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ORIGINAL PAPER

Reconstructing hydrological variability from testate amoebae analysis in Carpathian peatlands

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Abstract Peatlands offer the potential for high resolution records of water balance over Holocene timescales, yet this potential is under-exploited in many areas of the world. Within Europe, peatlands are mostly confined to areas north of 55° N, but several areas of southern and eastern Europe contain small peatlands which may be suitable for palaeoclimatic reconstruction. In this paper we test the potential of peatlands in the Carpathian region for deriving quantified estimates of water table changes using testate amoebae analysis. A training set for palaeohydrological reconstruction from testate amoebae assemblages was obtained by collecting surface samples from 13 peatlands, including 9 from Hungary and 4 from Transylvania (Romania). Using a simple measure of mean annual water tables estimated from staining of PVC tape, we found that some peatlands were heavily influenced by runoff and groundwater, and were therefore not suitable as modern analogues of ombrotrophic climatically sensitive sites. The relationship between the testate amoebae assemblages in the modern samples and the environmental variables was explored using CCA. The CCA biplot showed that the most important variables are depth to water table and moisture content, confirming that hydrology is a key control on taxon distribution. pH was a secondary gradient. A transfer function for % moisture and depth to water table was established and applied to fossil assemblages from a sequence from Fenyves-tető, Transylvania, Romania. The reconstructed water table shows a number of variations which have parallels with other palaeoclimatic records from Europe and the North Atlantic prominent phases of higher water tables are associated with the periods 8000–8300 cal BP, 3000–2500 cal BP and after 600 cal BP. We suggest that these were periods of particular intensification of westerly airflow which affected eastern Europe as well as western and central Europe.

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Introduction

Reconstructions of hydrological changes on peatlands have been used to infer palaeoclimatic change on peatlands for the past 25 years (Barber and Charman 2003). Much of the work has been concentrated in northern Britain but it is clear that there is much potential for the development of similar reconstructions from raised bogs throughout the rest of northwestern Europe where ombrotrophic peatlands occur (e.g., Barber et al. 2003). The techniques used in peatland palaeoclimate reconstruction assume that the surface wetness of the peatland is directly linked to climate variability because the peatlands receive no surface runoff and water balance is controlled by precipitation and evapotranspiration alone. Suitable ombrotrophic peatlands are widely distributed throughout northern Europe, especially north of 55° N and increasingly to the south of this latitude in more western regions (Lappalainen 1996). However, it is clear that, in order to reconstruct spatial variability in past climate change at the pan-European (or larger) scale, it is necessary to generate reconstructions from a geographical range that is as wide as possible. Extending the geographical range of individual climate proxies is important to achieve maximum geographical spread of data and to provide areas of overlap between different climate proxies for multi-proxy cross validation of climate reconstructions. For peatland records, attention has naturally focused on northern Europe, but several areas in southern Europe have small regions where small peatlands have developed. In the Carpathian region, peat has formed in a variety of small depressions, and in some areas active *Sphagnum* peat growth is taking place under oligotrophic or ombrotrophic conditions. These peatlands may hold suitable deposits for palaeoclimate reconstruction.

In this paper we aim to assess the potential for Carpathian peatlands to provide palaeoclimatic records using testate amoebae analysis. In particular we aim to test the applicability of this technique by examining the relationships between testate amoebae and environmental conditions and to derive a suitable training set for palaeohydrological reconstruction from *Sphagnum* peatlands in the region. A pilot study (Schnitchen et al. in press) attempted to derive a suitable transfer function from Hungarian peatlands and apply this to a profile from northwest Romania. This was difficult because of a poor relationship between modern species distributions and hydrological variables and a poor match between modern analogues and fossil data. In this study we have improved the quality and nature of the environmental data and expanded the modern training set to include sites from northwest Romania. This enabled a more detailed exploration of the nature of the species–environment relationship and the development of a more appropriate palaeohydrological transfer function.

Specific questions which we aim to address are:

(i) Can we find more suitable analogues for the fossil samples from higher elevation Carpathian peatlands by extending the range of training set sites?
(ii) Can we resolve the problematic relationships between testate amoebae species and hydrological variables already observed in Hungarian peatlands by obtaining more detailed hydrological data with simple long-term monitoring?
(iii) Can we use the transfer function to provide more quantitative estimates of Holocene palaeoclimatic variability in southeast Europe?

Study area

The basis for peatland formation is that organic productivity must exceed decay. Both productivity and decay are initially determined by factors external to the peatland system and these factors enable or prevent the initiation of peat. The climate must be wet enough to provide adequate water for plant growth and to provide sufficient waterlogging for at least part of the year so that decay of dead material is inhibited. The temperature must also be adequate for plant growth but also low enough so that evaporation is limited and the waterlogged substrate is maintained (Charman 2002). Conditions suitable for peat formation become much less frequent further south and east in Europe due to increased temperatures and reduced precipitation. However, there are some areas where the precipitation–evaporation balance is sufficiently positive to allow small peatlands to develop. The broader Carpathian region including parts of Hungary, Romania, The Ukraine and Slovakia, is one such area.

The Carpathian region can be broadly divided into two areas; the Carpathian basin lying mostly within Hungary, and the mountain areas surrounding Hungary to the north and east and extending into Slovakia, the Ukraine and Romania (Fig. 1). Our study area covers Hungary and northwest Romania (Transylvania). The Carpathian basin is dominated by the mixed influences of the mild, humid oceanic and the colder, drier continental Eurasian air masses, and shows extreme east–west variability (Bacsó 1959; Szász and Tőkei 1997). In general, the basin has a continental climate, with cold, humid winters and warm summers. Average annual temperature is 9.7°C, with extremes from 35°C in the summer to −29°C in winter. The average January temperature varies between 0.5°C (SE Hungary) and −3.5°C (NE Hungary), while July mean temperatures range between 19.4°C (N Hungary) and 21°C (SE Hungary). The average annual rainfall is approximately 600 mm, but the western part of Hungary may receive up to 800–900 mm (Justyák 2002). Summer droughts are common in the south.

The climate in the Carpathian Mountains of Romania is continental temperate, but varies across the region with a strong altitudinal and latitudinal variation. The north-western part has a rather mild and moist climate, which is influenced by western oceanic air masses, while the southwest receives more warm air masses from sub-Mediterranean areas. Annual precipitation varies between 600–700 mm and 1200–1400 mm depending upon the precise location in relation to the main air masses and altitude (Justyák 1994). Temperatures are also very variable, especially with altitude. Baia Mare (228 masl) is a typical of mid-range conditions, with a mean annual temperature of 8°C, and mean winter and summer temperatures are −3°C and 12–13°C, respectively. However, in some areas there is a regular temperature inversion that results in the reversal of mountain vegetation belts; spruce forests dominate in the valley, while the hill slopes and summits are covered by oak and beech forests.

Considering the climatic constraints, it is not surprising that there are very few peatlands in Hungary. *Sphagnum*-mires occur only in the most humid parts of the Carpathian basin; in the NE edge of the Hungarian Plain, in the North Hungarian Mountain Range and in the foothills of the Alps that border the

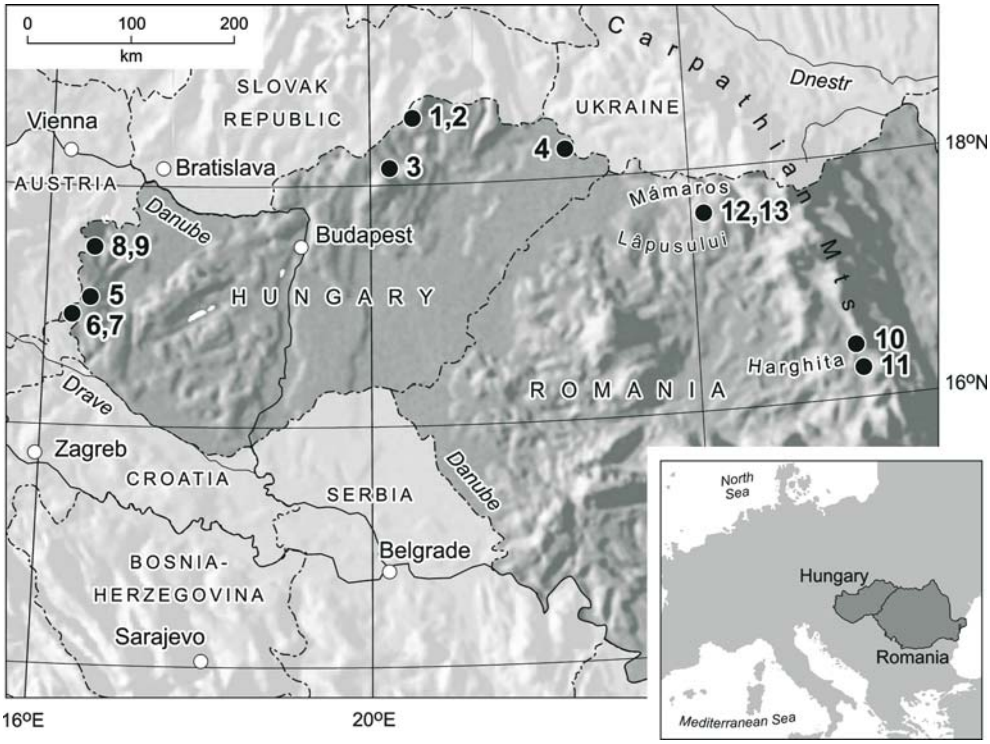

Fig. 1 Locations of study sites; see Table 1 for site names

western part of the basin (Fig. 1). Annual rainfall in these areas exceeds 650 mm, with a maximum in June. These few peatlands in Hungary are glacial or directly postglacial relicts. The climate in northwest Romania is more suitable for peat formation but the topography prevents the development of extensive peatlands. The high mountains are especially well-suited to peatland development and there are a number of small *Sphagnum* dominated peatlands in the Lăpus, Máramaros and Hargitha Mountains, especially over 1000 m elevation. We collected samples from 13 peatlands altogether; 9 from Hungary, 4 from Transylvania (Romania). The main features and the geographical locations of the peatlands are presented in Fig. 1 and Table 1. All sites were previously known as oligotrophic peatlands containing *Sphagnum* moss and therefore potentially of interest for palaeoclimatic reconstruction or as modern analogues for palaeohydrological transfer function development. However, few of these sites are classic raised mires similar to those found in northwest Europe. The sites in low elevation areas of Hungary (Szőce, Farkasfa, Fekete-tó, Alsó-erdő I, Alsó-erdő II, Nyíres-tó) are often influenced by flood water or runoff from surrounding slopes and can be categorised as basin or floodplain fens. Despite the fact that these sites are clearly influenced by groundwater and runoff, the surface waters are oligotrophic with pH 4.0–5.4 (Table 1) and all sites support *Sphagnum* growth. Several of these sites are *Sphagnum*-dominated (Nyíres-tó, Fekete-tó). A second sub-group of sites are the *Sphagnum*-dominated sites in northern Hungary, formed in small depressions (Kismohos, Nagymohos, Sirok). The vegetation is typically a continuous layer of *Sphagnum* moss with low growing herbaceous plants and birch (*Betula* spp.) tree cover in some sites. The high mountain mires of Romania are located in small depressions near the tops of the mountains (Lucs, Taul-Negru, Fenyves-tető) or in the case of Mohos, in an extinct volcanic crater. The vegetation on these sites is *Sphagnum*-dominated and microtopography of hummocks, hollows and pools is sometimes evident. Tree cover is variable and almost entirely of *Pinus sylvestris*.

Methods

Modern sampling

The surface sampling took place in September 2003 at the Hungarian sites and in August 2004 in Romania. A series of sample locations which covered all the main vegetation zones and microtopographic niches on the sites were identified. Typically this covered the zonation from mire margin to mire centre and microtopographic gradient from hummock top to pool where this was present. Deep open water pools were not sampled. At each location a sample of 10×10 cm of reasonably monospecific *Sphagnum* or other moss species was removed with a sharp knife down to a depth of 10 cm. The upper 5 cm of *Sphagnum* or from the surface to the point where the *Sphagnum* stems had collapsed (whichever was the smaller length) was trimmed and retained for analysis. The samples were stored in airtight plastic bags in cold storage until processing. At each sample location the dominant *Sphagnum* species and other plant

Table 1 Study site characteristics and locations. See Fig. 1 for locations

Site number	Site name	Latitude	Longitude	Elevation (m)	Peatland type	Mean pH (± SE)	No. recent samples
1	Kismohos	N 48°20′	E 20°26′	390	Raised bog	3.96 ± 0.16	7
2	Nagymohos	N 48°20′	E 20°26′	394	Raised bog	3.94 ± 0.16	8
3	Sirok	N 47°56′	E 20°11′	280	Raised bog	4.23 ± 0.21	8
4	Nyíres-tó	N 48°11′	E 22°30′	106	Basin fen	5.37 ± 0.28	7
5	Szőce	N 46°54′	E 16°34′	225	Basin/floodplain fen	5.14 ± 0.66	4
6	Farkasfa	N 46°54′	E 16°19′	258	Basin/floodplain fen	4.98 ± 0.21	2
7	Fekete-tó	N 46°53′	E 16°18′	310	Basin fen	4.08 ± 0.09	8
8	Alsó-erdő I	N 47°24′	E 16°34′	340	Basin fen	No data	3
9	Alsó-erdő II	N 47°24′	E 16°34′	340	Basin fen	4.35 ± 0.19	7
10	Lucs	N 46°18′	E 25°44′	1079	Raised bog	3.41 ± 0.03	10
11	Mohos	N 46°08′	E 25°54′	1050	Raised bog	3.58 ± 0.02	13
12	Taul-Negru	N 47°40′	E 23°56′	1264	Raised bog	4.16 ± 0.16	15
13	Fenyves-tető	N 47°40′	E 24°02′	1340	Raised bog	4.04 ± 0.05	18

cover, depth to water table and temperature were recorded in the field. pH and conductivity of pore water were measured using a field pH meter in Romania and in the laboratory immediately after collection for the Hungarian samples.

Water table measurements

One of the biggest problems in developing reliable transfer functions for water table reconstruction from testate amoebae analysis has been the difficulty of providing estimates of longer-term water table conditions. Modern samples typically contain 2–3 years of living and death assemblages of testate amoeba populations. However, it is often only possible to measure water tables at the time of sampling with a few exceptions where long-term monitored data are already available (e.g., some sites in Tolonen et al. 1992; all data in Woodland et al. 1998). One possible solution which could meet the need for long term data without the considerable costs of instrumental monitoring of water tables in widely dispersed and inaccessible locations, has been proposed by Belyea (1999) who used PVC tape discolouration to indicate the locations of water tables. In this study we used the technique to gain additional information on water table regimes at the Hungarian sites because a number of the bogs were rather different to the raised bogs more conventionally used for palaeoclimatic reconstruction.

We installed plastic pipes with PVC tape attached to the sides in all sample locations after removing the surface moss samples. The pipes were inserted to a known depth at each sample location. The depth protruding from the ground was recorded for each pipe. All pipes were labelled with the sample number. The pipes were collected in September of 2004 at the Hungarian sites. The length of the pipe protruding from the surface was recorded as a check to see if they had risen or fallen. The depth to partial discolouration and depth to complete discolouration on each rod were measured to estimate highest and lowest water tables, respectively (Belyea 1999).

Fossil sampling

At Fenyves-tető (Fig. 1), the coring was carried out using a 5 cm diameter Russian corer (Jowsey 1966). The depth of the peat in the basin was 380 cm under which there was a 20 cm thick lake clay sediment above the andesite of the rock-bed. Radiocarbon dating, humification measurements (Bahnson 1968) and testate amoebae analysis carried out on the peat section only.

Radiocarbon dating

Radiocarbon ages were calibrated using BCal calibration system (http://bcal.shef.ac.uk) using the INTCAL04 calibration data set. The age–depth relationship was estimated using PSIMPOLL4.1 (Bennett 2002). Calculations were based on the weighted average of the calibrated ages with linear interpolation age model. All ages are expressed as calibrated radiocarbon years before present (cal year BP).

Testate amoebae

The surface and fossil testate amoebae samples were prepared for analysis and the tests were identified to species level according to Charman et al. (2000). This involved disaggregating the samples in boiling water followed by sieving using 300 and 15 μm sieves. The size fraction between these sieves was mounted on slides and tests were identified and counted to a minimum sum of 150 at ×100 to ×400 magnification. A total of 110 modern samples and 95 fossil samples were analysed.

Humification

For humification measurements subsamples of 1 cm^3 were used from every 4 cm of the core sample. These were oven dried and the weights were measured. 50 g 0.1 M NaOH were added to the samples and they were heated for 1 h on a 100°C sand-bath. The samples were topped up to a standard volume with distilled water and allowed to settle. The supernatants were transferred to test-tubes and the absorbance was measured by photometry. Humic acid concentrations were calculated from the absorbance values according to the calibration of Bahnson (1968).

Data analysis

The relationship between the testate amoebae assemblages in the modern samples and the environmental variables was explored with CANOCO (Ter Braak 1988). Canonical correspondence analysis

(CCA) was applied to the whole data set and Monte Carlo permutation tests were used to test the significance of the relationship between individual hydrological variables (moisture and depth to water table). In addition, the fossil samples were included in a further CCA to asses the similarity of assemblages with the modern samples. The transfer functions for hydrological variables were tested and applied to the fossil data with C^2 (Juggins 2003). A variety of models were tested including variants of weighted averaging, partial least squares and modern analogue matching approaches. The sequence of analysis is discussed in the results section below.

Results

Water table variability in the Hungarian peatlands

It was not possible to retrieve the PVC tape from all sites due to loss or damage of pipes after one year in the field. The depth to partial discolouration and depth to complete discolouration were highly correlated with most samples only having a range of 1–3 cm between them (Fig. 2a). The relationship between measured summer water table and long-term water tables estimated from the PVC tape was poor for the data set considered as a whole (Fig. 2b, c). In particular at some sites, where very low water tables were recorded in the summer, the PVC tape suggested water tables close to, or even above, the surface. There was little difference in this pattern whether the depth to the start of discolouration or depth to complete discolouration was considered (Fig. 2b, c).

However, it is clear that there are two subsets of site types which have very different hydrological regimes to each other. One group is very similar to raised bogs (although it seems doubtful that they are completely ombrotrophic). These are the larger peatlands of Kismohos, Nagymohos and Sirok which have continuous *Sphagnum* cover over deep peat deposits and lake muds and clays. Nyíres-tó is a further site in this group, although it is a basin peatland which has developed over oxbow lake deposits but also has a thick *Sphagnum* cover and deep peat. The other group is of the basin fens, which are smaller mires sometimes affected by flooding from adjacent rivers. In these sites, *Sphagnum* cover is patchy and peat is generally shallow or even restricted to surface growth over mineral soils. One site (Fekete-tó) has much higher *Sphagnum* cover but is only a shallow peat over clay.

The basin and flood plain sites have very low water tables in summer and probably experience water table rises in the late autumn through to early spring. This hydrological regime is very different to that on the other peatlands where seasonal water table variability appears to be much lower. We conclude that while the basin and floodplain mires sometimes have significant *Sphagnum* cover and the surface vegetation can even appear very similar to raised mires in the region, they are unlikely to provide modern analogues for fossil testate amoebae assemblages. These sites are therefore excluded from further analyses and transfer function development.

Testate amoebae species–environment relationships in Hungary and Romania

The CCA biplot shows that the most important variables are depth to water table and moisture content, confirming that hydrology is a key control on taxon distribution (Fig. 3a). The secondary gradient is more closely related to pH, similar to findings from most other studies (e.g., Tolonen et al. 1992; Charman and Warner 1992; Woodland et al. 1998). A Monte Carlo permutation test on water table and moisture content as the only environmental variables confirms that these parameters have a statistically significant relationship with species assemblages ($P < 0.001$ for water table and $P < 0.001$ for moisture).

The location of many testate amoeba taxa along the hydrological gradient is as expected with taxa such as *Trigonopyxis arcula* (Leidy 1879a) Penard 1912 type*(14), Bullinularia indica* Penard 1907*(5)* and *Corythion-Trinema* type (combined from *Corythion dubium* Taranek 1881 and *Trinema enchelys* Leidy 1878 according to Charman et al. 2000) *(6)* occurring at the dry end of the gradient and others such as *Amphitrema wrightianum* Archer 1869 *(2), Hyalosphenia elegans* Leidy (1874) 1875 *(12)* and several *Difflugia* taxa (*D. lanceolata* Penard 1890 *(9), D. acuminata* Ehrenberg 1838 type *(8)*) at the wettest end of the gradient. Some taxa (e.g., *Arcella discoides* Ehrenberg 1872 type *(3), Nebela carinata* (Archer 1867) Leidy 1876b *(13)*) are not located in

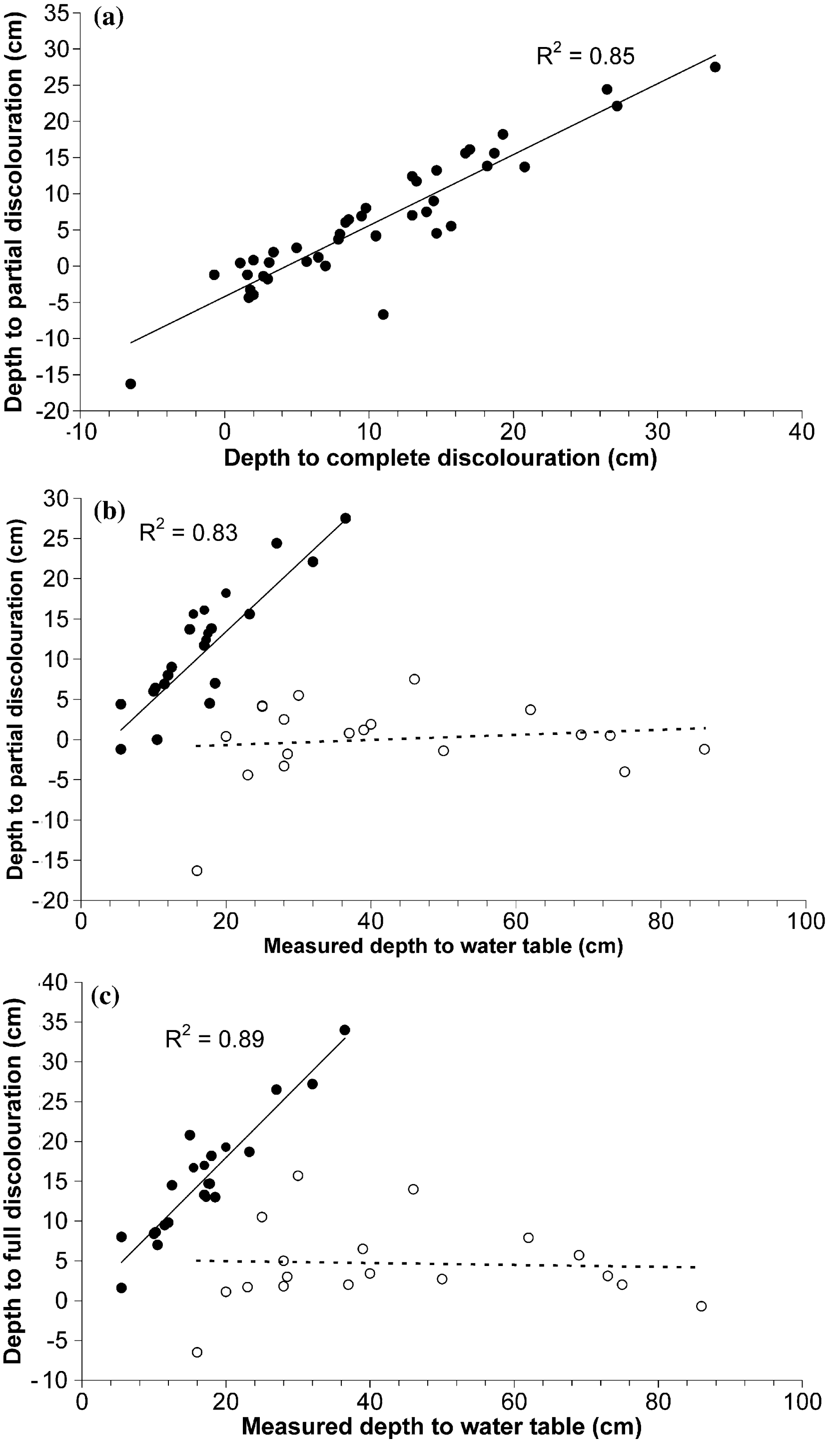

Fig. 2 Relationships between short and long term water table measurements. (a) Depth to partial and complete discolouration of the PVC tape. (b) Measured summer water table against depth to partial discolouration of PVC tape after one year. (c) Measured summer water table against depth to complete discolouration of PVC tape after one year. In (b) and (c) the samples are separated into those from basin and shallow peat sites (open symbols) and those from deep peat raised peatlands (closed symbols)

such extreme positions as would be expected from previous studies. The hydrological niches of taxa will be discussed in greater detail below.

The location of host moss taxa on the ordination is also interesting. *Sphagnum cuspidatum* Ehr. ex Hoffm. *(B)* is at the extreme wet end of the

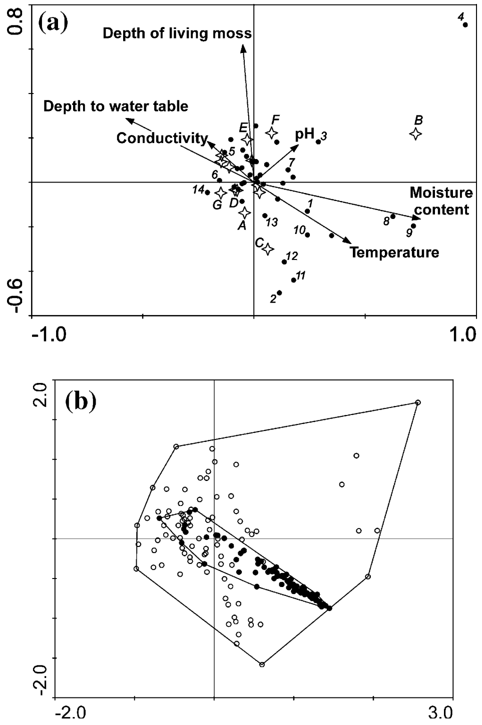

Fig. 3 CCA analysis on the raised bog sites from Hungary and Romania. (a) Species and environment (1, *Amphitrema flavum*; 2, *A. wrightianum*; 3, *Arcella discoides* type; 4, *A. hemispherica* Perty 1852; 5, *Bullinularia indica*; 6, *Corythion-Trinema* type; 7, *Cyclopyxis arcelloides* (Penard 1902) Deflandre 1929 type; 8, *Difflugia acuminata* type; 9, *D. lanceolata*; 10, *Heleopera petricola* Leidy 1879a; 11, *Heleopera sylvatica* Penard 1890; 12, *Hyalosphenia elegans*; 13, *Nebela carinata*; 14, *Trigonopyxis arcula* type; A, *Sphagnum capillifolium*; B, *S. cuspidatum*; C, *S. fuscum*; D, *S. magellanicum*; E, *S. palustre*; F, *S. squarrosum*; G, *S. tenellum* (Brid.) Pers ex Brid.). (b) Sample ordination showing active modern (open symbols) and passive fossil (close symbols) samples

gradient followed by *S. fuscum* (Schimp.) Klinggr. *(C)*, *S. capillifolium* (Ehrh.) Hedw. *(A)* and *S. magellanicum* Brid. *(D)*. It is interesting to note that *S. magellanicum* occurs in drier conditions than *S. fuscum* and *S. capillifolium*, rather different to its niche on more oceanic mires where it occupies low hummocks or lawns (Lindsay et al. 1988). Some *Sphagnum* species are separated on the pH gradient, *S. palustre* L. *(E)* and *S. squarrosus* Crome *(F)* at higher pH than the more commonly found *S. capillifolium*, *S. fuscum* and *S. magellanicum*. These taxa also tend to have a more lax form and develop a very thick living, erect surface layer, reflected in the position of the depth of living moss measurements on axis 2.

Before developing a transfer function for depth to water table, a check was made on the ability of the modern data set to provide suitable analogues for the fossil data, by including the fossil samples as passive in the CCA analysis. All of the fossil samples fall within the envelope of the modern sample distribution, mostly towards the wet end of the hydrological gradient (Fig. 3b). The fossil samples are stretched along the main hydrological gradient suggesting that they are strongly related to varying hydrological conditions rather than other environmental variables.

Palaeohydrological transfer functions for the Carpathian bogs

For water table, a tolerance downweighted model with inverse deshrinking showed the best performance assessed by root mean squared error of prediction (RMSEP) and r^2 statistics following a leave one out cross validation (Table 2). However, several other models performed almost as well. The model performance was strongly affected by samples from very dry locations on the mires which had water table depths in excess of around 35 cm deep (Fig. 4a). Prediction errors were largest for these samples with water table depth underestimated by up to almost 50 cm. These samples were removed from the model

Table 2 Performance of the transfer function models in leave-one-out cross validation for water table reconstruction. In the model runs with all data, WAPLS performed no better than the WA model

Model	R^2	RMSEP	Max bias
All data			
WA, tolerance downweighting, inverse deshrinking	0.444	10.23	43.62
WA, inverse deshrinking	0.433	10.32	45.24
WMAT	0.431	10.53	39.37
PLS 2 components	0.403	10.62	48.73
After filtering			
WA, tolerance downweighting, inverse deshrinking	0.632	6.48	18.19
PLS 5 components	0.611	6.68	12.99
WAPLS 2 components	0.607	6.73	17.30
WA, inverse deshrinking	0.594	6.81	18.48
WMAT	0.469	8.14	25.16

WA: Weighted averaging

WMAT: Weighted modern analogue technique

WAPLS: Weighted averaging partial least squares

PLS: Partial least squares

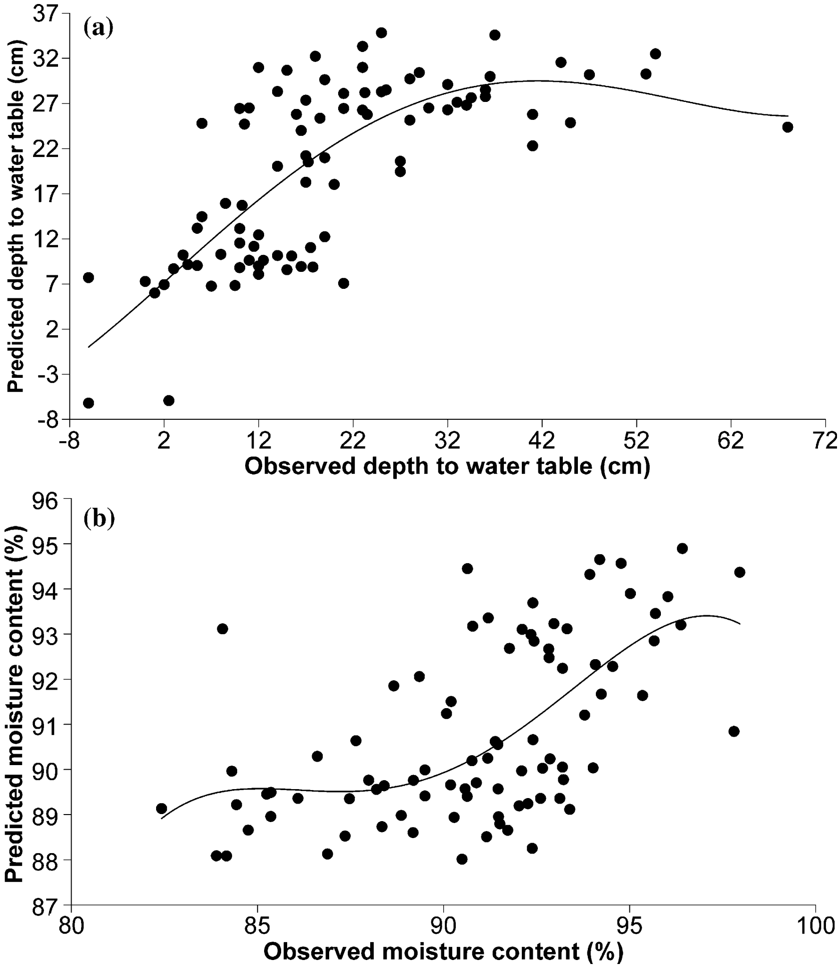

Fig. 4 Observed against predicted hydrological variables for all samples using all sample data. Only the results from the best performing models are shown. (a) Water table (cm) from the weighted average tolerance downweighted model with inverse deshrinking. (b) Moisture (%) from the weighted average partial least squares component 1 model

using a screening procedure based on exclusion of samples with residual values greater than 14.8 cm (i.e., 20% of the total range of values). This removed 12 samples including 4 with observed water tables over 20 cm. The revised model performs better in cross validation and is less likely to be affected by the samples from very dry locations. A similar procedure was carried out with moisture as the dependent variable. The same problem of poor performance of the model for drier samples was observed (Fig. 4b) but the outliers occupy less extreme positions. A similar filtering exercise was carried out based on 20% of the range of moisture values (Table 3). Performance of all models for moisture is poorer than those for water table depth.

Figure 5 shows the species' optima calculated from weighted averaging. There is a clear group of very wet indicators including *Nebela carinata*, *Centropyxis cassis* type, *Amphitrema wrightianum*, *Nebela griseola* and two *Difflugia* types; *D. lanceolata* type and *D. acuminata* type. The gradient is more gradual from this point with a sequence of taxa beginning with *Cyclopyxis arcelloides* type through to *Difflugia pulex* type. There is a distinct break in the gradient separating a drier group of taxa beginning with *Euglypha rotunda* type and ending with *Assulina muscorum*. Finally, two taxa (*Corythion-Trinema* type and *Bullinularia indica*) stand out as being particularly dry indicators. Compared to species' optima from other studies (Woodland et al. 1998; Tolonen et al. 1994) on peatlands in northern Europe, *Arcella catinus* Penard 1890 type, *Assulina muscorum* Greeff 1888, *Assulina seminulum* (Ehrenberg 1848) Leidy 1879a, *Bullinularia indica* and *Centropyxis aculeata* (Ehrenberg 1830, 1832a) von Stein 1859 type indicate drier conditions in our study, while *Centropyxis cassis* (Wallich 1864) Deflandre 1929 type and *Cyclopyxis arcelloides* (Penard 1902)

Table 3 Performance of transfer function models in cross validation for moisture reconstruction

Model	r^2	RMSEP	Max bias
All data			
WAPLS C. 1	0.315	2.830	5.449
WA, inverse deshrinking	0.308	2.845	5.449
WA, tolerance downweighting, inverse deshrinking	0.305	2.856	5.302
PLS component 1	0.302	2.860	5.681
WMAT	0.256	2.996	6.092
After filtering			
WA, inverse deshrinking	0.505	1.611	2.716
WA, tolerance downweighting, inverse deshrinking	0.491	1.636	2.689
PLS component 4	0.478	1.665	2.800
WMAT	0.350	1.902	2.899

WA: Weighted averaging

WMAT: Weighted modern analogue technique

WAPLS: Weighted averaging partial least squares

PLS: Partial least squares

Deflandre 1929 type indicate slightly wetter environments. However, the rank order of most taxa is similar to that found in other studies. *Hyalosphenia subflava* is notable by its absence from the taxa recorded here, perhaps reflecting the fact that it is sometimes regarded as being a taxa mainly of very dry and often damaged peatlands (Tolonen et al. 1992).

Reconstructed water table from Fenyves-tető

The model was tested on a data set from Fenyves-tető, one of the study sites in northwest Romania (Fig. 1). These data have been discussed in qualitative terms in a previous paper (Schnitchen et al. 2003) and the emphasis here is on the value and interpretation of the palaeohydrological reconstruction. The reconstructions of moisture variability and depth to water table are the inverse of each other, a not unsurprising result in view of the strong negative autocorrelation of these variables in the modern data set (Fig. 6a, b). The results of the radiocarbon date calibration are shown in Table 4. The key changes in the profile are as follows, with estimated ages to the nearest whole decade:

FET1: Before c. 9790 BP (>379 cm)

Very wet conditions at the base change to drier conditions after 9790 BP. The presence of high abundance of *D. lanceolata* and *A. wrightianum* suggest a change from minerotrophic to oligotrophic conditions at this time. Humification values also show a minor change from higher to lower humification.

FET2: c. 9790–8320 BP (379–319 cm)

Relatively stable moderately wet conditions with a minor change to wetter conditions at 9110 BP persisting until 8320 BP. The assemblage is dominated by *Amphitrema flavum* (Archer 1877) Penard 1902 and *Assulina muscorum*. Humification values also stabilise with a decrease in humification coincident with the minor wet shift at 9110 BP.

FET3: c. 8320–3390 BP (319–187 cm)

Following an initial change to much drier conditions at 8320–7980 BP (319–305 cm), the surface becomes gradually wetter to reach a high water table point at 3570 BP. The initial shift to drier conditions is inferred from a reduction in *A. flavum* and an increase in *A. muscorum*, a change which is gradually reversed through this period. A series of small peaks in *A. wrightianum* also occurs throughout this period. Peat humification values also show a gradual change but with greater variability about this trend.

FET 4: c. 3390–3030 BP (187–175 cm)

A major shift to drier conditions occurs at c. 3390 BP but this is followed by a switch back to wet conditions at 3030 BP (175 cm). A large peak in *A. muscorum* infers the dry shift, with the major wet shift resulting from a change to high levels of *A. wrightianum*, one of the biggest assemblage changes in the profile. Peat humification reaches a peak at the same time followed by a subsequent fall.

FET5: c. 3030–370 BP (175–55 cm)

This is a period of much greater variability in hydrological conditions. There is a general drying trend throughout this period taken as a whole but with significant shifts to wet conditions peaking at 2725 (165 cm), 2240 (149 cm), 1665 (129 cm), 1170 (105 cm), 590 (77 cm) and 385 (57 cm) BP. The changes are inferred from fluctuations in *A. wrightianum*, *A. flavum*, *Hyalosphenia papilio* Leidy (1874) 1875 and *A. muscorum*. Humification data

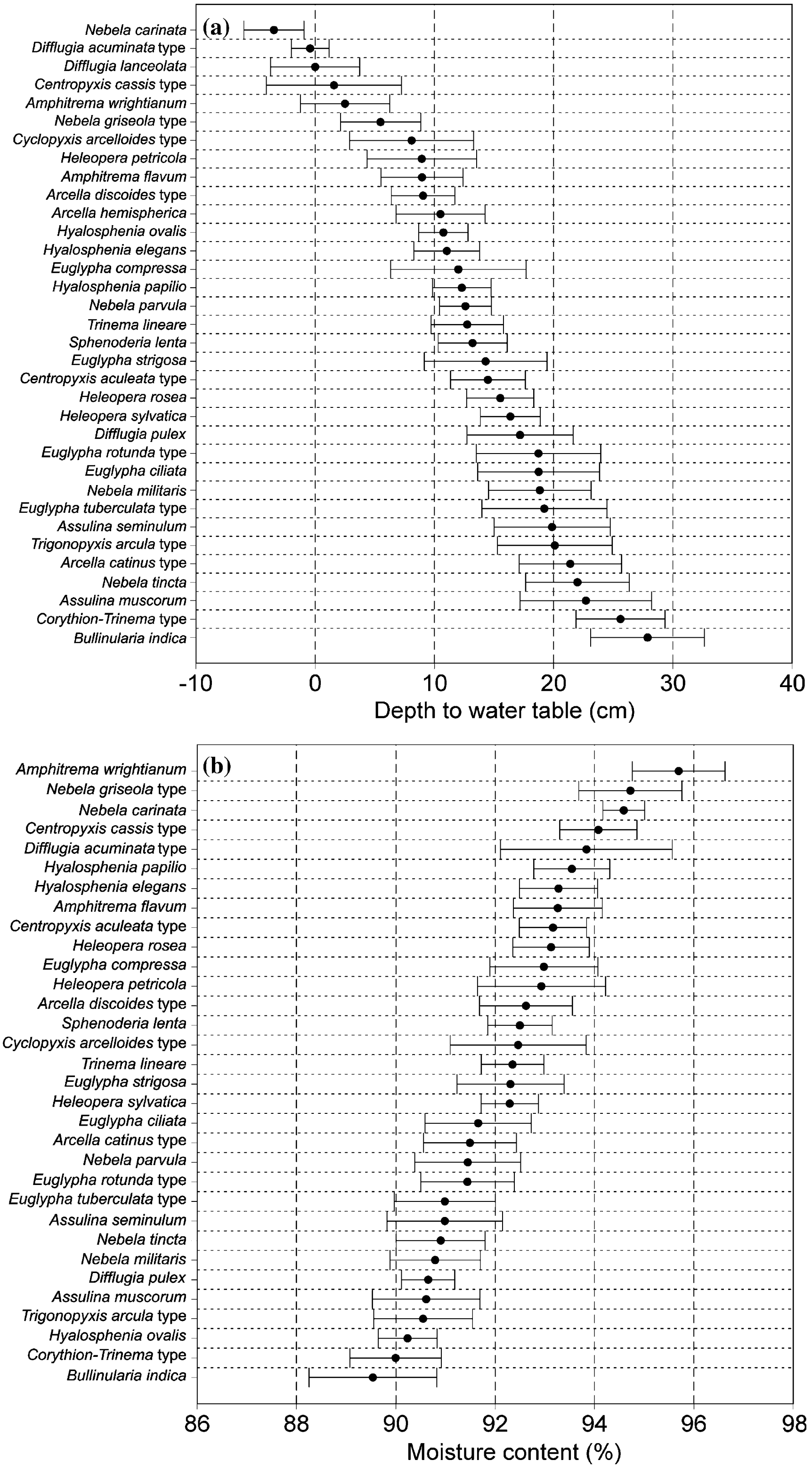

Fig. 5 Hydrological optima for main testate amoeba taxa in the Carpathian peatlands used in the transfer function. Species optima and tolerance for (a) water table, and (b) % moisture

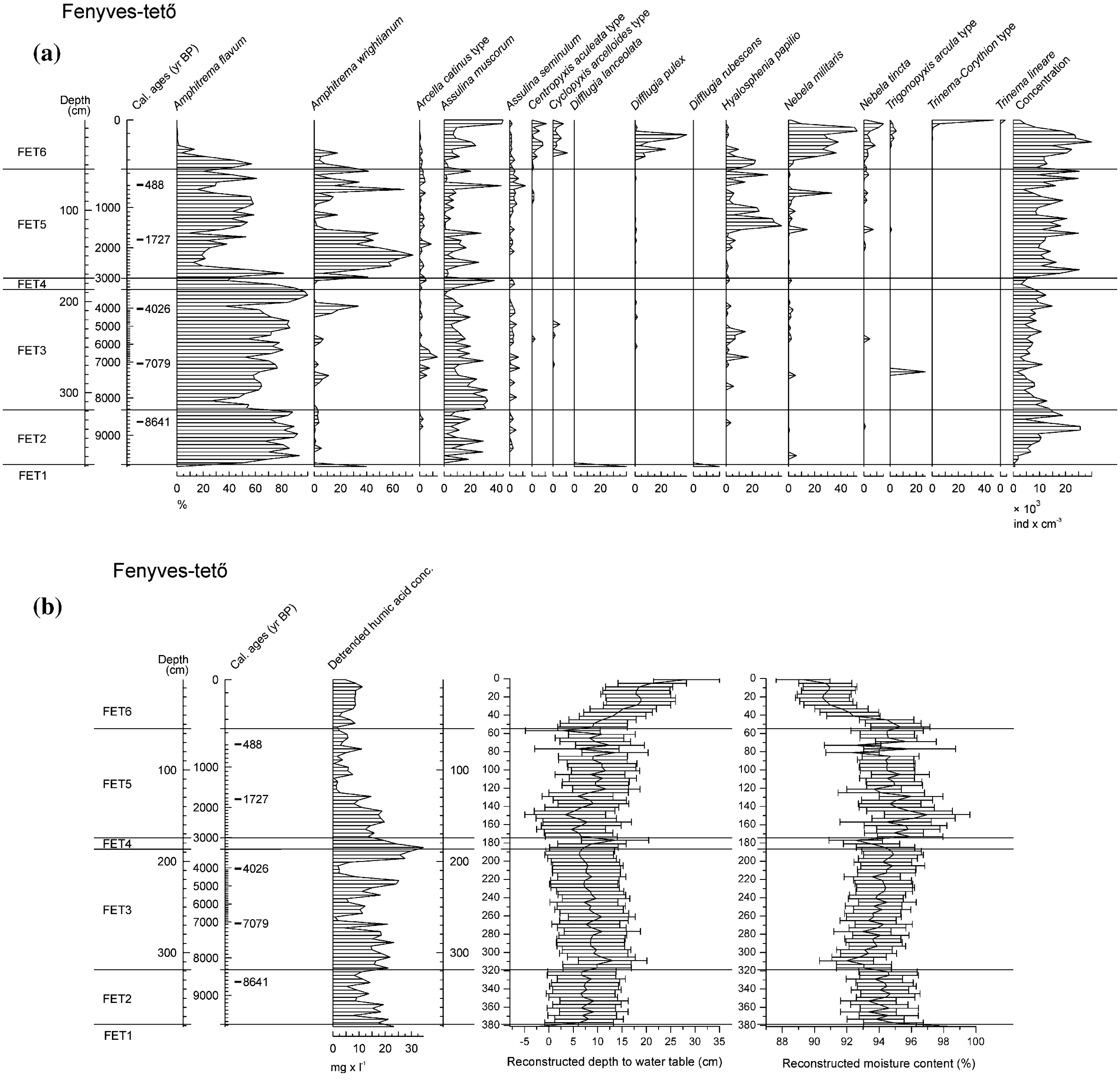

Fig. 6 Results of testate amoebae analysis in relation to depth/calibrated ages in the profile of Fenyves-tető. (a) Relative abundances of main testate amoebae species and concentration of testate amoebae individuals. (b) Detrended humic acid concentrations and reconstructed depth to water table and moisture content changes

also show an initial shift to wetter conditions at the start of this period and similar initial variability to begin with. However, in the latter part of the profile, the trend is to wetter conditions rather than the drier conditions suggested by testate amoebae. This is probably a result of incomplete decay of peat in the upper peats rather than a real reflection of the surface wetness during peat deposition.

FET6: c. 370–0 BP (55–0 cm)

There is a major drying trend over this period with some stabilisation since 190 BP (29 cm). During this period the assemblage changes from *Amphitrema* dominance to *Nebela militaris* Penard 1890, *Difflugia pulex* Penard 1902, and high levels of *A. muscorum* and *Corythion-Trinema* type

Table 4 The results of radiocarbon date calibration

Core	Laboratory code	Dated material	Depth (cm)	^{14}C age years BP	δ^{13}C(PDB) ± 0,15[‰]	Calibrated range years BP (2σ)
FT-5	deb-6805	bulk peat	331–333	7835 ± 60	−25.97	8431–8932
FT-4	deb-6807	bulk peat	267–269	6180 ± 55	−26.13	6912–7243
FT-3	deb-6856	bulk peat	207–209	3690 ± 60	−25.90	3866–4226
FT-2	deb-6857	bulk peat	131–133	1805 ± 65	−26.20	1566–1871
FT-1	deb-6853	bulk peat	71–73	445 ± 45	−25.77	428–551

closer to the surface. The severity of the change to drier conditions is demonstrated by increased humification during a phase when incomplete decay normally creates a decrease in humification values.

Discussion

Environmental data for palaeohydrological transfer functions

One of the key aims in this research is to explore the potential of Carpathian peatlands for palaeoclimatic reconstructions, specifically by the use of palaeohydrological reconstruction from testate amoebae analysis. From the analysis of the modern testate amoebae assemblages from Hungarian *Sphagnum* mires, it initially appeared that relationships with hydrological variables were not as clearly defined as for peatlands in other regions studied (Schnitchen et al. in press). Collection of long-term water table data using PVC tape (Belyea 1999) demonstrated that the Carpathian *Sphagnum* peatlands fall into two distinct hydrological site types (Fig. 2). Only the sites where water tables are unaffected by groundwater and runoff in the winter months are suitable for developing training sets for palaeohydrological transfer functions. The hydrological differences between sites are not always apparent from surveys conducted during the summer season. This result highlights the need for careful selection of sites used for transfer function development. Furthermore, it suggests the simple, cheap but effective method of hydrological monitoring with PVC tape is invaluable in assessing generalised hydrological regimes. Belyea (1999) demonstrated very close correspondence between measured water tables and estimates from PVC tape on single, carefully monitored raised mire.

Here we have shown that there is a strong relationship between measured and PVC tape estimates of long-term water tables even where a number of different sites are combined in a single data set and the measured water tables are only a ‘snapshot’ from one time of the year. This bodes well for the use of this method in developing large data sets from sites too widely dispersed and inaccessible for more detailed instrumental monitoring of water tables. In contrast to Belyea (1999) we found a stronger relationship between the measured water table and the depth to maximum discolouration than with the depth to partial discolouration although the difference is small (r^2=0.89 and 0.83 respectively). Over long periods, the depth to maximum discolouration may reflect the typical position of the water table more accurately as there is presumably a limit to the degree of colour change. On the red PVC tape we used, colour change was to black in most cases rather than the brown discolouration reported by Belyea (1999). As long as the length of time tape is left on site and interpretation is consistently applied, the method certainly seems capable of improving on environmental training sets which use water table measurements made on only a single or a few occasions.

A transfer function for the Carpathian peatlands

Extending the geographical range of the training sets to the broader Carpathian region improved the quality of modern analogues for reconstruction, as there is an improved overlap between modern and fossil samples in the CCA ordination. The reconstruction which results from the transfer functions for water table and moisture changes seems to be a reasonable interpretation of the fossil data based on previous understanding of hydrological niches of the different taxa (Charman et al. 2000).

However it is apparent that there are some taxa which are important in fossil assemblages that are poorly represented in the modern data set. Perhaps most notable is *A. wrightianum* which occurs in high abundance in the fossil samples (up to 75%) but is present in only a single modern sample at very low abundance. The effect of this on the reconstruction may have been to reduce the influence of *A. wrightianum*, resulting in lower amplitude shifts to wetter conditions when it occurs. The optimum value for *A. wrightianum* in the training set is 2.5 cm, similar in relative position to other training sets from Europe (Tolonen et al. 1992; Woodland et al. 1998; Mitchell et al. 1999). By chance then, the effect on the reconstructed values may not be very great. However, the low abundance and frequency of taxa such as *A. wrightianum* in a reasonably comprehensive survey of extant peatlands in the region suggests that peatland conditions analogous to those found in the past may no longer be found in the immediate area. This highlights the need for training sets which cover much larger regions. It is likely that better analogues for the mid-late Holocene *A. wrightianum* dominated samples can be found in northwest Europe where *A. wrightianum* is more commonly found (Woodland et al. 1998). Some of the data for a pan-European training set already exist, but further data are still required and it will be crucial to harmonise data before any merging of data sets can be done. Harmonisation of taxonomy is less difficult than harmonisation of environmental data because of the variable times of sampling for water tables.

The palaeoclimatic record at Fenyves-tető

The reconstructed water table curve from Fenyves-tető shows a series of hydrological changes at the site since c. 10,000 cal year BP. The application of the transfer function allows an estimate of the magnitude of many of these changes for comparison with other palaeoclimate records. However, there are rather few records from central eastern Europe with which to compare the record. Some peatland records are available from the Czech Republic (Speranza et al. 2000, 2003) and there are pollen records from the north western part of Romania which include Holocene sequences (Bodnariuc et al. 2002; Bjorkman et al. 2002; Tantau et al. 2003). However, these pollen records focus primarily on tree migration and vegetation patterns, rather than climate change. The following discussion aims to relate the changes at Fenyves-tető to other palaeoenvironmental records in the immediate region, but also to suggest relationships within Europe as a whole.

The radiocarbon chronology is uncertain at the base of the profile, but the early transition from shallow water to a terrestrial peatland above the basal lake clay marks the early succession from open water to terrestrial peatland shortly after the start of the Holocene. The extrapolated age estimate from radiocarbon ages above this transition is 9810 cal year BP but peatlands often begin with relatively slow accumulation rates so this may be an underestimate of the true age. Following this transition, the assemblage reflects the development of an ombrotrophicmire primarily dependent upon precipitation for its moisture supply and therefore directly linked to climate variability.

The first major change recorded in the ombrotrophic phase is to drier conditions at around 8320 cal year BP, a change which is followed by an immediate shift back to wetter conditions from 8080 cal year BP. This period marks the highest amplitude change during the early to mid Holocene part of the sequence and they occur at around the same time as the well known 8.2 k cal year cooling event, manifested as higher lake levels in mid-latitude Europe (Magny et al. 2003). The chronological control is not adequate to be certain whether it is the initial change to dry conditions or the subsequent shift to wet conditions which occurs at the same time as the 8.2 k year event. If the latter interpretation is taken as correct, the change to wetter conditions supports Magny et al.'s hypothesis that all of mid-latitude Europe became wetter during this phase as a result of a displacement and intensification of westerly circulation. A direct comparison of the Romanian water table record with the ice rafted debris record in the North Atlantic (Bond et al. 2001) also supports this suggestion. The long phase of gradually rising water tables after c. 8000 cal year BP, is interrupted by several minor wet phases peaking at 7100, 5910, 5100–4700 and 3570 cal year BP. On the basis of the age–depth model suggested here, these are similar in timing to phases of higher lake levels in central Europe (Magny 2004). The latter change is also in accord with increased surface wetness on peatlands in western Europe (Barber et al. 2003; Charman et al. 2005). There is no indication of a major abrupt change in climate associated with the widespread development of *Fagus* forest in northwest Romania during the period between around 4500 and 3000 cal BP (Bjorkman et al. 2002; Bodnariuc et al. 2002; Tantau et al. 2003). This is one the most significant Holocene changes in the vegetation of the region. However, while there is no clear evidence of a single event which might have caused this development, the gradual rise in water tables during this period may indicate that a competitive threshold was reached, which favoured *Fagus* at the expense of other tree taxa.

The short dry phase between 3390 and 3030 cal year BP is terminated by a major rise in water tables culminating at 2725 cal BP. This also represents one of the biggest biostratigraphic changes in the profile to dominance by *Amphitrema wrightianum*. It is coincident with the events which have been associated with the sharp rise in ^{14}C content of the atmosphere and recorded in peatlands from western Europe and other areas (Van Geel et al. 1996), including the Czech Republic (Speranza et al. 2003). Our evidence therefore supports the assertion that this was the largest single climate change towards wetter conditions during the late Holocene throughout Europe. The increasing dryness from 2240 BP is also similar to the declining and generally low lake levels after 2350 BP in the central European record (Magny 2004), a general correlation which is reflected by the change to a phase of wetter conditions at Fenyves-tető after 590 BP and higher lake levels after AD 1394. The change to wetter conditions at around 600 BP in mid-latitude Europe coincides with the intensification of the Icelandic low pressure and the Siberian high pressure systems suggested by Meeker and Mayewski (2002) which would have caused stronger westerly airflow over the region and presumably increased precipitation. The more minor changes to wetter conditions recorded during the late Holocene record peaking at 1670 and 1170 BP are harder to relate to other records, although potentially they may correlate with higher lake levels between 1800–1700 and 1300–1100 BP (Magny 2004). However, they are relatively small in magnitude and clearly are not as significant as the longer term changes on which they are superimposed.

The final prominent change to drier conditions after 370 cal BP is more difficult to relate to broad-scale changes and could be a result of human activity in the catchment, although there are no signs of disturbance to the mire itself. The only change in the catchment might have been a reduction in forest cover, but this would produce an increase rather than a decrease in surface wetness. Pollen data from another site in the immediate area (about 50 km to the NW) suggests that there has only been very minor forest disturbance, with some reduction in tree cover from around 300 cal BP (Bjorkman et al. 2002). Speranza et al. (2000) found that deforestation in the catchment of a Czech ombrotrophic peatland had produced increases in surface wetness in the medieval period. It is possible that mire disturbance of some other kind (drainage, peat cutting) could have resulted in the water table draw-down but that no evidence of this remains visible. However, it seems unlikely that drainage would be carried out because of the abundance of drier slopes for grazing animals and the more than adequate timber for fuel. Exploitation of the mire for water is a further possibility as there are only a few small springs this close to the summit of Fenyves-tető, but again there is no physical or other evidence for this practice.

Conclusions

The work reported here is the first quantitative peat-based paleohydrological reconstruction from mid-latitude eastern Europe. The record demonstrates that there is clear potential in the peatlands of this region for developing Holocene palaeoclimate records of moisture balance. The results extend the geographical range of peat palaeoclimate records in Europe, and offer the prospect of much broader scale climate reconstructions from peatlands.

An important part of the work is the application of quantitative transfer functions for water table reconstruction based on testate amoebae analysis. A number of problems were encountered during the development of a modern training set for the testate amoebae transfer function. The principal problem is that the *Sphagnum* peatlands in the Carpathian region fall into two main hydrological classes. One type experiences significant summer water table draw-down and is replenished by winter and spring runoff and groundwater. The other receives almost all of its water from precipitation and has a much more stable water table regime. The former type is unsuitable for developing a hydrological transfer function because the testate amoebae assemblages are not clearly related to any easily measured hydrological variable such as water table. The two types are not easy to separate on the basis of topographic setting or surface vegetation but we distinguished them using a simple method of long-term water table monitoring. This highlights the need for a good understanding of ecosystem functioning when deriving transfer functions from ecological data.

After filtering out unsuitable sites, a regionally applicable transfer function for depth to water table was derived from the remaining data and applied to a fossil sequence from northwest Romania covering the last 10,000 cal years. Comparison of this record with other palaeoclimatic data suggests that some of the changes are clearly related to wide-scale climate change, especially around 8000–8300 cal BP, 3000–2500 cal BP and after 600 cal BP. A prominent rise in the water table at these times suggests that the intensification of westerly airflow associated with these periods was strong enough to affect the eastern areas of Europe as well as the western and central parts of Europe where changes in lake levels and peatland hydrology have previously been reported. Further work on peatland and other proxies in this region is required to test the initial results, and to assess the magnitude of these and other changes in moisture balance during the Holocene.

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References

Bacsó N (1959) Magyarország éghajlata (The climate of Hungary). Akadémiai Kiadó, Budapest, pp 302

Bahnson H (1968) Kolorimetriske bestemmelser af humificeringstal i højmosetørv fra Fuglsø Mose på Djursland. Medd Dansk Geol Foren 18:55–63

Barber KE, Charman DJ (2003) Holocene palaeoclimate records from peatlands. In: Mackay AW, Battarbee RW, Birks HJB, Oldfield F (eds) Global change in the Holocene. Edward Arnold, London, pp 210–226

Barber KE, Chambers FM, Maddy D (2003) Holocene palaeoclimates from peat stratigraphy: macrofossil proxy-climate records from three oceanic raised bogs in England and Ireland. Quat Sci Rev 22:521–539

Belyea LR (1999) A novel indicator of reducing conditions and water-table depth in mires. Funct Ecol 13:431–434

Bennett KD (2002) Documentation for psimpoll 4.10 and pscomb 1.03. C programs for plotting pollen diagrams and analysing pollen data. Quaternary Geology Geocentrum, Uppsala University, Uppsala

Bjorkman L, Feurdean A, Wohlfarth B (2002) Late-Glacial and Holocene forest dynamics at Steregoiu in the Gutaiului Mountains, Northwest Romania. Rev Palaeobot Palynol 2514:1–33

Bodnariuc A, Bouchette A, Dedoubat JJ, Otto T, Fontugne M, Jalut G (2002) Holocene vegetational history of the Apuseni mountains, central Romania. Quat Sci Rev 21:1465–1488

Bond G, Kromer B, Beer J, Muscheler R, Evans MN, Showers W, Hoffmann S, Lotti-Bond R, Hajdas I, Bonani G (2001) Persistent solar influence on North Atlantic climate during the Holocene. Science 294:2130–2136

Charman D (2002) Peatlands and environmental change. J. Wiley and Sons, London, New York

Charman DJ, Warner BG (1992) Relationship between testate amoebae (Protozoa: Rhizopoda) and microenvironmental parameters on a forested peatland in northeastern Ontario. Can J Zool 70:2474–2482

Charman DJ, Hendon D, Woodland W (2000) The identification of peatland testate amoebae. Quaternary Research Association, Technical Guide no.9, London

Charman DJ, Blundell A, Chiverrell RC, Hendon D, Langdon PG (2005) Compilation of non-annually resolved Holocene proxy climate records: Stacked Holocene peatland palaeo-water table reconstructions from northern Britain. Quat Sci Rev 25 (in press)

Jowsey PC (1966) An improved peat sampler. New Phytol 65:245–248

Juggins S (2003) C^2 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne

Justyák J (1994) Európa éghajlata (The climate of Europe). Kossuth Lajos University, Debrecen

Justyák J (2002) Magyarország éghajlata (The climate of Hungary). University of Debrecen, Debrecen

Lappalainen E (ed) (1996) Global peat resources. International Peat Society, Finland

Lindsay RA, Charman DJ, Everingham F, O'Reilly RM, Palmer MA, Rowell TA, Stroud DA (1988) The flow country: the peatlands of Caithness and Sutherland. Nature Conservancy Council, Peterborough

Magny M (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quat Int 113:65–79

Magny M, Begeot C, Guiot J, Peyron O (2003) Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. Quat Sci Rev 22:1589–1596

Meeker LD, Mayewski PA (2002) A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. The Holocene 12:257–266

Mitchell EAD, Buttler AJ, Warner BG, Gobat JM (1999) Ecology of testate amoebae (Protozoa : Rhizopoda) in Sphagnum peatlands in the Jura mountains, Switzerland and France. Ecoscience 6:565–576

Schnitchen C, Magyari E, Tóthmérész B, Grigorszky I, Braun M (2003) Micropaleontological observations on a Sphagnum bog in East Carpathian region—testate amoebae (Rhizopoda: Testacea) and their potential use for reconstruction of micro- and macroclimatic changes. Hydrobiologia 506–509:45–49

Schnitchen C, Magyari E, Charman DJ, Tóthmérész B, Grigorszky I, Béres V, Braun M The possibility of reconstruction of past hydrological changes in a Sphagnum bog by the use of testate amoebae (Rhizopoda: Testacea) in the Carphatian Basin. Proceedings of SIL XXIX Congress, Lahti, Finland, 8–14 August, 2004 (in press)

Speranza A, van Geel B, van der Plicht J (2003) Evidence for solar forcing of climate change at ca. 850 cal BC from a Czech peat sequence. Global Planetary Change 35:51–65

Speranza A, Hanke J, van Geel B, Fanta J (2000) Late-holocene human impact and peat development in the Cerna Hora bog, Krkonose Mountains, Czech Republic. Holocene 10:575–585

Szász G, Tőkei L (1997) Meteorológia mezőgazdáknak, kertészeknek, erdészeknek (Meteororlogy for agrarians, horticulturists and foresters). Mezőgazda Kiadó, Budapest

Tantau I, Reille M, de Beaulieu JL, Farcas S, Goslar T, Paterne M (2003) Vegetation history in the Eastern Romanian Carpathians: pollen analysis of two sequences from the Mohos crater. Veg Hist Archaeobot 12:113–125

Ter Braak CJF (1988) CANOCO—a FORTRAN program for canonical community ordination by (partial) (detrended) (canonical) correspondence analysis, principal components analysis and redundancy analysis (version 2.1). Technical Report LWA-88-02, GLW, Wageningen

Tolonen K, Warner BG, Vasander H (1992) Ecology of testaceans (Protozoa, Rhizopoda) in mires in southern Finland I. Autecology. Arch Protistenkd 142:119–138

Tolonen K, Warner BG, Vasander H (1994) Ecology of testaceans (Protozoa: Rhizopoda) in mires in southern Finland: II. Multivariate analysis. Arch Protistenkd 144:97–112

Van Geel B, Buurman J, Waterbolk HT (1996) Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. J Quat Sci 11:451–460

Woodland WA, Charman DJ, Sims PC (1998) Quantitative estimates of water tables and soil moisture in Holocene peatlands from testate amoebae. Holocene 8:261–273