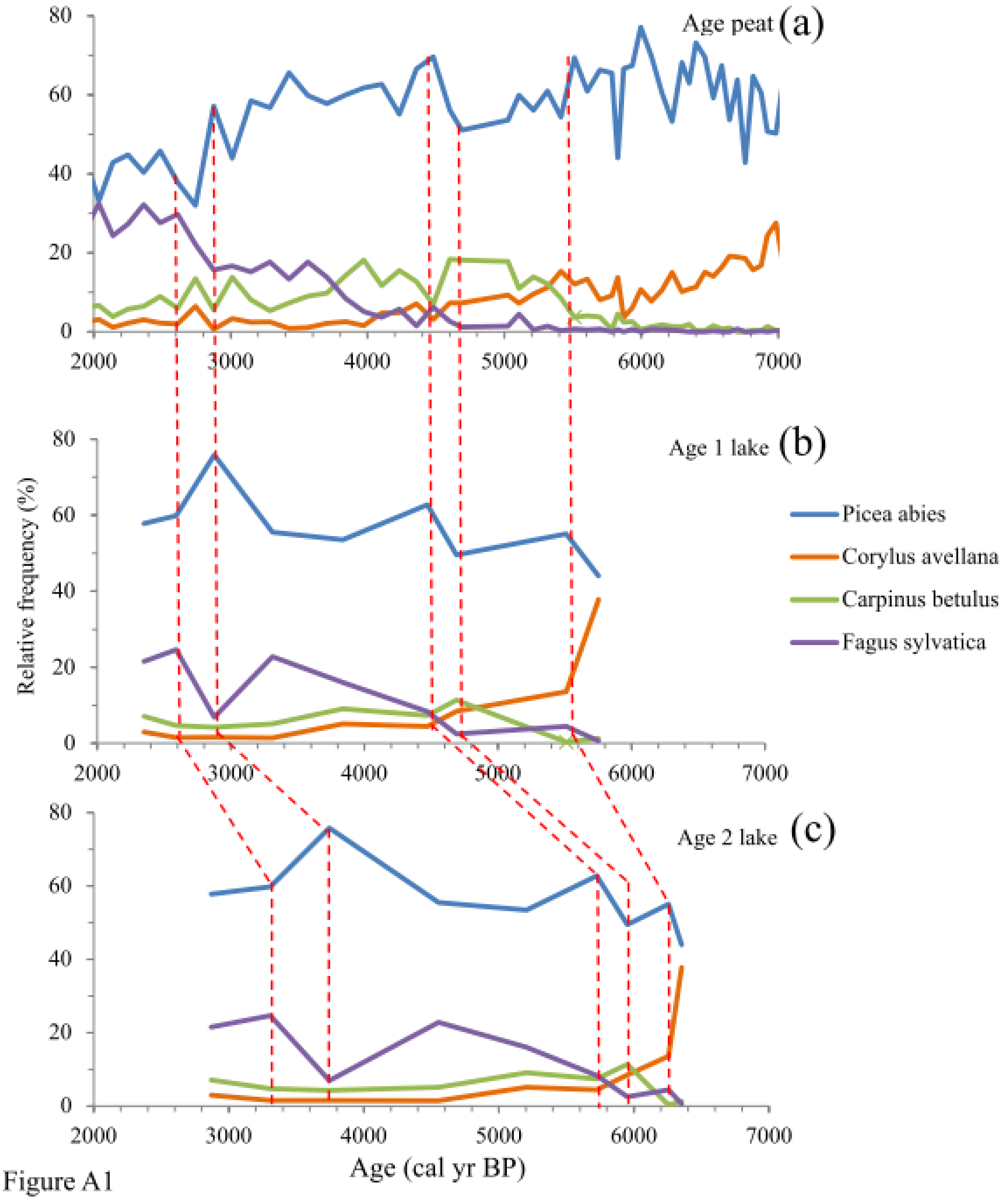


Figure A1

Figure A1. Pollen-based stratigraphic correlation between selected pollen curves used to constrain the chronology of the Tăul Muced pond sequence and the pollen stratigraphical markers used to constrain the pond chronology. a) Selected pollen curves from the Tăul Muced peat sequence, b) selected pollen curves from the Tăul Muced pond sequence using the 3985±33

BP measurement and rejecting the 4008±31 BP measurement, c) selected pollen curves from the Tăul Muced pond sequence using the 4008±31 BP measurement and rejecting the 3985±33 BP measurement.