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Preliminary data on the bog surface wetness from the Sirok Nyírjes-tó peat bog, Mátra Mts, Hungary

Gusztáv Jakab
Institute of Environmental Sciences
Szent István University, Szarvas

Pál Sümegi
Department of Geology and Paleontology
University of Szeged, Szeged

The Sirok Nyírjes-tó peat bog provides an almost full Holocene climatic record reconstructed by bog surface wetness investigations based on plant macrofossil analysis. The method of bog surface wetness reconstruction has not so far been adapted to the characterization of continental peat bogs. The emergence of a deep oligotrophic lake was dated to cc. 9500 cal. yr BP. The driest phase of the peatland was recorded at 6400 cal. yr BP, at the time of the Holocene climatic optimum. The deterioration of the climate, which began at 3500 cal BP, culminates here in the Carpathian Basin, as was shown by numerous records. An increase in the amount of Sphagna from 2800 cal. yr BP in the Nyires-tó peat bog marks the cooling of the climate and the accompanying rise in rainfall. The first oligotrophic Sphagnum peatland developed at Sirok between 2300 and 1500 cal. yr BP. Since 2300 cal. yr BP a record of alternating phases of Sphagnum peatlands and sedge/reed peatlands was demonstrated. A sudden expansion of Sphagna was recorded at least 10 times. Sphagnum-peaks at 2150, 1750, 1300, 1000, 850, 500 and 200 cal. yr BP perfectly match the humid periods identified in western Europe.

Key words: Holocene, climate reconstruction, plant macrofossils, peat bog, Sphagnum, Holocene climatic optimum, Little Ice Age

Introduction

The first Holocene millenial-scale climatic scheme was based on the studies of peat stratigraphy in Scandinavia a century ago (Blytt 1876; Sernander 1908). This widely applied scheme was recognized as too simplistic and not realistic. On the basis of high-latitude ice-core data Holocene climate is considered relativily even

Addresses: G. Jakab: H-5540 Szarvas, Szabadság u. 1–3. Hungary, e-mail: cembra@freemail.hu
P. Sümegi: H-6722 Szeged, Egyetem u. 2–6. Hungary, e-mail: sumegi@geo.u-szeged.hu
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and invariable (Oldfield 2005). Climate fluctuation of the Holocene has been now a major research focus in Quaternary paleoecology, because these proxy-climate data archives can be compared with the recent global warming.

One of the most popular approaches is looking for proxies reflecting transformations in the biological and chemical composition of peat sequences as signals of past climatic fluctuations. A frequently used approach in chemical analysis is the investigation of humification (Aaby 1976; Barber 2007). This approach relies on the logic that surface humidity ultimately determines the rate of decay of plant matter. When peatlands are dried out, this is reflected in a sudden increase in humic acids within the deposits. These acids are extracted from the deposits using various alkalis and their concentration is determined in the solution by spectrophotometric approaches.

The most widely adopted method in the analysis of biological components is the study of plant macrofossils, including mosses or testacea (Hughes et al. 2000; Barber and Langdon 2001; Barber and Charman 2005; Birks 2007; Mauquoy and van Geel 2007). These studies enable us to identify various peatland types and past communities. However, there is a special feature of peatland plants that can aid the interpretation of earlier environmental conditions. Certain species are distributed along a gradient reflecting differing water depths. Bog surface wetness investigations using the QLCMA technique (semi-quantitative quadrat and leaf-count macrofossil analysis technique) of Barber et al. (1994) permitted high-resolution reconstruction of past climatic changes. Former bog surface wetness studies aimed at deciphering past climatic conditions via detailed analysis of peatland deposits, primarily focusing on the investigation of *Sphagnum* peat from so-called ombrotrophic peatlands (Mauquoy and Barber 1999; Barber et al. 2000; Blackford 2000; Barber and Langdon 2001; Barber and Charman 2005). Climatic conditions favoring the evolution of these type of peatlands are mainly restricted to the western parts of Europe under oceanic climatic influence (Barber and Charman 2005; Barber 2007) or in Fenno-scandinavia (Väliranta et al. 2007), where the moisture gradient is un-ambiguously reflected in the distribution of certain Sphagnum taxa; no discussion, however, occurs on SE Europe, including Hungary. Barber and Charman (2005) questioned the suitability of strongly continental peatlands for paleoclimatic reconstructions. This area appears blank on the data source maps, pointing to the paucity of available Holocene bog surface wetness records in this region (Buczkó et al. 2009).

The general climatic characteristics of Hungary are far from ideal for the emergence of *Sphagnum* peatlands. The majority of Sphagnum peatlands are restricted to the northern areas of the North Hungarian Range and the northern Great Hungarian Plain (GHP), as well as the eastern parts of the country enjoying more precipitation thanks to the positive effect of the oceanic and montane climatic influences (Boros 1968; Szurdoki and Nagy 2002). The actual number of *Sphagnum* peatlands is below 20, the majority being tiny, with an extension of a couple of ha. Raised bogs are completely absent. After the artificial desiccation of *Sphagnum* peatlands there is an advance of reed, sedge and birch into these areas, depending on local availability (Borhidi and Sánta 1999; Lájer 1998). The bulk of Hungarian peat mosses can be found in fens and willow and alder swamps, where they create mixed-extent carpets, but the microtopography, as f.i. in Nordic mires (hummock, hollow, pool, etc.), are more or less absent. The most frequent species in bigger mires are *Sphagnum angustifolium*, *S. fallax, S. palustre* and *S. fimbriatum*, which are not able to build a hummock-hollow system. The species which could create a compact hummock (e.g. *S. capillifolium, S. rubellum, S. magellanicum*) are very rare and show only scattered distribution in these mires. Hollow and pool-forming species are also absent except for some *S. cuspidatum* occurrences.

This paper presents the preliminary results of bog surface wetness investigations on the deposits of a *Sphagnum*-bog called Nyírjes-tó in the Mátra Mts (Fig. 1). Specific questions which we aim to address are:

1. Can we use the bog surface wetness method based on plant macrofossil analysis to obtain a proxy-climate record under conditions of a strongly continental climate? Which are the most characteristic features of peat composition under wet and dry conditions?

2. Can we find any correspondence in the bog surface wetness record from Hungary and western Europe? How does the obtained bog surface wetness record correlate with other proxy-climate records from the Carpathian basin?

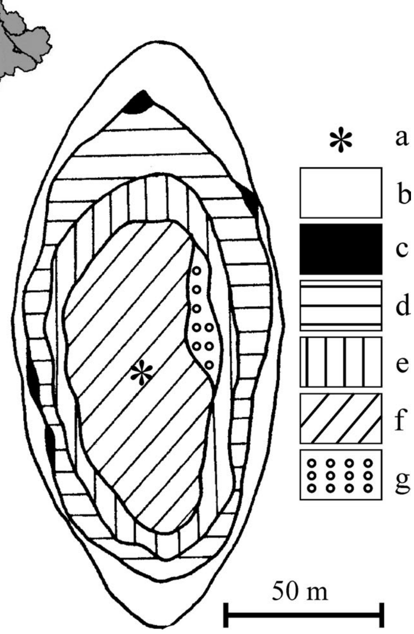

Fig. 1
Location of the study site in Hungary and the coring point in the peat bog (a: coring point, b: marginal marsh, c: Lemno-Utricularietum, d: Salicetum cinereae, e: Salicetum cinereae with Sphagnum, f: Carici lasiocarpae-Sphagnetum, g: Saliceto-Sphagnetum, original map: Máthé and Kovács 1958)

Study site

The location of the Nyírjes-tó peat bog of Sirok is situated in the northern part of the country, in the eastern foothills of the Mátra Mts, at an elevation of 250 m (Fig. 1). It covers a small area, of about 9,000 m^2. No surficial watercourses feeding or draining the peatland are known. The basin is fringed by a woodland of hornbeam (*Carpinus betulus*) and oak (*Quercus petraea*). The following plant communities are present, moving from the margins towards the center: *Salicetum cinereae, Salicetum cinereae-Sphagnetum, Carici lasiocarpae-Sphagnetum*. There is a small stand of reedbed on the eastern side of the peat bog. This peatland harbors the following peat moss taxa: *Sphagnum palustre, S. subsecundum, S. magellanicum, S. recurvum* s. l., *S. fimbriatum, S. squarrosum, S. obtusum* and *S. angustifolium*. The most common are those of *Sphagnum recurvum* s. l. and *S. palustre* (Máthé and Kovács 1958; Szurdoki and Nagy 2002).

Szurdoki (2005) investigated the abiotic conditions of some of the most frequent *Sphagnum*, in five Hungarian mires, among others the Nyírjes-tó peat bog. Conductivity, pH, height above water table, Na, K, Ca and Mg concentrations were detected. The investigated peat bogs were similar, but there were many significant differences between them in terms of analytical variables, and only weak differences within mires. On the basis of water table, pH, and conductivity the investigated species can be separated. *S. fallax* and *S. angustifolium* do not differ from each other, which is not a surprise since they live together in mixed carpets in most investigated mires. They mainly occur in wet and acidic locations with poor mineral content. *S. palustre* lives in the driest places and *S. fimbriatum* in wet and less acidic ones, which are characterized by the highest mineral content.

According to Szurdoki (2005) the most characteristic features of the Hungarian peat bogs are low pH (c. pH 4) and conductivity of 40–80 μS/cm; however, the concetration of calcium proved to be relatively high (10 mg/dm^3) within a European context. The pH of the Nyírjes-tó surface peat layer fluctuated between 3.5 and 4.5 (Máthé and Kovács 1958; Szurdoki 2005). The concentration of nutrients and the water level of Nyírjes-tó is the lowest among the Hungarian peat bogs. The main water level is 17 cm from the peat surface, but in late summer it can be as low as 30 cm (Szurdoki 2005).

Penksza et al. (1994) investigated the heavy metal accumulation in peat and in peat-forming mosses and vascular plants from the Nyírjes-tó. Unfortunately the stratigraphic resolution was insufficient and radiocarbon dating was lacking. Therefore the comparison with our paleoecological results is problematic. A detailed palynological work on the peatland was published by Gardner (2002). The comparison of terrestrial and wetland vegetation development is based on the results of Gardner.

Methods

The sampling of the 401 cm deep, undisturbed sedimentary sequences of the Nyírjes-tó Basin was carried out using a 5 cm-diameter Russian-type corer (Jowsey 1966). Overlapping cores were extracted conforming to the general practice in Quaternary paleoenvironmental studies (Aaby and Digerfeldt 1986). Coring was carried out in the central part of the bog, now occupied by the Carici lasiocarpaea-Sphagnetum community. Samples taken between the depths of 401 and 4 cm were subjected to plant macrofossil analyses. The Psimpoll program (Bennett 1992) was used for plotting the analytical results.

The main lithostratigraphic features of the sedimentary sequence were determined and analyzed. For the description of the cores, the internationally accepted system and symbols of Troels-Smith, developed for unconsolidated sediments, was adopted (Troels-Smith 1955).

Dating of the sequence was carried out by conventional radiocarbon dating at the radiocarbon dating facility in Gliwicze, Poland. Four bulk samples (6–10 g peat) of sediment were analyzed for radiocarbon ages. In order to allow comparison with other archeological data, the dates were calibrated using the CalPal-2007 online calibration programme, using the most up-to-date CalPal-2007Hulu calibration data set (Weninger et al. 2008). The original dates (^{14}C) are indicated as BP, while the calibrated dates are indicated as cal BC/AD or cal BP. For a more accurate dating of the lower part of the core, additional radiocarbon measurements are under way.

For the description of macrofossils a modified version of the QLCMA technique (semi-quantitative quadrat and leaf-count macrofossil analysis technique) of Barber et al. (1994) (Jakab et al. 2004a) was used. To obtain concentrations for the macrofossil components, a known amount of marker grains (0.5 g poppy seeds, ca. 960 pieces) were added to the samples. In the diagrams the total number of seeds relates to 20 cm^3 sediment, while other macrofossil components are expressed as concentrations (piece cm^{-3}). Organic remains from peat and lacustrine sediments rich in organic matter can be divided into two major groups. Some remains can be identified with lower ranking taxa (specific peat components), while others cannot be identified using this approach (non-specific peat components). The most important non-specific peat components are the following:

– Unidentified organic material (UOM): irregularly shaped tissue fragments, often moderately decomposed.

– Undifferentiated monocotyledon remains (Monocot. undiff.): opaque or slightly pigmented rhizomes and epidermal tissue fragments, with elongated or short cells.

– Unidentified bryophyte fragments (UBF): Only the tubular, brown pigmented "stem" survives in decomposed peat with the stub of the "leaf veins".

– Unidentifiable leaf fragments (ULF): Moderately humified deciduous tree leaf fragments. Easily recognizable by the remains of web-like veins.

– Charcoal: Tiny, 1–3 mm large charcoal fragments (macro-charcoal), probably of allochthonous origin.
– Wood: Lignified plant tissues can be easily recognized from their compact, thick-walled wood fibres.

Results

Chronology and sediment stratigraphy

On the basis of the sedimentological features the core was divided into 12 units. In general mixed *Sphagnum*, reed and sedge peat was found down to a depth of 210 cm. Between 210–300 cm mixed reed and sedge peat was encountered; between 300–340 cm occurred a brown moss peat with high wood content. Between 340–410 cm dark gray, silty lacustrine sediments were found with wood and moss fragments. The detailed sediment description is presented in Table 1.

Table 1
Lithological description of the Nyírjes-tó sequence (Sümegi and Jakab)

Depth (cm)	Troels-Smith (1959) sediment description	Lithological characteristics
0–20	Tb(Sphag.)4Th+As+Gs+	Light brown fresh *Sphagnum* peat with little silt and sand
20–60	Tb(Sphag.)2Th2	Light brown mixed *Sphagnum,* reed and sedge peat
60–80	Tb(Sphag.)4Tl+	Dark brown *Sphagnum* peat
80–120	Th3Tb1Tl+	Dark brown mixed *Sphagnum,* reed and sedge peat with wood fragments
120–160	Tb(Sphag.)3Th1Tl+	Dark brown mixed *Sphagnum* and reed peat with wood fragments
160–185	Th3As1Tb(Sphag.)+Tl+	Dark brown mixed reed and sedge peat with wood fragments and *Spagnum* remains
185–210	Tb(Sphag.)4Th+Tl+	Dark brown *Sphagnum* peat with wood, reed and sedge fragments
210–285	Th2As1Tl1Tb(Sphag.)+	Dark brown mixed reed and sedge peat with some *Sphagnum* remains and many wood fragments
285–300	Th3As1Tl+Tb+	Dark brown *Carex elata* peat
300–340	Tb2As1Tl1Th+	Dark brown brownmoss peat with many wood fragments
340–360	As2Ag2Gs+	Dark grey clayey silt
360–410	As3Sh1Gs+Tb+Dg+	Dark grey clayey silt with moss and wood fragments and some sand

The results of the radiocarbon measurements of the sequence described in this study are shown in Table 2. The age-depth model was established by linear interpolation between the calibrated radiocarbon dates (Fig. 2). Sedimentation rates are shown in Table 3. The bottom part of the investigated part of the core, between 195–315 cm, is characterized by very low values (0.25 mm yr^{-1}); the sedimentation rate increases gradually between 38–195 cm from 0.25 to 1.16 mm yr^{-1}, and attains the highest values in the top 38 cm of the core (3.39 mm yr^{-1}).

Table 2
Radiocarbon data from the Nyírjes-tó (Sümegi)

Sample No	Depth (cm)	Sample type	^{14}C age (uncal BP)	cal AD/BC (2 σ)
GdA-565	37–38	Bulk sediment (peat)	55 ± 30	1889 ± 83
GdA-566	99–100	Bulk sediment (peat)	560 ± 30	1364 ± 41
GdA-567	195–196	Bulk sediment (peat)	1680 ± 30	353 ± 41
GdA-568	315–316	Bulk sediment (peat)	5640 ± 40	4465 ± 52

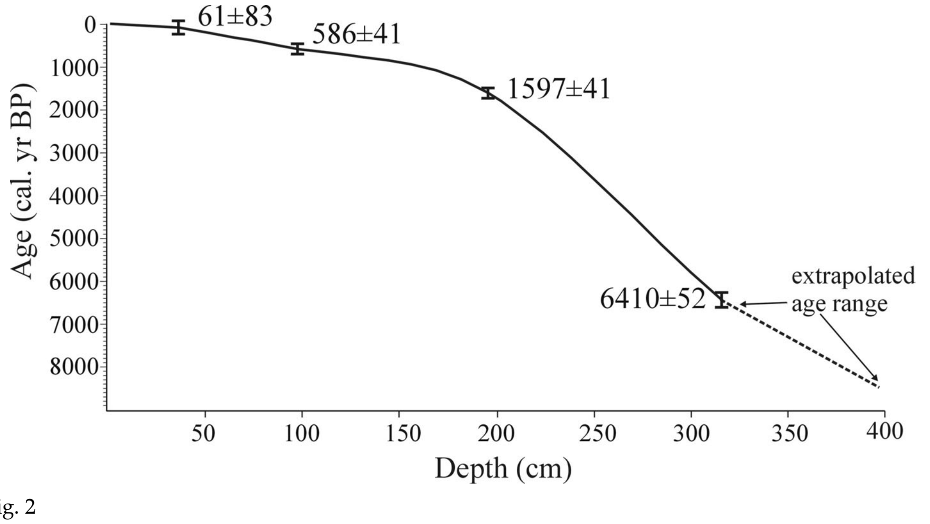

Fig. 2
Calibrated radiocarbon age ranges (1) and suggested age-depth curve for core SI (Sirok Nyírjes-tó). All dates were converted into calendar years BP using the CalPal-2007 online calibration program (Danzeglocke et al. 2008). See also Table 3 (Sümegi and Jakab)

These sedimentation rates are related to the sediment types accumulated in the basin. Above 210 cm *Sphagnum* and reed peat can be found with high organic content. Subsamples for macrofossil analysis were taken at 4 cm intervals, which correspond to 40–50 yr resolution in the last 2000 years and 130–150 yr resolution before 2000 yrs BP. Nevertheless the resolution of radiocarbon dating in the lower 2 meters is unsatisfactory, so a more accurate stratigraphic resolution requires further radiocarbon measurements.

Table 3
Sediment accumulation rates from the Nyírjes-tó sequence

Depth ranges (cm)	Sediment accumulation rates (mm/yr)
0–38*	3.39
38–99	1.16
99–195	0.95
195–315	0.25

*The age of the upper point concerned AD 2007 (Sümegi and Jakab)

Terrestrial and wetland vegetation development

Figure 3 displays the tissue, moss, animal and seed remains extracted from the investigated sequence. Table 4 presents the most important characteristics of the local macrofossil zones. On the basis of the results the following evolutionary history of the peatland and the sorrounding watershed can be drawn.

Table 4
Discussion of the macrofossil assemblages of the Nyírjes-tó sequence (Jakab)

Depth (cm)	Age (cal. yr BP)	Local macro-fossil zone	Yone description
32–6	61–	SIM–9	Degrading oligotrophic peat bog conditions. Beside the high amount of *Sphagnum recurvum*, the leaves of *S. squarrosum* and *S. palustre* indicate gradual eutrofication. Clay particles and mollusc shells indicate soil erosion in the catchment. *Calamagrostis canescens* and *Carex lasiocarpa* were the most common vascular plants.
71–32	380–61	SIM–8	Dry oligotrophic peat bog conditions. *Sphagnum* concentrations decrease, *Carex elata* and *Phragmites* concentrations rise. *Juncus* sp. remains indicate degradation.
88–71	500–380	SIM–7	Wet oligotrophic peat bog conditions. Beside the dominant *S. recurvum* s. l., *S. cuspidatum* show a remarkable peak. Peat bog vegetation dominated by *Calamagrostis canescens, Carex lasiocarpa, C. canescens, C. limosa* and *Eriophorum vaginatum*. Occurrence of *Sphagnum cuspidatum* and *Carex limosa* indicates conditions wetter than now.
188–88	1500–500	SIM–6	Macrofossil concentrations show remarkable fluctuations in this zone. High concentrations of reed and peat moss remains alternate from time to time. The first *Sphagnum* peaks dominated by *S. obtusum,* and later by later *S. subsecundum*, *S. magellanicum* and *S. recurvum* s. l., were typical.
213–188	2300–1500	SIM–5	Oligotrophic peat bog conditions with high concentrations of *Sphagnum* leaves (mostly *S. magellanicum*), *Carex lasiocarpa* and *C. rostrata* rhizomes and *Betula* remains.
284–213	5200–2300	SIM–4	Amount of *Quercus* remains decreased caused by rising water level. Pond weeds (e.g. *Potamogeton natans*), weeds living on wet mud (e.g. *Rorippa amphibia*) and planctonic invertebrates (e.g. cladocera species) were characteristic of this zone. Lakeshore vegetation dominated by *Carex elata, C. paniculata, C. pseudo-cyperus* and *Glyceria maxima.* Later *Phragmites, Carex rostrata* and *Typha angustifolia* become dominant. A short peat bog expansion was detected at ca. 3900 cal. yr BP, with *Sphagnum magellanicum*, *S. palustre, S. recurvum* s. l. and *Eriophorum vaginatum*.
299–284	cc. 5800–5200	SIM–3	High macrofossil concentrations. Shallow mesotrophic mire conditions with higher water levels. Hummock-hollow structure with *Carex elata* and *Menyanthes trifoliata*.
343–299	cc. 7500–5800	SIM–2	High macrofossil concentrations. Shallow mesotrophic mire conditions, with fluctuating water level and abundant brown moss carpet. Remains (bud scale, leaf fragments, seeds) of *Quercus* were quite frequent in this zone. The rhizomes of *Phragmites australis, Carex elata, C. paniculata, Glyceria maxima* and the moss *Drepanocladus aduncus* dominated the macrofossil record. A short peat bog expansion was detected at ca. 6800 cal. yr BP, when *Sphagna, Carex rostrata, C. pseudocyperus, C. lasiocarpa, Thelypteris palustris* and *Meesia longiseta* spread in the basin.
401–343	cc. 9500–7500	SIM–1	Low macrofossil concentrations. Deep oligotrophic lake conditions., with a short peatland expansion at ca. 8200 cal. yr BP. Lakeshore vegetation was dominated by *Carex elata, Phragmites, Sphagnum magellanicum* and *S. recurvum* s. l.

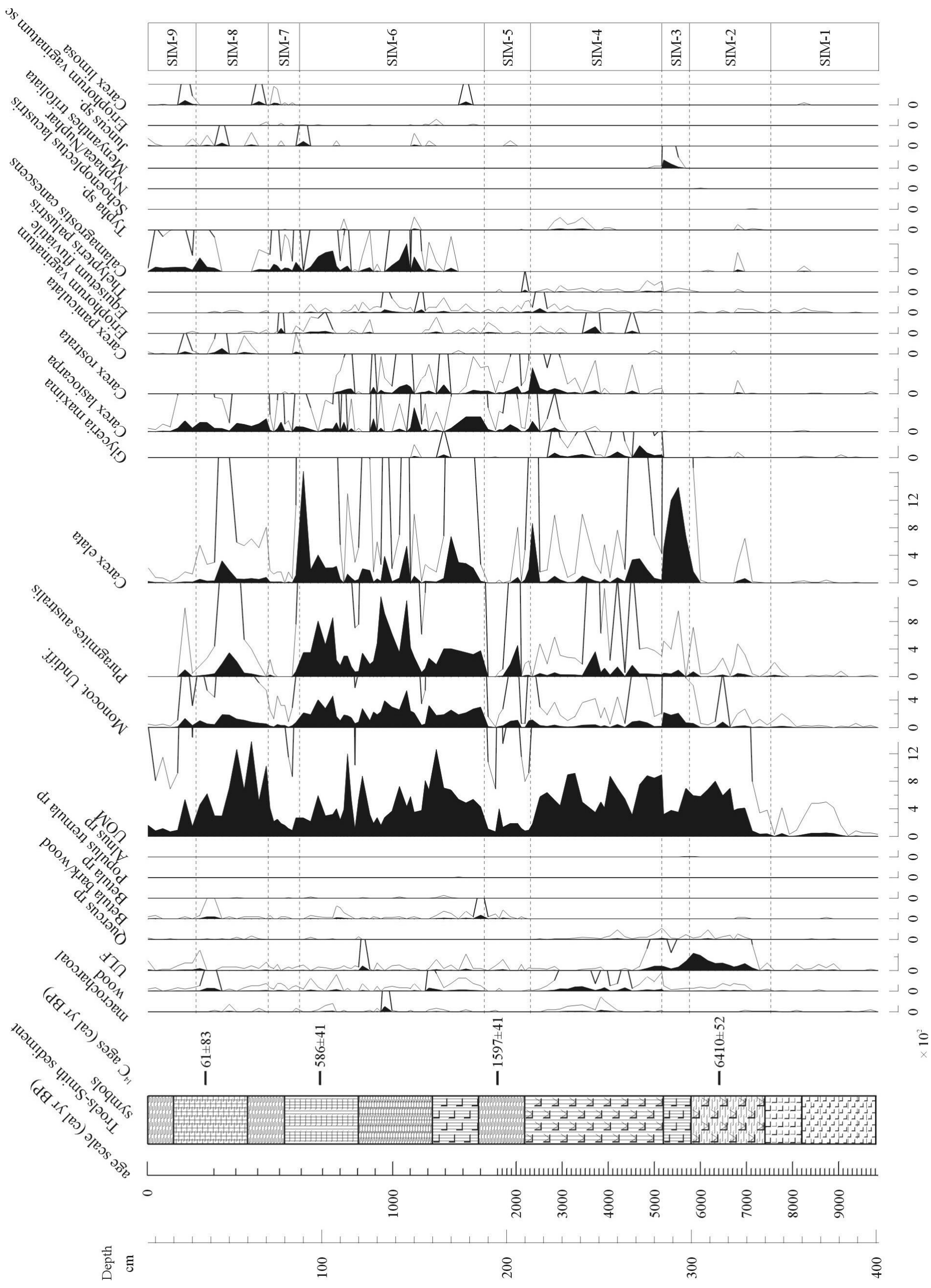

Fig. 3a
Macrofossil diagram of the Sirok Nyírjes-tó peat bog (tissues, pc/cm^3) (Jakab)

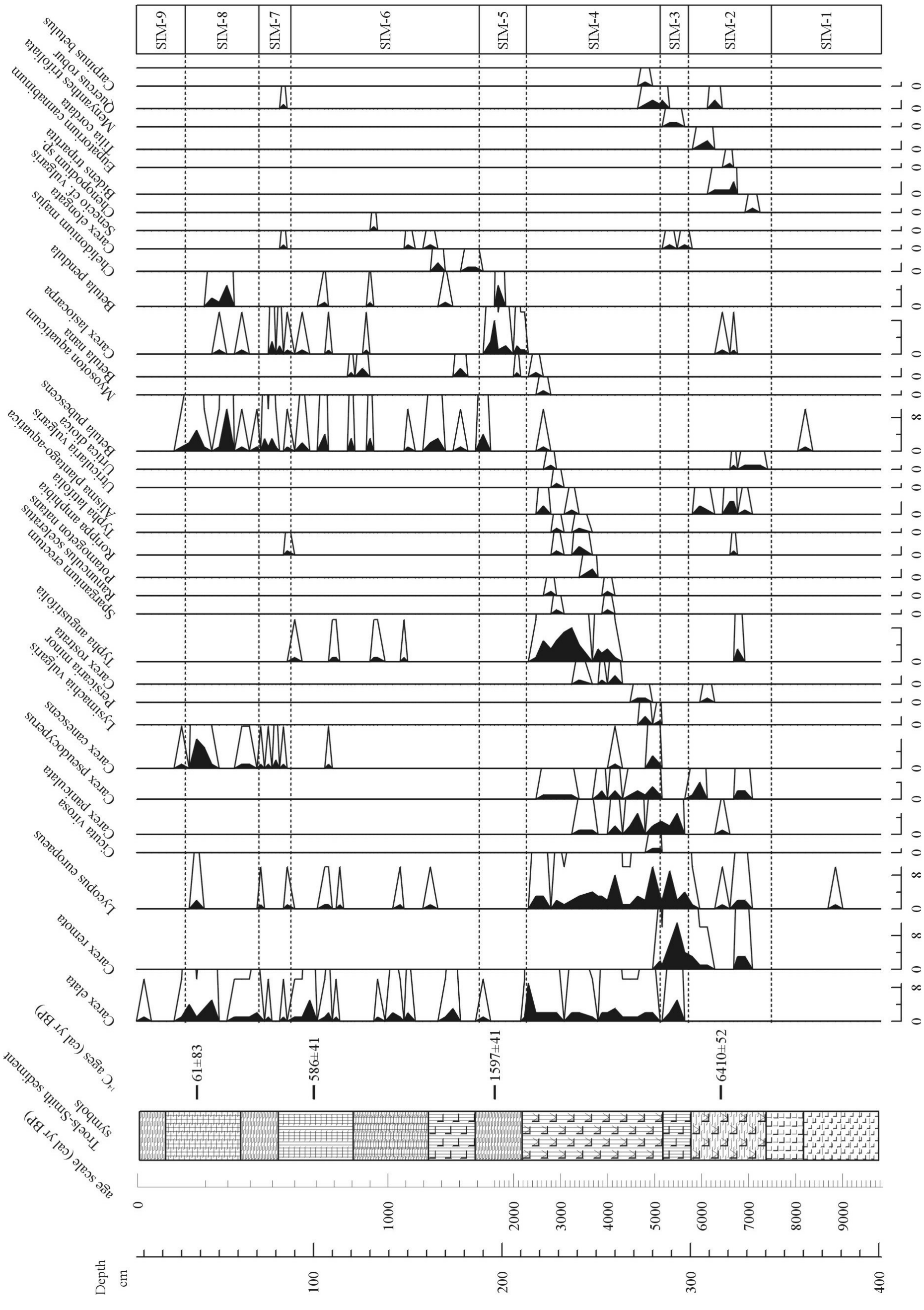

Fig. 3b
Macrofossil diagram of the Sirok Nyírjes-tó peat bog (seeds, pc/20 cm^3) (Jakab)

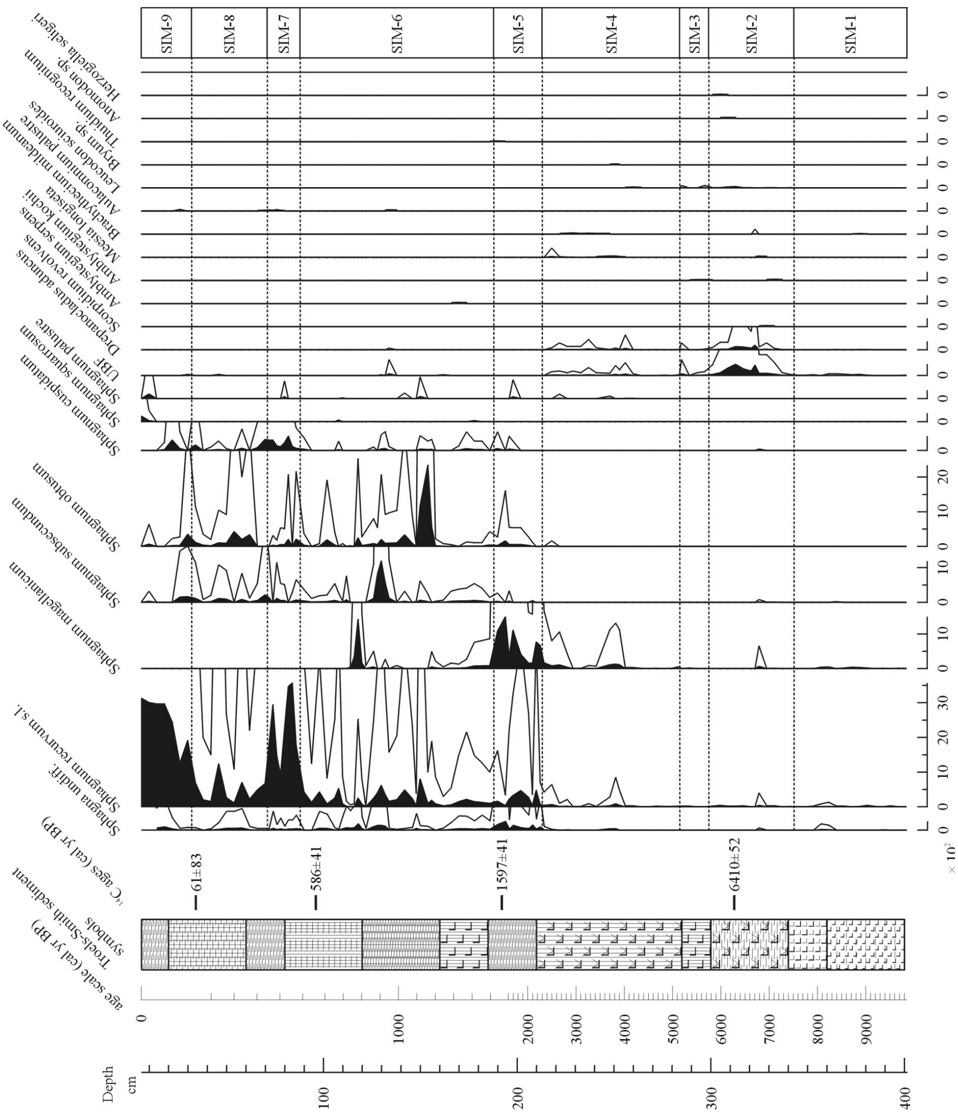

Fig. 3c
Macrofossil diagram of the Sirok Nyírjes-tó peat bog (mosses, pc/cm^3) (Jakab)

The first emergence of aquatic conditions in the depression can be dated to 9500 cal. yr BP, resulting in the emergence of a relatively deep, oligotrophic lake with scant aquatic vegetation. As shown by the palynological study of Gardner (2002) the lake basin was fringed by an open parkland-type woodland with predominance of *Picea*, *Quercus* and *Corylus* untill about 8950 cal. yr BP. This was transformed into a woodland dominated by *Tilia* until 8300 cal. yr BP, which was then finally transformed into a deciduous woodland dominated by *Quercus*, *Tilia* and *Ulmus* until 6900 cal. yr BP, with substantial stands of *Corylus*. Despite the clearly observable transformation of the surrounding vegetation, water levels remained relatively stable in the basin, apart from minor fluctuations, until 7500 cal. yr BP. A drop in water level (increasing concentrations of UOM, UBF and wood) and peat initiation took place almost 1000 years after the development of a closed, deciduous woodland. Therefore there is no direct link between the transformation of the vegetation of the peatland itself and the surrounding terrestrial areas. There is a gradual decrease in water levels from 7500 cal. yr BP, reaching an all time minimum at 6400 cal. yr BP. Open water areas almost completely disappeared, giving way to the expansion of oak shoots in the major part of the basin. The deepest areas turned into an eutrophic marshland and as such we must assume a gradual decrease in the water level from 5800 cal. yr BP, yielding a tussock vegetation. During this period the peatland was fringed by a woodland of *Corylus*, *Quercus* and *Carpinus betulus* (Gardner 2002).

There is another rise in the water level from 5200 cal. yr BP, resulting in the expansion of the peatland. This was accompanied by the appearance of floating mats in the expanding shallow eutrophic pond harboring peat mosses in larger amounts. There is a rapid spread of *Carpinus betulus* in the adjacent closed oak woodlands at that time (Gardner 2002). Peak distribution of *Fagus sylvatica* and *Carpinus betulus* was found between 3700 and 1750 cal. yr BP (Gardner 2002). A similar expansion of Sphagna is indicated by the macrofossil diagram after 3900 cal. yr BP in the basin, with the first appearance of real acidophyllic *Sphagnum* peatlands dated between 2300 and 1500 cal. yr BP.

From 1500 cal. yr BP there is an alternating succession of *Sphagnum* peatlands with reed and sedge peatland horizons, reflecting the alternations of cooler (*Sphagnum* peaks) and warmer (*Phragmites* peaks) periods up to the present day. Optimal *Sphagnum* peatland conditions were inferred at 500 cal. yr BP (AD 1550), with such taxa as *Sphagnum cuspidatum*. As shown by the results of Gardner (2002) there is an increase in human influence in the area from 1750 cal. yr BP as seen in the drop in the amount of *Fagus* and *Carpinus*, accompanied by an advent of *Quercus*.

The past century was also a period of *Sphagnum* peatland expansion. The presence of clayey horizons embedding mollusc shells and carbonate concretions intercalating the peat horizons are clear signs of soil erosion in the adjacent areas, triggered by deforestation of the nearby slopes. As an outcome of these activities the amount of rainfall reaching the surface substantially increased, resulting in an increase of the water level in the bed of the peatland and triggering the expansion of Sphagna. A similar phenomenon was described from several other European sites (Grosse-Brauckmann et al. 1973; Rybnícek and Rybnícková 1974; Rybnícková 1974).

Changes in bog surface wetness

The climate reconstrucion is based on the plant macrofossil investigations of the peat sequence. Figure 4 presents the changes of the main macrofossil groups on the cal. BP timescale. In contrast to Fig. 3 this diagram shows the percentage values of the different macrofossil groups in the total macrofossil volume. Seeds, ephippia and other generative organs were excluded. This kind of data presentation removes the effect of the gradual decay of organic matter.

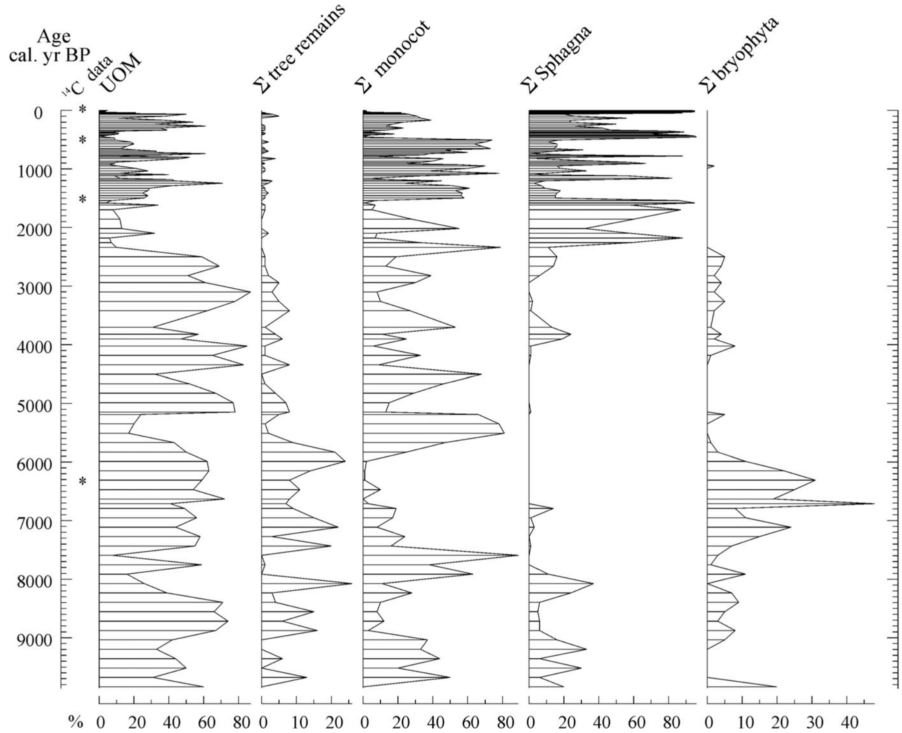

Fig. 4
Selected macrofossil diagram of the Sirok Nyírjes-tó peat bog

The most conspicuous feature of this diagram is the alternating amount Sphagna and monocot remains (together with UOM and tree remains). The spread of shrubs, trees and sedges at the expense of Sphagna due to the drainage or the present-day climate change is a well-known phenomenon of the Hungarian peat bogs, which are under strong continental climatic effects (Lájer 1998; Borhidi and Sánta 1999). It is an obvious assumption that the detected shifts in Sphagna percentages were triggered by climatic deteriorations (colder or more humid climate). Such climate deteriorations can be noticed at 8200, 6800, 3800, 2150, 1750, 1300, 1000, 850, 500 and 200 cal. yr BP. During these wet shifts different *Sphagnum* taxa become dominant in the basin, producing an unusual assemblage. According to the ecological investigations of Szurdoki (2005) the niche breadth of the different *Sphagnum* species in the Hungarian peat bogs was wide, with high overlap. Szurdoki (2005) argues that certain *Sphagnum* species utilize the different ecological resources similarly; therefore the competition between the different *Sphagnum* species is minimal. It is concluded that the strongly fluctuating environment caused the vanishing and re-establishment of Sphagna in the Hungarian peat bogs; therefore competition shortly after appearance determines the abundances. These frequently changing habitats produce strange species compositions.

The period between 7500 and 5200 cal. yr BP can be labeled as the driest part of the bog surface wetness history. The concentration of monocot remains is very low (<5%); Sphagna remains are completely absent. In contrast UOM and tree remains (wood, ULF and budscales) show high peaks (>60 % and >20%). Open water almost completely disappeared from the basin, and an oak forest occupied most of it.

Discussion

Investigations of the Sirok Nyírjes-tó peat bog provides an almost full Holocene record of vegetation development affected by climatic changes. The emergence of an oligotrophic lake in the area was dated to 9500 cal. yr BP, with deeper lake water conditions. Changes in the surficial moisture gradient of peatlands in the Carpathian Basin and those of lake level fluctuations are rather contradictory for this period. High lake-level phases are known at 8500 cal. yr BP for Szigliget Bay of Lake Balaton (Jakab et al. 2005; Sümegi et al. 2008), and Lake Nádas at Nagybárkány (Cserhát) (Jakab et al. 2009; Sümegi et al. 2009a). The inferred water levels of Lake Sf Ana in Romania show a highstand at 9500 cal. yr BP, with the emergence of a lowstand at 9000 cal. yr BP (Magyari et al. 2006, 2009). Conversely, studies implemented at various sites of the Great Hungarian Plain (Császártöltés) reconstructed a long-lasting dry and warm period till about 4400 cal. yr BP (Jakab et al. 2004a; Sümegi 2007; Sümegi et al. 2009b). There seem to be substantial regional differences in the Early and Middle Holocene climate of the Carpathian Basin.

Decreasing water levels inferred at 7500 cal. yr BP culminated in the driest phase of the peatland, recorded at 6400 cal. yr BP. This period is the time of Holocene climatic optimum, when there is a substantial retreat of the Swiss Alp glaciers between 7450 and 6650 cal. yr BP and between 6200 and 5650 cal. yr BP (Joerin et al. 2008). Conversely, there is an inferred increase in the water level of Lake Sf Ana in Romania from 7500 cal. yr BP onward, interrupted by a short decrease between 5500 and 5300 cal. yr BP (Magyari et al. 2006, 2009). According to Cheddadi et al. (1997) and Davis et al. (2003) the traditionally postulated

Holocene climatic optimum is identifiable only in Northern Europe. At this time southern Europe was characterized by colder conditions, with Central Europe occupying a transitionary phase. This assumption is refuted by the findings of paleoecological studies made on lake and marshland basins in the Carpathian Basin.

Nevertheless the definition and limitation of the Holocene climatic optimum is ambiguous and depends on the geographic position and the type of applied methodology. Paleoclimatological reconstructions based on pollen analytical results from Hungary argue that the Holocene climatic optimum can be detected between 7000 and 8000 cal. yr BP (Magyari et al. 2001), or somewhat earlier between 7000 an 8100 cal. yr BP (Magyari et al. 2010).

Following the climatic optimum there are two periods when a substantial increase in the surface moisture gradient was observable in the referred study site: at 5800 and 5400 cal yr BP. This change is congruent with the pattern observable in other lacustrine and marshland basins of the Carpathian Basin, also displaying an increase in the water level. There is a sudden increase in the water level of the Lake Sf Ana from 5500 cal. yr BP (Magyari et al. 2006, 2009) and Lake Balaton from 5200 cal. yr BP (Jakab et al. 2005; Sümegi et al. 2008). A somewhat delayed, similar pattern is observable in the peatlands of the GHP starting at 4400 cal. yr BP (Jakab et al. 2004a). This period between 5600 and 5300 cal. BP is referred to as the Middle Holocene Climatic Transition, characterized by a sudden deterioration of the previously warm conditions as a result of the collective transformation of orbital forces, solar activity and ocean currents (Magny et al. 2006; Iizuka et al. 2008).

Three short-lived peat formation events were identified at 8200, 6800 and 3800 cal. yr BP, reflecting cooler conditions. Paleoecological records available from the Carpathian Basin have yielded no information of climate change for this period so far. There is a marked cooling related to a global cooling event lasting for merely 200 years, known as the '8.2 ky event' (Alley et al. 1997, Alley and Agústsdóttír 2005; Bond et al. 1997; Nesje and Dahl 2001). At 6000 cal. BP a high lake-level phase of Swiss lakes (Magny 1998; Magny and Schoellammer 1999) and changes in the moisture gradient of some British peatlands (Hughes et al. 2000) point to the emergence of cooler conditions. Similarly at 3500 cal. yr BP, the higher lake phase of Swiss lakes (Magny 1998; Magny et al. 2002), the expansion of Alpine glaciers (Haas et al. 1998), and an increase in the moisture gradient of numerous Western European peatlands marks a cooling of the climate (Hughes et al. 2000; Barber and Charman 2005). These *Sphagnum* shifts around 8200, 6800 and 3800 cal. yr BP at Nyírjes-tó coincide with the short-term climatic oscillations presented by Feurdean et al. (2008) using pollen-based climate reconstruction methods.

An increase in the amount of Sphagna from 2800 cal. yr BP in the Nyires-tó peat bog also marks a cooling of the climate and the accompanying rise in rainfall. This deterioration of the climate, starting at 3500 cal yr BP, culminates here in the Carpathian Basin, as was shown by numerous records. Water levels were the highest in the Lake Sf Ana in Romania at this time, and there is information concerning the development of layering in the water body for this period (Magyari et al. 2006, 2009). Along with this data, information from studies of testacea and humic content of peatlands in the Eastern Carpathians show an increase in the moisture gradient (Schnitchen et al. 2003). The resuming peat formation in certain Hungarian peatlands marks the cooling of the climate here (Jakab and Sümegi 2007). On the whole these data suggest increasing moisture availability in the Carpathians and the adjoining Carpathian Basin from ca. 3400 yr BP, with maximum moisture availability around 2700–2800 years BP.

The first real acidophyllic *Sphagnum* peatland developed at Sirok between 2300 and 1500 cal. yr BP. From here on we have a record of alternating phases of *Sphagnum* peatlands and sedge/reed peatlands. As displayed by the record of vegetation changes, the catchment of the referred peatland was highly prone to climatic fluctuations. Certain periods are characterized by a rapid expansion of Sphagna, and others by the expansion of sedge and reed. A sudden expansion of Sphagna was recorded at least 10 times. Figure 5 displays a comparison of changes inferred from the Nyírjes-tó peat bog with cooler periods determined by Barber et al. (1994) and Mauquoy and Barber (1999), emphasizing changes for the last 3000 years. The *Sphagnum* peaks perfectly match the more humid periods identified in the British Isles at 2150, 1750, 1300, 1000, 850, 500 and 200 cal. yr BP (Barber et al. 1994; Mauquoy and Barber 1999; Barber and Charman 2005), indicating some collective global force as the cause for these changes. Barber and Charman (2005) identified centennial-scale climatic fluctuations in different parts of Western Europe. The length of these cycles was variable, spanning 210, 600, 800 or 1100 years in different peatlands. No such cycles have been identified in Central Europe so far.

The bog-surface wetness investigations with testate amoebae of Schnitchen et al. (2006) from the eastern Carpathians presented a period of greater variability in hydrological conditions after 3000 cal. yr BP. Significant shifts to wet conditions occurred, peaking at 2725, 2240, 1665, 1170, 590 and 385 cal. yr BP. These wet shifts more or less coincide with the wet periods of the Nyírjes-tó (Fig. 5).

It is worth comparing paleoecological data of the site of the present study over the last 2000 years with those of written historical records. One major climatic crisis in the Carpathian Basin is connected to the fall of the Avar Empire in the 8th century AD. Written records blame famines and wars triggered by the extreme droughts during this period (Györffy and Zólyomi 1994; Györffy 1995). Little environmental historical data for this time has been available so far. As shown by the *Sphagnum* curve of our referred study site, this period was indeed characterized by dry conditions (Fig. 5).

Another major historical crisis was the appearance of Mongol tribes in the area in 1241–1242. Certain sources blame this on severely cold weather, while others talk about the extreme droughts (Kiss 2000, 2003). As shown by our paleo-

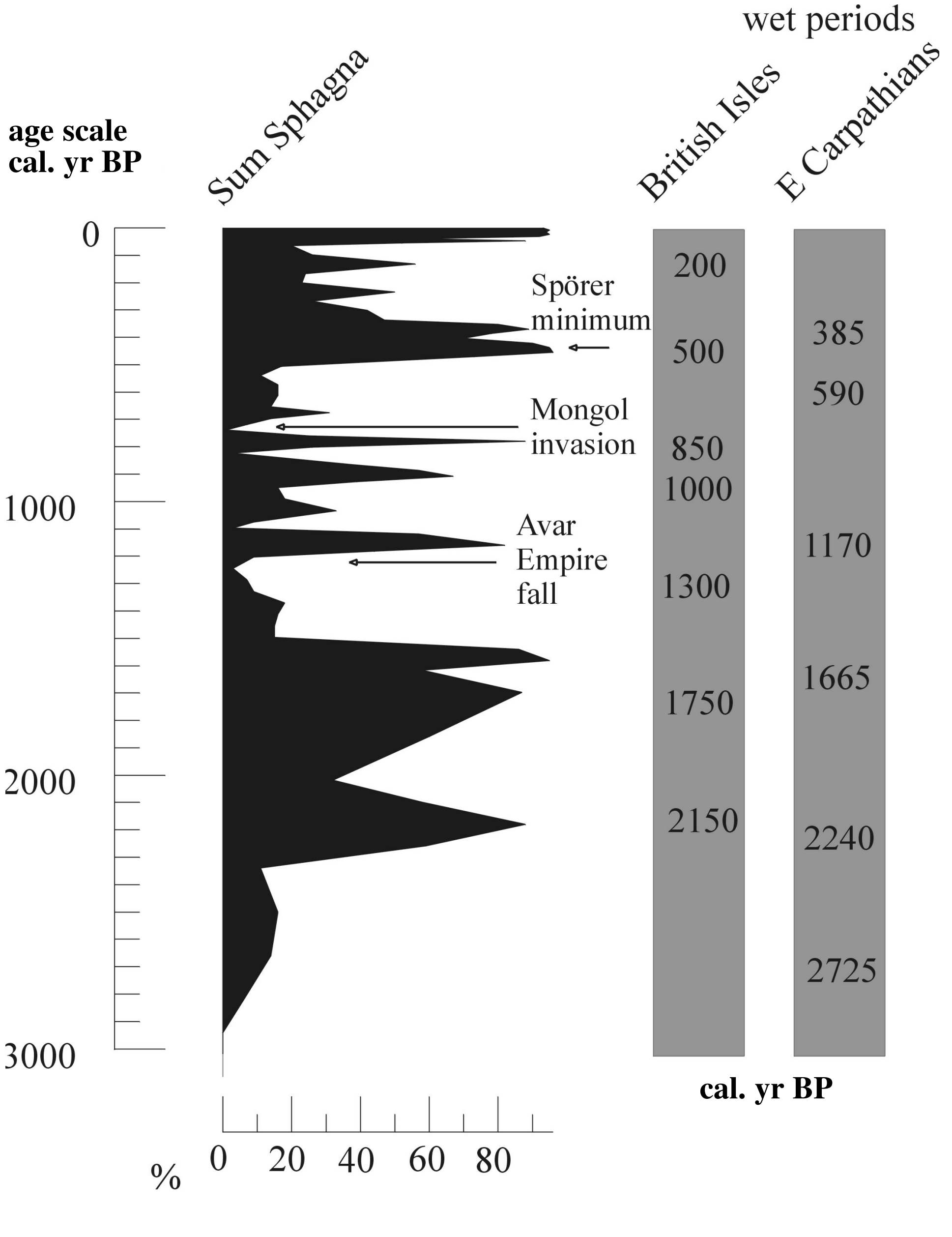

Fig. 5
Comparison of bog surface wetness changes of the Sirok Nyírjes-tó and some British (Barber et al. 1994; Mauquoy and Barber 1999) and Romanian (Schnitchen et al. 2006) peat bogs in the last 3000 years. The arrows show some historical events

ecological data for the Nyíres-tó peat bog, Hungary was characterized by extremely warm conditions during this period, resulting in an almost complete dessication of the *Sphagnum* peatland.

The *Sphagnum* curve of the Nyíres-tó enables us to identify the period of the Little Ice Age (LIA), dated between the middle part of the 16th century till the middle part of the 19th century (Pfister 1999; Pfister and Brázdil 1999; Bradley et al. 2003). The environmental record for the Nyírjes-tó peat bog fits with these events as well. The most diverse *Sphagnum* taxa, including the hygrophilous *Sphagnum cuspidatum*, was present here at the end of the 16th century. *Sphagnum cuspidatum* does not currently occur in the Nyírjes-tó. Western European peatlands were similarly prone to the fluctuating climate of the LIA (Mauquoy et al. 2002). Wetter conditions were identified from the beginning of the 16th and middle part of the 17th centuries. LIA climate deterioration can be detected in several proxy-climate records in the Carpathian Basin as well. Based on the Eastern Carpathian tree-ring width chronology of Popa and Kern (2009) the fingerprint of the LIA is visible between AD 1370 and 1630, followed by lagged cold decades in AD 1820 and 1840. Tree-ring data between AD 1460 and 1510 strongly correlated with Alpine reconstructions. This suggests strong regional forcing predominant over the eastern Carpathians and the Alps, producing a uniquely European signal. The high-resolution stable isotope and trace element records from a stalagmite from Hungary showed that during the LIA, the coldest years (longer or colder winters) occurred from around AD 1550 to ca. 1700 (Siklósy et al. 2009).

Conclusions

According to Blaauw et al. (2004) there is a strong relationship between the moisture gradient of peatlands and solar activity reflected in the correlation of the former parameter with a proxy for $\delta^{14}C$. One may properly ask what component of the climate controls the moisture gradient of peatlands via fluctuating solar activities? Surficial wetness is controlled by a complex interplay of precipitation and evapotranspiration of the plants, seen in such parameters as annual average rainfall and evaporation and influenced by the temperatures of the growth season. There are no surficial water courses feeding the Nyírjes-tó peat bog, so runoff must have been influential only during the past 100 years on the hydrology of the peatland.

As was shown in western Europe the moisture gradient of peatlands for the past 3000 years was primarily determined by fluctuations in the temperature of the vegetation season, rather than the amout of rainfall (Barber et al. 2000; Barber and Langdon 2001, 2007; Barber and Charman 2005; Schoning et al. 2005; Charman et al. 2009; Swindles et al. 2010). According to Charman (2007), in the Atlantic part of Europe summer precipitation and summer temperatures control the moisture gradient of peatlands. The pollen-based climate reconstructions from the eastern Carpathians (Feurdean et al. 2008) suggest that summer temperatures between 11200 and 8300 cal. yr BP were similar to those of the present. Between 8000 and 2400 cal. yr BP summer temperatures were higher than now. Pollen-based climate reconstructions indicated that summer temperatures became cooler in the last 2400 years. It seems that these general trends of summer temperatures determined the surface wetness history of the Nyírjes-tó peat bog. The relationships to other climatic parameters (e.g. annual precipitation, annual and winter temperature) investigated by Feurdean et al. (2008) are conflicting.

Unfortunately, macrofossil studies are not acapable to accurately predict former temperatures or precipitation rates. Only the major trajectories of climate changes can be identified. The modern distribution of *Sphagnum* peatlands in Hungary enable us to provide a rough estimate. *Sphagnum* peatlands appear in areas characterized by a precipitation of 600 mm per annum. Below this threshold one comes across only sporadic occurrences, while there are no Sphagna known below the lower limit of 550 mm. Based on the results for the Nyírjes-tó peat bog conditions in the lower hilly areas during the drier periods of the past 3000 years may be inferred to have been similar to those of the central parts of the GHP. The complete disappearance of Sphagna from the area must be linked to a steady drop in rainfall, resulting in an least 50 mm deficit in the local water balance. This could have been achieved by an increased evapo-transpiration as a result of elevated temperatures of the summer growth season. This deficit value must have exceeded even 100 mm during the Middle Holocene Transition.

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