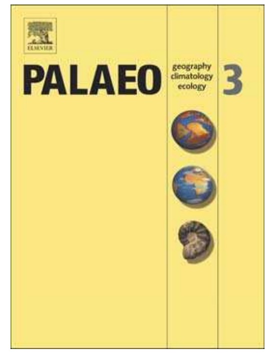

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PII:	S0031-0182(16)00072-9
DOI:	doi: 10.1016/j.palaeo.2016.02.007
Reference:	PALAEO 7682
To appear in:	*Palaeogeography, Palaeoclimatology, Palaeoecology*
Received date:	5 June 2015
Revised date:	1 February 2016
Accepted date:	3 February 2016

A 9000 year record of cyclic vegetation changes identified in a montane peatland deposit located in the Eastern Carpathians (Central-eastern Europe): Autogenic succession or regional climatic influences?

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Key words

Sphagnum succession, plant macrofossil remains, Holocene, climate change, Sphagnum magellanicum, Eriophorum vaginatum

Abstract

We present a high-resolution, continuous plant macrofossil remains record complemented by a pollen sequence from Tăul Muced bog, in the Eastern Carpathian Mountains (Romania). The record spans the last 9000 years and we test whether peatland development in the Eastern Carpathians is linked to climate change or to autogenic succession. We find that Sphagnum magellanicum was the dominant peat-forming species for ca. 8000 years but we also identify ten phases of increased representation of Eriophorum vaginatum at approximately 8100, 7550, 6850, 6650, 5900, 4650, 3150, 1950, 1450, 750 cal yr BP. Visual inspection and wavelet analysis show that the episodic increases in the relative abundances of Eriophorum vaginatum were simultaneous with decreased abundances of Sphagnum magellanicum and Sphagnum angustifolium. Comparison with published palaeoclimatic records in this region suggests that these cyclical successions of S. magellanicum and E. vaginatum appear to be primarily a result of climate changes, with E. vaginatum developing mainly during dry phases and S. magellanicum during wetter periods. We therefore suggest that the development of this peatland was largely influenced by changing climatic conditions, although the role of autogenic plant succession cannot be excluded. Our results show the value of ombrotrophic peat deposits as archives of past climate change.

Introduction

Ombrotrophic peatlands (peatlands fed entirely by precipitation) are habitats for a range of rare species and play an important role in the maintenance of biodiversity. Many of these peatlands are designated as protected areas, but knowledge of the rate and nature of their long-term development, and their response to past climate change is often limited. Pristine ombrotrophic montane peatlands exist in the Eastern Carpathians and because these peatlands have not been subjected to drainage, forest clearance and peat exploitation, they represent reliable archives for the history of local vegetation development and peat accumulation. This is of particular significance for the reconstruction of local vegetation development and its response to climate changes, given that in many areas of the world natural peat dynamics have been profoundly affected by anthropogenic influences. Two main hypotheses are used to explain the causes of vegetation changes on peatlands: i) local vegetation dynamics resulting from regional climate changes (Barber, 1981; Mauquoy and Barber, 1999; Barber et al., 2004; Schoning et al., 2005; Charman et al., 2006), and ii) local vegetation changes related to autogenic vegetation successions within the peatland (Osvald, 1923; Kulczyński, 1949). However, paleoecological studies from north-western and northern Europe, and in Patagonia showed that peatland development cannot be fully explained by either of these hypotheses (Loisel and Yu, 2013; Swindles et al., 2012; Tuittila et al., 2007), especially when detailed stratigraphic studies have been conducted (Walker and Walker, 1961). High-resolution plant macrofossil remains analyses of peat sequences in mountain areas were also performed in the Swiss Alps (van der Knaap et al., 2011) and the Schwarzwald, SW Germany (Hölzer, 2010), however only the most recent peat layers (the last ca. 1000 years) were analysed. Multi-proxy studies of montane raised peat bog deposits (pollen, macrofossils, testate amoebae and peat characteristics) were conducted in the Krkonoše Mountains (Speranza et al., 2000) and Hrubý Jeseník Mountains, Czech Republic (Dudová et al., 2012). At these sites Sphagnum species such as S. magellanicum, S. russowii and S. fuscum, and Eriophorum vaginatum played a dominant role during local plant succession.

Despite their excellent preservation, the Eastern Carpathian ombrotrophic bogs have not yet been used for the reconstruction of local vegetation development or for understanding the processes leading to their formation. To fill this gap, we reconstruct for the first time the local vegetation dynamics of a mountain raised bog in the Eastern Carpathians based on contiguous, high-resolution plant macrofossil remains analyses. We evaluate if regional climate changes had a stronger influence on the development of small ombrotrophic mountain peatlands in this region or if the local autogenic succession was more important. Our temporal perspective and high- resolution, contiguous sampling approach allows the identification of the time of the appearance, expansion, and retraction of local plant taxa. Furthermore, our results have implications for understanding the response of mires to past hydroclimate changes and demonstrate the potential of peat records as valuable proxies of past climates.

Study site

The study site is located in the Rodna National Park and Biosphere Reserve, in the Rodna Mountains, Eastern Carpathians, Romania (Fig. 1). The study area has a moderate, temperate continental climate with Atlantic and Baltic influences (Donita, 2005). Mean annual temperature is ca. 5 °C and annual precipitation is ca. 1400 mm, with the highest rainfall in the summer and the lowest in winter. The regional vegetation is composed of Norway spruce (Picea abies) forest (Feurdean et al. 2015). Marked deforestation is ongoing in the region, but not in the immediate vicinity of the bog. The study site, Tăul Muced (47°34′26″N, 24°32′42″E; 1360 m a.s.l.; 2 ha) is an ombrotrophic raised bog, and 0.5 ha of its total surface has the status of scientific reserve category Ia IUCN (Management Plan of Rodna Mountains National Park). The site is surrounded by almost mono-dominant Picea abies forest, which also covered the bog itself alongside with patches of dwarf pine (Pinus mugo). The moss communities in the central part of the cored peatland are dominated by Sphagnum russowii and S. magellanicum, whereas S. girgensohnii and Vaccinum myrtillus are dominant on the hillsides. There are no distinctive hummocks and hollows at the coring point.

Materials and Methods

Coring and subsampling, chronology of the core

Two parallel cores from two boreholes were extracted from the centre of the bog (lawn). This includes recovery of a complete core (560 cm) using a combination of Livingstone (for the bottom sandy material) and Russian (5 cm diameters, peat) coring equipment, and a 500 cm overlapping profile. The cores were wrapped in plastic film, sealed for transportation and stored at 4 ^{o}C. The chronology of the full sequence was established based on 12 AMS radiocarbon measurements of plant macrofossils and peat (Belfast Radiocarbon Laboratory, Northern Ireland) and a ^{210}Pb profile (Faculty of Environmental Science, University of Babes Bolyai Cluj, Romania) (Feurdean et al., 2015). The age–depth model of this 560 cm sequence 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 IntCal13 data set of Reimer et al. (2013), whereas the ^{210}Pb age estimates for the top 20 cm were calculated using a Constant Rate of Supply (CRS) model (see Feurdean et al., 2015).

Plant macrofossils remains

Plant macrofossils remains were analysed contiguously (sample volume of 10-12 cm^3), mainly at 1-cm intervals resulting in 499 samples. These were washed and sieved under a warm-water current using a 0.20-mm mesh sieve. Initially, the entire sample was examined with a stereomicroscope to obtain volume percentage of individual subfossils of vascular plants and mosses. The subfossil carpological remains and vegetative fragments (leaves, rootlets, epidermis) were identified using identification keys (Smith, 1985; Mauquoy and van Geel, 2007). The volume percentages of the different vegetative remains and the Sphagnum sections were estimated to the nearest 5%. The number of seeds, fruits, needles, bud scales and leaves were counted separately. The relative proportions of taxonomic groups of

Sphagnum, which are of key importance for interpretations, were estimated on the basis of the branch leaves, which were investigated under the microscope on two 22x22-mm cover glasses. The identification of Sphagnum remains to the species level was performed separately on the basis of stem leaves and cross-sections, using specialist keys (Hölzer, 2010; Laine et al., 2011). The volume percentage of amorphous organic matter was estimated to the nearest 25% during sieving, and serves as a measure of peat decomposition (Gałka et al., 2013a). We use the nomenclature of Mirek et al. (2002) for vascular plants and Ochyra et al. (2003) for bryophytes.

Pollen

Pollen was extracted from sediment samples (1 cm^3) at intervals of 4-8 cm after treatment with NaOH, HCl, and sieving with a 250 μm mesh for coarse organic material. Pollen counts ranged between 400 and 500 pollen grains of terrestrial taxa. The atlases of Reille (1992, 1995) were used for pollen identification and all counted terrestrial pollen types were converted into a percentage pollen sum. Percentages of Cyperaceae, spores and aquatic pollen types were calculated separately based on a on a total sum including terrestrial pollen and their own sums.

Wavelet analysis

Continuous wavelet transforms are useful for analyzing data that contain non-stationary power at several different frequencies and can therefore identify cycles both in time and frequency domains. This is an advantage compared to the classical Fast Fourier Transform (FFT) methods, which are localized in frequency but not in time. The data were interpolated to equal time steps of 50 years with a Gaussian window of 150 years and we used a Morelet wavelet in order to evaluate the presence of non-stationary cycles in our time series (Torrence and Compo, 1998). We also tested the localised correlation of the two most common macrofossil time series i.e., Sphagnum magellanicum and Eriophorum vaginatum in the time frequency space by using wavelet coherence (Grinsted et al., 2004). This analysis relates power with coherence between two time series, while also indicating the phasing between them (i.e. it can identify synchronous responses or leads and lags between the time series analyzed). The statistical significance level in the wavelet coherence analysis was determined using Monte Carlo methods against an autoregressive red noise background spectrum (Grinsted et al., 2004).

Results

Lithology, chronology, and peat accumulation rate

The peat deposit at Tăul Muced (TM) is developed on peatty-gyttja, overlaid by gyttja and sandy clay sediments (560-500 cm) likely of Late Glacial and early Holocene origin. This sediment succession suggests the presence of a shallow lake phase with peat formation started at ca. 9000 cal yr BP by the process of terrestrialization (filling of shallow lakes).

The mean peat accumulation rate for the entire period was approximately 0.55 mm/year. The lowest peat accumulation rate was from 5000 to 2000 cal yr BP (0.32 mm/year), and the highest from 1800 to -50 cal yr BP (1.1 mm/year). The highest degree of peat decomposition occurred at the initial phase of accumulation, i.e, between 9000 and 8000 cal yr BP (up to 100%), but also between 4100 - 3600 cal yr BP, and 3000 - 2600 cal yr BP (up to 75%).

Plant macroremains and pollen

Four phases in the local vegetation development were visually delimited (Fig. 2).

- Phase TM 1 (9000-8000 cal yr BP, 500-459 cm)

During the initial phase of peatland development Scirpus sylvaticus, Rubus idaeus and Sambucus racemosa were abundant (Fig. 2). Sphagnum magellanicum and Sphagnum angustifolium appeared at ca. 8500 cal yr BP, followed by Eriophorum vaginatum at 8200 cal yr BP. Numerous macrofossil remains (needles, bud scales and seeds) of Picea abies were recorded during this period, whereas its pollen percentage was 20-40%.

- Phase TM 2 (8000-1200 cal yr BP, 459-152 cm)

This time period was characterized by nine periodic increases of S. magellanicum and E. vaginatum (up to 60 %) and five for S. angustifolium (up to 50 %). The frequent occurrence of Picea abies macrofossil remains, was associated with maximum pollen percentages of spruce in the record (up to 70-80%). Two peaks of Cyperaceae pollen (up to 7 %)

- Phase TM 3 (1200-80 cal yr BP, 152-26 cm)

S. magellancium dominated throughout this period, with only a low proportion of S. angustifolium (up to 10 %) and E. vaginatum (up to 30 %). Macrofossil remains of Oxycoccus palustris and Picea abies were recorded in the bottom part of this zone. Picea abies pollen percentages declined compared to the previous zone but it remained the dominant species in the record.

- Phase TM 4 (80- - 63 cal yr BP, 26-0 cm)

The most recent part of the profile was characterized by a significant decline of Sphagnum magellanicum (25-75%), the disappearance of Sphagnum angustifolium and the first time appearance of Sphagnum russowii (max. 50%). There was also an increased proportion of Polytrichum strictum (max. 5%). Picea abies pollen percentages declined abruptly in the top of the sequence.

Statistics

The wavelet analysis of Sphagnum magellanicum and Eriophorum vaginatum time series revealed that both have significant power on millennial timescales with the strongest cycles occurring at intervals of 1400-1500 years, although they are significant above the 95% confidence threshold only during the mid-Holocene. There were other weaker and intermittent cycles occurring at ~600 years and 200-300 years intervals, respectively (Fig. 3). The wavelet coherence analysis identifies areas where the two time series have high power and coherence and indicates that the cycles in the two species are related, but with opposite phasing. The consistent phasing at intervals with strong wavelet power suggests that the changes are due to the same forcing, but affecting the two species in opposite ways.

Discussion

We explore whether the cyclical replacement of Sphagnum magellanicum and S. angustifolium with Eriophorum vaginatum at Tăul Muced was associated with regional changes in climatic conditions or it was a result of autogenic succession. The role of climate in controlling the peatland dynamics is explored by comparing our plant macrofossil data set with published regional palynological and palaeoclimate records. We hypothesise that if the dominant control on the peat development was climate then changes in our plant succession should coincide with broader scale climatic shifts.

Are episodic increases in Sphagnum magellanicum and Sphagnum angustifolium associated with wet conditions?

According to Burescu and Togor (2010), in the Eastern Carpathians, S. magellanicum grows in habitats with pH between 3.5 and 4.8. In Romania, this species was reported from numerous peats and bogs e.g., Molhaşul Mare and Izbucul Călinesei (Burescu and Togor, 2010), Gutâi, Bistriței, Harghita, Bodoc, Vrancei (Coldea and Plămadă, 1989), Poiana Stampei (personal observations, 2013). In Schwarzwald, south-west Germany, S. magellanicum was found in similar pH environments i.e, 3.2 and 4.3 (Dierßen and Dierßen, 2001), whereas in the western Italians Alps it was found in habitats with pH of 4.61±0.44 (Miserere et al., 2003). In the montane area of Bulgaria, S. magellanicum grows in less acidic environments (pH 5.1±1.0 - 5.7±0.9; Hájková and Hájek, 2007). Regarding the preference of water level depth, S. magellanicum grows in both dry hummocks and medium wet hollows and floating mats (wet), but it also develops extensive carpets (Bragazza and Gerdol, 1996; Miserere et al., 2003; Hölzer, 2010; Koperski, 2011; pers. observ.). In the western Italian Alps, S. magellanicum occurs in habitats where the water table depth averages 28 ± 10.98 cm (Miserere et al., 2003), whereas in Schwarzwald it mostly grows in habitats with water level of 11-31 cm, although the full water table depth range for this species spans 1-50 cm (Dierßen and Dierßen, 2001). Sphagnum angustifolium has a smaller range for water depth than S. magellanicum. In Schwarzwald, Germany, Dierßen and Dierßen (2001) found S. angustifolium in habitats where the water level oscillated between 3 and 17 cm below the surface. In the Sudety Mts. (SW Poland) S. angustifolium was identified in habitats ranging from bog to intermediate fen with pH oscillating around 4.73, where it occupies carpets, lawns and hummocks (Wojtuń et al., 2013).

At Tăul Muced bog, the past abundance of S. magellanicum was accompanied by S. angustifolium, which generally occurred after periods of E. vaginatum dominance. The predominance of each of these species shows a clear cyclic variability and a strong antiphase between the dominance of S. magellanicum and E. vaginatum (Fig. 2 and 3). The cooccurrence of S. magellanicum and S. angustifolium is common in modern ombrotrophic peatlands (Daniels and Eddy, 1985; Bragazza et al., 2005; Hölzer, 2010; Laine et al., 2011) and it was also documented in fossil records in northern hemisphere (Kuhry et al., 1993; Novenko et al., 2009; Drzymulska and Zieliński, 2013; Gałka et al., 2013b; Gałka et al., 2014).

Intervals of S. magellanicum and S. angustifolium domination were found around 8250, 7800-6900, 6500, 5800-4800, 3700-3200, 2500, 2200, 1800-1500, 1250-80 cal yr BP. Our wavelength analysis reveals strong millennial variability in both Sphagnum magellanicum and Eriophorum vaginatum with a 1400-1500 year cyclicity, which was particularly pronounced during the mid-Holocene. Events of solar minima were recorded at approximately 1500 year intervals: 11,100; 10,300; 9400; 8100; 5900; 4200; 2800; 1500 cal yr BP (Bond et al., 2001). In contrast, periods of solar maxima took place at approximately 11,000–10,500; 10,000; 8750; 7650; 5000; 3500 and 2400 cal yr BP (Bond et al. 2001). The link between changes of peatland plant assemblages and solar activity was documented in various parts of Europe (van Geel et al., 1998; Swindles et al., 2007; Mauquoy et al., 2008; Gałka et al., 2014). The strong association between the abundant occurrence of Sphagnum magellanicum at Tăul Muced bog and short-lived declines in biomass burning at Lake Ştiucii, Transylvanian Plain (more evident over the past 3000 years), suggest their response to a common driver (Fig. 3 and Fig. 4). In temperate regions, fire activity was found to be driven by warm and dry summer conditions with low soil moisture (Daniau et al., 2012; Feurdean et al., 2013). It is therefore apparent that the increased proportion of S. magellanicum and the decline in biomass burning was likely a response to wet climatic conditions, at least during summers. Periods of S. magellanicum abundance at our site were generally linked to high lake levels in Central Europe occurring at 8300-8200, 7400-7300, 6400-6100, 5700-5200, 4200-3900, 3500-3200, 2700-2400, 1800-1700, 1200-1100 cal yr BP, and further supports the hypothesis of past Sphagnum dominance during moister conditions in this part of Europe (Fig. 4). During wet climate phases, S. magellanicum and S. angustifolium could have developed extensive carpets, similarly to what is presently common in mountain areas in central Europe eg. Schwarzwald Mts. (Hölzer, 2010) or Harz Mts. (Koperski, 2011).

We further compare our peaks in occurrence of S. magelanicum with short-term wet and or cold events documented in the literature. However, it should be noted that the short duration of these climatic events, chronological uncertainties, and wiggle matching complicates the picture of globally synchronous rapid climate change (Baillie, 1991; Blaauw, 2012). Our first episodic increase of S. magellanicum around 8300 cal yr BP was synchronous with the high lake levels in C Europe (Fig. 4).

The 7800-6900 cal yr BP increased abundance in S. magellanicum, corresponded with an overall decrease in fire activity at Stiucii Lake (Fig. 4). Wet conditions on the peatland between 7700 and 7400 cal yr BP was also noted in the Apuseni (Grindean et al., 2015). The increased abundance of both pollen and plant macrofossil of Picea abies at 7600 cal yr BP at Tăul Muced matches a similar feature seen at the neighbouring site, Poiana Stiol (Feurdean et al., 2016) and suggests the dominance of P. abies in this area. P. abies can grow on peat, developing a Sphagno girgensohnii-Piceetum complex (Matuszkiewicz, 2001) and is a climatically tolerant species, which grows in both extreme oceanic and central continental climates, although it thrives more vigorously in wet conditions (Giesecke and Bennett, 2004). The regional dynamic pattern for P. abies in Romania also suggests that wetter conditions may be better suited for this species (Feurdean et al., 2011). This temporal dominance of S. magellanicum partly corresponds with high lake levels in Central Europe.

The next phase of S. magellanicum abundant occurrence (up to 70 %) is from 5800 to 4800 cal yr BP. Although this generally corresponds to a high lake levels in Central Europe (Magny, 2004), low lake levels were documented between 5500 and 5300 cal yr BP in the

Eastern Carpathians (Magyari et al. 2009) and the Transylvanian Plain (Feurdean et al., 2013), followed by an abrupt rise in lake water levels from 5300 cal yr BP in the Eastern Carpathians and from 5000 cal yr BP in Transylvania. A general increase in fire activity and dry peat surface conditions was identified between 5500 and 4800 cal yr BP in the Romanian Carpathians (Feurdean et al., 2012). Warmer/drier climatic conditions were also reconstructed around 5500 cal yr BP based on stalagmite stable oxygen isotopes from the Apuseni Mountains (Tămas et al., 2005; Perşoiu et al., 2011) and on pollen-based quantitative climate reconstructions in the Gutâiului Mountains, NW Romania (Feurdean et al., 2008). This change in Sphagnum domination at this time in Tăul Muced bog may coincide with 5.2 event, that has been reported globally (Magny et al., 2006; Roland et al., 2015) and characterized by locally wet and/or cool conditions.

A smaller amplitude population increase of S. magellanicum took place around 4200 cal yr BP after the longest period with domination of E. vaginatum. Cooler and wetter conditions associated to the 4.2 kyr event (Mayewski et al., 2004) have been widely documented in the region by various records such as an increase of fluvial activity (Howard et al., 2014; Perşoiu, 2010), lake level rise (Magyari et al., 2009; Feurdean et al., 2013), oxygen isotopes (Perşoiu et al., 2010; Dragusin et al., 2014) and chironomid-based summer temperature reconstruction (Toth et al., 2015). However, wetter and cooler climatic conditions during 4.2 kyr event are not always clear and a lack of a coherent climatic response during the 4.2 kyr event was documented in peat archives from Great Britain and Ireland (Roland et al., 2014).

The increased proportion of Sphagnum magellanicum at 2700 cal yr BP at our site coincided with high peat decomposition, suggesting dry climate conditions. This change in vegetation at Taul Muced could be linked to reduced solar activity inferred at 2.8 ka from many peatlands in NW Europe (van Geel at al., 1998; Mauquoy et al., 2004; Swindles et al., 2007). However, some records in the study region suggest wetter conditions during this time period (Magyari et al., 2009; Feurdean et al., 2013; Schnitchen et al., 2006), whereas others indicate decreasing moisture availability around 2800 cal yr BP. (Feurdean et al., 2008; Onac et al., 2002)

The dominance of S. magellanicum between 2250 and 2100 cal yr BP, could be connected with a short-term increase in the lake level and decline in biomass burning in Romania (Feurdean et al., 2013). However, palaeohydrological data from a wider regional scale in Europe (Poland, Germany) show dry climate conditions during this time (Gałka et al., 2013a). Then, the increase of Sphagnum magellanicum since ca. 1900-1600 cal. BP could be associated with generally cooler and wetter condition of the Migration Period as documented for Central Europe by Büntgen et al. (2011).

A long period of sustained dominance of S. magellanicum took place over the past 1300 years (Fig. 3). On the other hand, the testate amoeba record at Tăul Muced indicate marked changes in the water table: wet surface mire conditions between 1200 and 800 cal yr BP, dry surface mire conditions between 700 and 250 cal yr BP, followed by a moisture rise between 200 and 50 cal yr BP (Feurdean et al., 2015). However, the local S. magellanicum populations appear to be resilient to the fluctuations in water availability over the last millennium. S. russowii was recorded for the first time in our sequence at about 80 cal yr BP and together with S. magellanicum remained the most common species in open parts in Tăul Muced bog until recently. Human activity, as documented by the pollen record, increased in the last 150 years (Feurdean et al., 2015). It is probable that the presence of S. russowii could be also connected with human disturbance, i.e, increase nitrogen deposition (dust fall). This association had also been observed at Vozka bog (Dudová et al., 2012). A decline of S. austinii in Fallahogy bog, Northern Ireland linked to the deposition of soil-derived dust and fire activity was suggested by Swindles et al (2015).

Could climate fluctuations be responsible for the cyclic increase in Eriophorum vaginatum?

According to modern (Silvan et al., 2004; Lavoie et al., 2005) and palaeoecological data (Herbichowa, 1998; Gałka et al., 2013a, 2014), the abundant occurrence of Eriophorum vaginatum on the peatland results from hydrological disturbances, usually a decrease in the water level. E. vaginatum is a native species in bogs or poor fen, but does not dominate undisturbed ombrotrophic peatlands (Lavoie et al., 2005). Currently, E. vaginatum can grow in acidic habitats, where pH is between 3.2 and 5.2 cm and water level up to 72 cm below the mire surface (Bragazza and Gerdol, 1996), but it can also grow in pools. This species can tolerate prolonged droughts due to its deep root system (Wein 1973).

The recurrent increased abundance of E. vaginatum in Tăul Muced bog took place predominantly in cycles of about 1400-1500 years. Ten phases of increased contribution of E. vaginatum were found over the past 9000 years i.e., around 8100, 7500, 6850 and 6650, 5850, 4650, 3150, 2350, 1950, 1450, 750 cal yr BP (Fig. 4), and those around 8100 and 3150 cal yr BP also coincided with high peat decomposition (Fig. 2). The increased proportion of E. vaginatum was positively associated with dry summers as documented by high fire activity and a lowering of the lake level at Ştiucii Lake (Fig. 4; Feurdean et al., 2013). The first E. vaginatum increase at ca. 8100 cal yr BP and decrease of Picea abies (needles) could be correlated with the known 8.2 kyr cold event. This event was widely recorded from the northern Atlantic to central eastern Europe, although in some parts was characterized by wet conditions while in others dry (Tinner and Lotter, 2001; Mayewski et al., 2004; Seppä and Poska, 2004; Gałka et al., 2014). In Romania, the 8.2 kyr climate event is suggested to have been cold and dry particularly during summers (Feurdean et al., 2008; Buzko et al., 2013; Toth et al., 2015; Tantau et al., 2014; Grindean et al., 2015). The episodic occurrences of E.

vaginatum at 7500, 5850, 3150 cal yr BP are also largely coincident with low peat accumulation (Bjorkman et al., 2003) and dry conditions on the peatland (Feurdean, 2005) in the Gutaiului Mountains. However, the increase in E. vaginatum at 4600 cal yr BP took place during a wetter phase. At 8050-7900, 6800-6500, 5900-5800, 4750-4300, 3100-2750, 2350, 1600-1250 cal yr BP the increase proportion of E. vaginatum also matched low lake levels in Central Europe (Fig. 4). The increase of E. vaginatum and a higher peat decomposition 3100-2700 may coincide with deterioration of climate during the 2.8 ka event documented based in a peat archive from NW Europe (Roland et al., 2014). It is worth emphasising that the increased values of Eriophorum vaginatum in five cases (ca. 8000, 6700, 5850, 4750, 2800 cal yr BP) are linked to decreased Picea abies pollen percentages and macrofossil (Fig. 4). It is therefore apparent that the decline of Picea abies abundance at Tăul Muced was connected with a change to dry conditions. Temporary declines in Picea abies around 8000 and 6700 cal yr BP were also noted at neighbouring site Poiana Stiol (Feurdean et al., 2016). However, little is known about the relationship between the occurrence of Picea abies and E. vaginatum, therefore additional studies are needed to determine the underlining factors for this association.

E. vaginatum plays an important role in the colonization of burned sites (Wein and Bliss, 1973; Keatinge, 1975; Sillasoo et al., 2011). However, there is also a suggestion that in the case of ombrotrophic peatlands with stable wet surface and high water level, the role of fire on the dynamics of Sphagnum population is limited (Kuhry, 1994; Magnan et al., 2012; Gałka and Lamentowicz, 2014). The absence of large macrocharcoal pieces at Tăul Muced bog suggests that the increased abundances of Eriophorum vaginatum were not caused by burning on the bog surface, nor was the vegetation succession at the coring point disturbed by fire. The constant presence of Sphagnum magellanicum indicates that our site has been an ombrothrophic peat bog fed by water from precipitation for the past 8000 years.

Are these cycles due to the autogenic succession?

The second hypothesis to explain the vegetation development on bogs states that the development of local vegetation, mainly of *Sphagnum* species, is a cyclic regeneration of the surface by hummock-hollow forms (Osvald, 1923; Kulczyński, 1949). Previous studies that have investigated the importance of autogenic succession as the main driving mechanism for microform development have focused on large raised peat bogs. In contrast, our study site is a relatively small mountain bog, and should be more sensitive to climate changes. However, autogenic succession of vegetation at Tăul Muced bog by development of the hummock-hollow forms could be suggested by the presence of *Polytrichum strictum* (Fig. 2). *P. strictum* was present on this peatland during four time intervals: at ca. 5000-4800 cal yr BP, ca. 1800 cal yr BP, ca. 1000 cal yr BP, and over the last 80 years (Fig. 2) and it was positively associated with *E. vaginatum* and negatively to *S. magellanicum*. *P. strictum* grows on the driest places on the peatland, i.e. usually on the top of hummocks with pH of ca. 4.3 (Hájková and Hájek, 2004) and water depth from ca. 15 to 65 cm below surface (Bragazza and Gerdol, 1996). Thus, a cyclic development of hummocks on the peatland, at least during these four time periods is suggested by the occurrence of *P. strictum*. It is probable that the top of the hummocks was occupied by *P. strictum*, but these hummocks decomposed during subsequent intervals of low water level. The decomposition of hummocks is often a process on bogs with well-developed hummock-hollow structure (personal observation).

Concerning the processes of autogenic succession we also have to take into account the role of competition between the two dominant species *S. magellanicum* and *E. vaginatum*. According to Tuittila et al. (2007) these two species prefer a similar moisture gradient in the southern boreal bogs of Finland, but *S. magellanicum* has a weaker competitive capacity. From recent observations we also know that *E. vaginatum* prevailed abundantly on the ombrothropic peatlands after a decline in hydrological stress (Silvan et al., 2004; Lavoie et al., 2005). Based on the above, a lowering of the bog water level due to a decrease in precipitation and or increase evapotranspiration may have given a competitive advantage to E. vaginatum to spread on the bog and therefore it may have temporary replaced S. magellanicum and S. angustifolium. On the contrary, during phases of increased water level due to a more humid climate and stable hydrological conditions on the bog surface, S. magellanicum became the dominant species.

Summary

The high-resolution plant macrofossil record presented here provides the first long-term reconstruction of local vegetation dynamics changes in a small mountain raised bog in the Eastern Carpathians. Results from our study improve our understanding of drivers of peat development, and attempt to elucidate whether the peat-forming vegetation of this small mountain bog is linked to climate changes, or if it the succession was autogenic.

In most cases the expansion of Sphagnum magellanicum and S. angustifolium has occurred during wetter climatic conditions, whereas that of Eriophorum vaginatum was generally associated with dry conditions. Our results thus give more support to the hypothesis that the development of the local vegetation at Tăul Muced bog was largely related to climate changes. However, the role of autogenic plant succession in driving the peatland development cannot be fully excluded. Nevertheless, the mountain ombrotrophic bogs in this region appear to be suitable as proxy-climate archives but more records are need to better understand the mountain peatland development and more confidently link the changes in peat forming vegetation to climatic conditions.

Acknowledgements

We acknowledge the support from the Polish National Science Centre project No. NN305062240 (M.G.) and Romanian National Authority for Scientific Research, CNCS – UEFISCDI PN-II-RU-TE-2014-4-2445 (A.F. and I.T.). We thank Adam Hölzer and Jan Janssens for help in the identification of Sphagnum and brown mosses species. We are thankful to Bas van Geel, Julie Loisel, Petra Hájková and Tom Roland for their constructive comments that considerably improve the quality of the manuscript.

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Description of figures:

Figure 1. A. Location map of the studied area in the Eastern Romanian Carpathians and sites mentioned in the text: 1, Bisoca (Tanțău et al., 2009); 2, Harghita Mts./Sfânta Ana (Magyari et al., 2009); 3, Gargalau (Tanțău et al., 2014); 5, Gutâi Mts. (Feurdean 2005); 6, Lake Ştiucii (Feurdean et al., 2013); 7, Apuseni Mts. (Feurdean et al., 2009). B. Location map of the studied site in the western part of Rodnei Mountains.

Fig. 2. Plant macrofossils and percentages of selected pollen types. Plant macrofossils marked with % are estimated volume percentages, others are absolute counts (with X-axis scale labels; note scale differences) or presence/absence (no X-axis scale labels).

Fig. 3. Wavelength analysis. A) Continuous wavelet power spectrum for S. magellancium (top) and E. vaginatum (bottom). The areas outlined in black are significant at the 95

% level and the shaded area represents the cone of influence where signal interpretation can be unreliable. B) Squared wavelet coherence between S. magellancium and E. vaginatum. The thick black contour line shows the 5% significance level against red noise. Relative phase relationships between the two time series are shown by arrows, with in-phase pointing right, anti-phase pointing left, S. magellancium record leading E. vaginatum by 90^{o} pointing straight up, S. magellancium record lagging E. vaginatum by 90^{o} pointing straight down. The anti-phase relationship between the two proxies is persistent at most periods.

Fig. 4. Comparison of the proxies: selected plant macrofossils and pollen types at Taul Muced, macroscopic charcoal accumulation rate at Lake Stiucii and lake level changes in Central Europe).

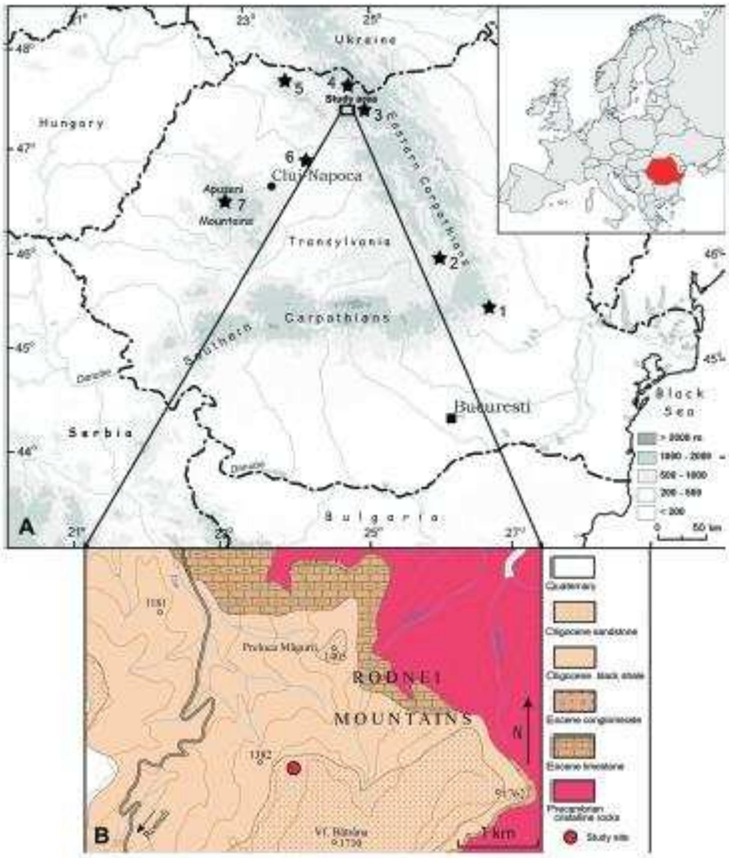

Ukraine
Hungary
Study area
Cluj-Napoca
Apuseni
Mountains
Transylvania
Eastern Carpathians
Carpathians
Southern
Danube
Serbia
Bucuresti
Black
Sea
Bulgaria
A
RODNEI
MOUNTAINS
N
B
1 km
Quaternary
Oligocene sandstone
Oligocene black shale
Eocene conglomerate
Eocene limestone
Precambrian crystalline rocks
Study site

Figure 1

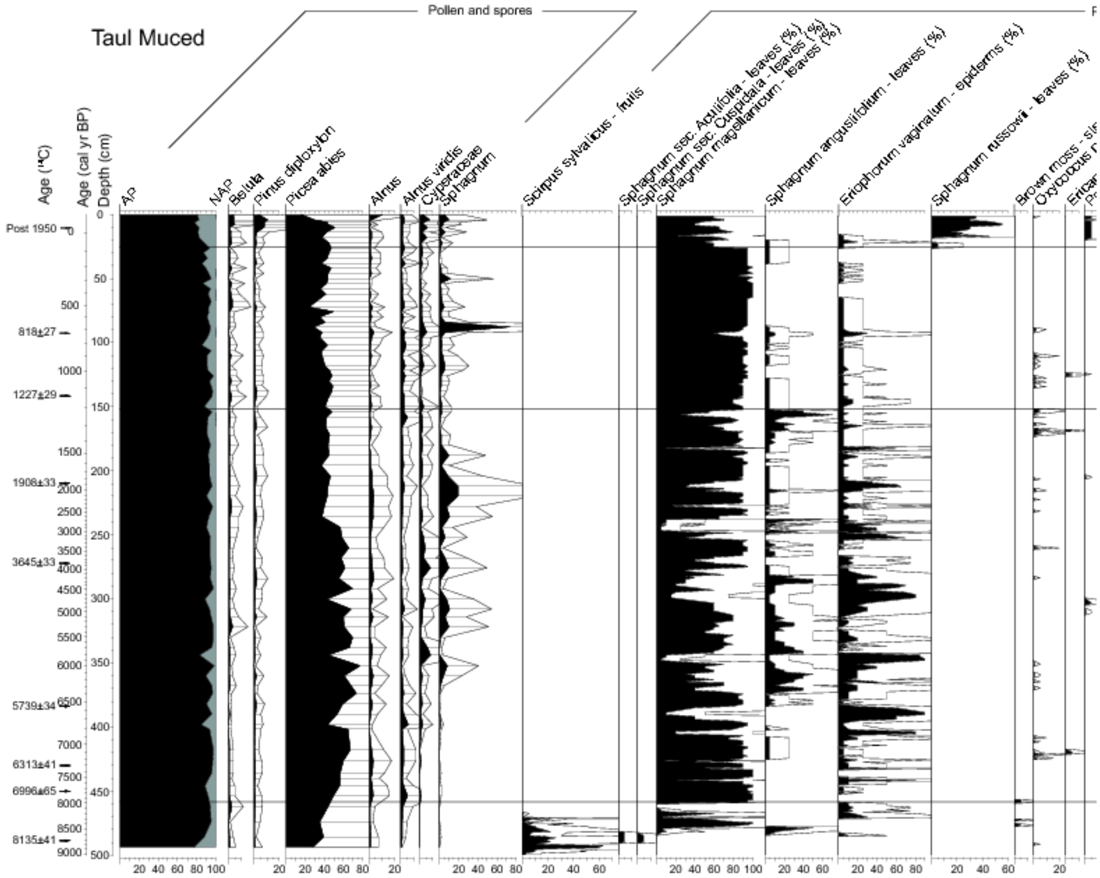

Taul Muced
Pollen and spores
Age (°C)
Age (cal yr BP)
Depth (cm)
AP
NAP
Betula
Pinus diploxylon
Picea abies
Alnus
Alnus viridis
Cyperaceae
Sphagnum
Scirpus sylvaticus - fruits
Sphagnum sec. Acutifolia - leaves (%)
Sphagnum sec. Cuspidata - leaves (%)
Sphagnum magellanicum - leaves (%)
Sphagnum angustifolium - leaves (%)
Eriophorum vaginatum - epiderms (%)
Sphagnum russowii - leaves (%)
Post 1950
818±27
1227±29
1908±33
3645±33
5739±34
6313±41
6996±65
8135±41

Figure 2

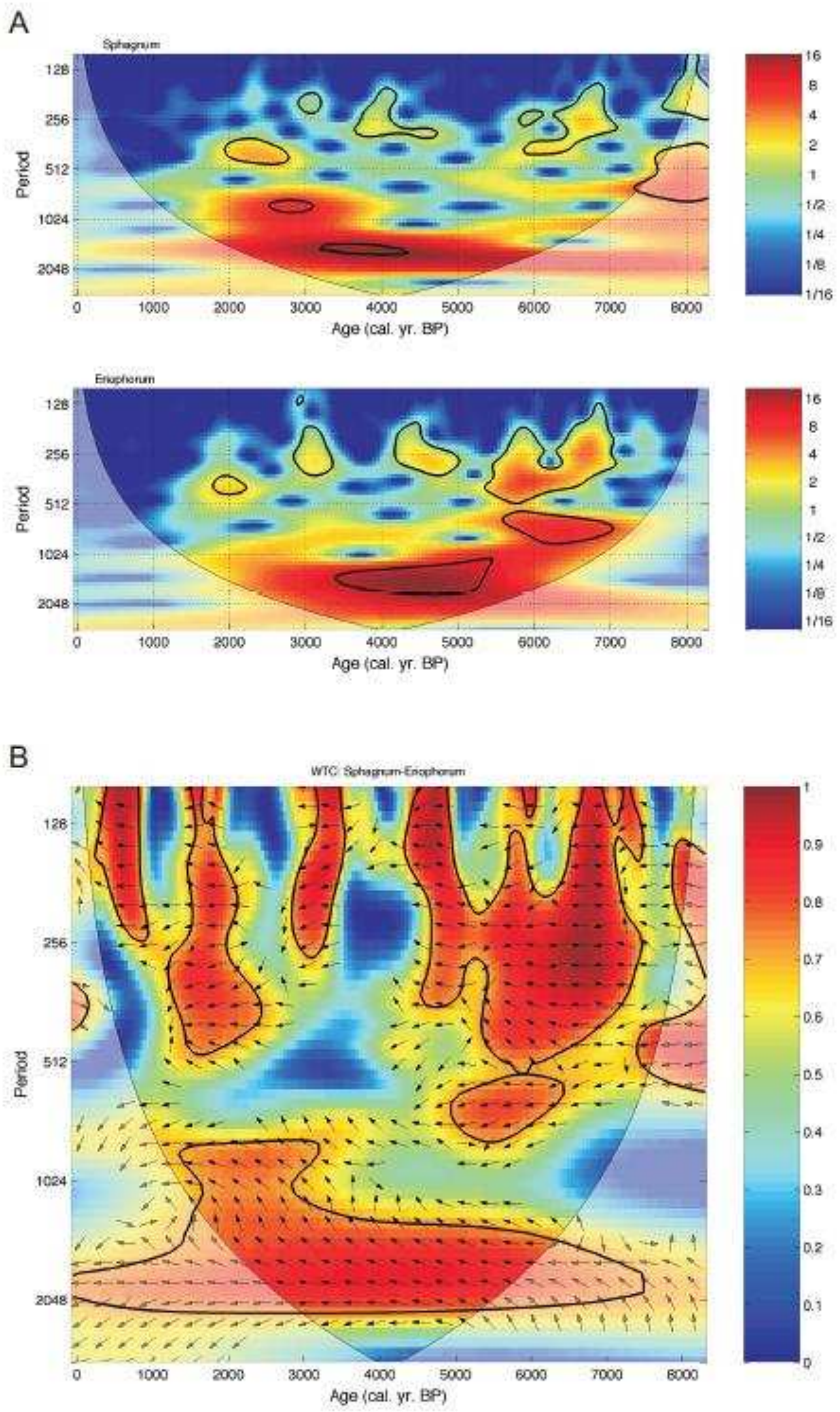
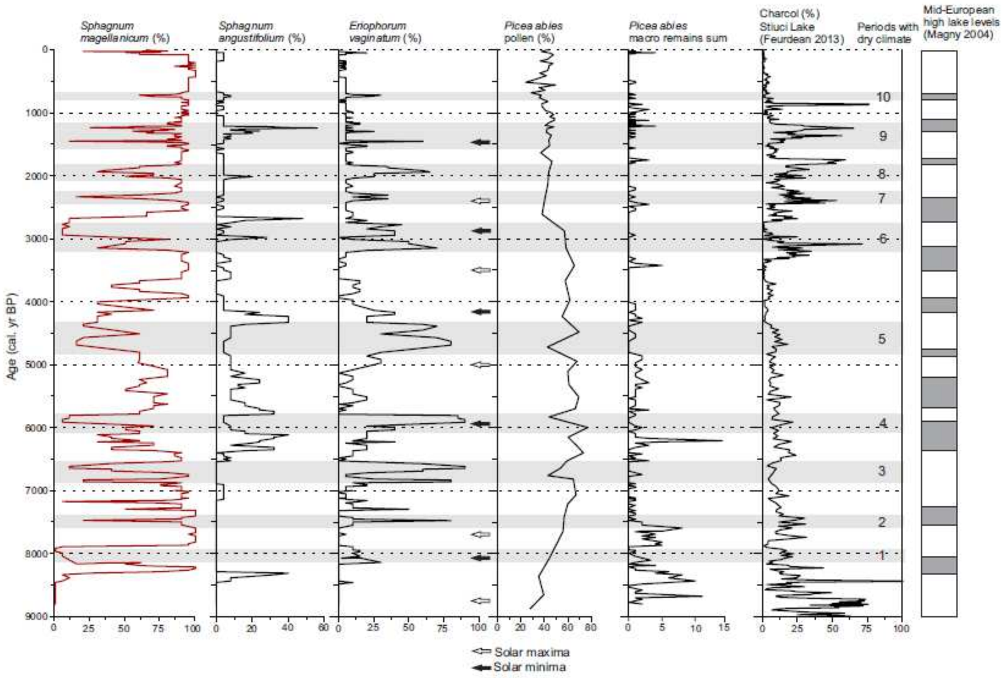

A
Sphagnum
Eriophorum
Period
Age (cal. yr. BP)
B
WTC: Sphagnum-Eriophorum

Figure 3



Sphagnum magellanicum (%)
Sphagnum angustifolium (%)
Eriophorum vaginatum (%)
Picea abies pollen (%)
Picea abies macro remains sum
Charcol (%) Stiuci Lake (Feurdean 2013)
Periods with dry climate
Mid-European high lake levels (Magny 2004)
Age (cal. yr BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10
9
8
7
6
5
4
3
2
1
0 25 50 75 100
0 20 40 60
0 25 50 75 100
0 20 40 60 80
0 5 10 15
0 25 50 75 100
Solar maxima
Solar minima

Figure 4

Highlights

The scientific merit of this paper resides from:

- It is the very first study concerning the development of a bog in Central Eastern Europe
- The use of high quality data set i.e., high-temporal resolution, continuous plant macrofossil record
- Hypothesis testing of a hotly debated subject regarding the driving factors for peatland development and functioning, that is regional climate changes versus autogenic succession from an area where nothing is know about the subject
- Implication of the use of ombrothrophic mountains bog as a palaeoclimatic archive
- Consolidates the geographical coverage of proxy reconstruction of past climate variability in a poorly studied region.