Published in Palaeogeography, Palaeoclimatology, Palaeoecology 265, issues 1-2, 93-106, 2008
which should be used for any reference to this work

Last millennium palaeoenvironmental changes from a Baltic bog (Poland) inferred from stable isotopes, pollen, plant macrofossils and testate amoebae

M. Lamentowicz [a,*], A. Cedro [h], M. Gałka [a], T. Goslar [b,c], G. Miotk-Szpiganowicz [d], E.A.D. Mitchell [e,f], J. Pawlyta [g]

[a] Department of Biogeography and Palaeoecology, Adam Mickiewicz University (Faculty of Geosciences), Dzięgielowa 27, 61-680 Poznań, Poland
[b] Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland
[c] Poznań Radiocarbon Laboratory, Foundation of the Adam Mickiewicz University, Rubież 46, 61-612 Poznań, Poland
[d] Polish Geological Institute, Branch of Marine Geology, ul. Kościerska 5, 80-328 Gdańsk, Poland
[e] Swiss Federal Research Institute WSL, Ecosystem Boundaries Research Unit, Wetlands Research Group, Station 2, CH-1015 Lausanne, Switzerland
[f] École Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Ecological Systems (ECOS), Station 2, CH-1015 Lausanne, Switzerland
[g] Department of Radioisotopes Institute of Physics, Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland
[h] University of Szczecin Laboratory of Climatology and Marine Meteorology, Institute of Marine Science Faculty of Natural Science, University of Szczecin, Wąska 13, 71-415 Szczecin, Poland

ABSTRACT

The Baltic coast of Northern Poland is an interesting region for palaeoclimatic studies because of the mixed oceanic and continental climatic influences and the fact that the dominance of one or the other of these two influences might have changed over time. Also, unlike many more intensively studied regions of Europe, human impact in the region was rather limited until the 19th century. We present a 1200-year high-resolution record from Stążki mire, an ombrotrophic bog located 35 km from the Baltic Sea coast. Using testate amoebae, stable isotopes ($\delta^{13}C$) of *Sphagnum* stems, pollen, plant macrofossils and dendroecological analyses, our aims were to: 1) reconstruct the last millennium palaeoenvironment in the study site and its surroundings, 2) identify the major wet–dry shifts, 3) determine if those events correlate with climate change and human impact, 4) assess the resilience of the Baltic bog ecosystem following human impact, and 5) compare the palaeo-moisture signal from the Baltic coast with records from more oceanic regions. Two dry periods are inferred at AD 1100–1500 and 1650–1900 (–2005). The first dry shift is probably climate-driven as pollen record shows little evidence of human indicators. The second dry shift can be related to local peat exploitation of the mire. In the 20th century additional limited drainage took place and since ca. AD 1950 the mire has been recovering. From 1500 AD onwards all proxies indicate wetter condition. The beginning of this wet shift occurred during the Little Ice Age and may therefore be a climatic signal. The macrofossil data show that *Sphagnum fuscum* dominated the pristine mire vegetation but then declined and finally disappeared at ca. AD 1900. This pattern is comparable with the timing of extinction of *Sphagnum austinii* (=*Sphagnum imbricatum*) in the UK. This study illustrates the value of high-resolution multi-proxy studies of peat archives to assess the magnitude of anthropogenic land-use changes. This study presents the first direct comparison of testate amoebae and stable isotope data from the same core. The two proxies correlate significantly throughout the record and most strongly for the latter part of the record when most of the variability was recorded.

Keywords:
Ombrotrophic peatland, Palaeoclimate, Last millennium, Surface moisture, Multi-proxy study, Testate amoebae, Stable isotopes

1. Introduction

The reconstruction of environmental changes over the last millennium has recently become a priority in palaeoenvironmental research (Jones and Mann, 2004). Because such studies require a high time resolution (at least decadal and ideally annual) records such as tree rings or laminated sediments are generally used. However, high temporal resolution can be achieved from well dated peat cores analysed at short intervals (0.5–1 cm) (Schoning et al., 2005; van der Linden and van Geel, 2006; Väliranta et al., 2007).

Ombrotrophic peatlands (or raised bogs) are usually considered as valuable repository of high-quality climatic signals because their sole source of water is from precipitation (Behre et al., 2005; Blaauw et al., 2004; Blundell and Barber, 2005; Hall and Mauquoy, 2005) and surface moisture therefore depends only on the balance between inputs from precipitation and losses from evaporation and runoff (Charman, 2002). Surface moisture affects communities of living organisms, which are preserved in the peat. Among these, the testate amoebae (protists) are now regularly used to infer changes in surface moisture (or water table depth) and this signal is in turn interpreted in terms of climate changes (Charman, 2002).

An additional challenge related to the use of peatlands for paleoclimatical studies is that the climatic signal is often difficult to

---

[*] Corresponding author.
E-mail address: mariuszl@amu.edu.pl (M. Lamentowicz).

read because of the increasing frequency and amplitude of direct (e.g. peat extraction and drainage) and/or indirect (e.g. land-use changes around the mires) human impact (Rydin and Jeglum, 2006). Indeed, palaeoecological studies covering the last 100–1000 years typically focus not only on climatic changes but also on the history of anthropogenic influence (Buttler et al., 1996). The challenge is therefore to separate these two types of signals (Kalis et al., 2003; Tarasov et al., 2005). Studies based on a combination of biotic (e.g.: pollen, testate amoebae, tree rings, and plant macrofossils) and abiotic proxies (e.g. stable isotopes) are generally considered to provide more reliable palaeoenvironmental information (Barber and Langdon, 2007). In addition to providing palaeoclimatic information, palaeoecological studies of peatlands can contribute to improving management and restoration of peatlands (Lavoie et al., 2001). Knowledge about recent changes e.g. in palaeohydrology helps in understanding the present state of peatland as well as their dynamics in relation to natural or anthropogenic changes (Scheffer et al., 2001).

With the current interest for climate change of the last millennium and human impact across Europe (Esper et al., 2005), the description of changes along climatic gradients is needed if we want to sort out global vs. local patterns. For example, it has been suggested that in a continental climatic context temperature may be more important than precipitation in controlling water table changes at the surface of peatlands (Schoning et al., 2005). The climatic context should therefore be taken in to account in the interpretation of water table records and palaeomoisture signals from different climatic regions should be compared. However, most studies reconstructing past surface moisture from ombrotrophic bogs were done in oceanic or suboceanic regions (Warner and Charman, 1994; Buttler et al., 1996; Charman, 1999; Charman and Blundell, 2007; Booth, 2007; Mitchell et al., in press). By contrast, there are fewer multi-proxy studies of peatlands in more continental regions such as Poland, be it for the last millennium or longer periods of the Holocene (Tobolski, 1987; Żurek, 1993; Żurek and Pazdur, 1999; Skrzypek and Jędrysek, 2000; Żurek et al., 2002; Andreev et al., 2003; Charman et al., 2004; Lamentowicz, 2004; Booth et al., 2006).

Regions such as Northern Poland located at the limit between continental and oceanic climatic influences could yield very valuable information. Polish Baltic raised bogs are located on the fringe of the southern range of lowland raised bogs in Europe (Herbichowa, 1998). Truly ombrotrophic raised bogs are very rare in Poland and are located mainly in NW part of the country along the Baltic shore (approx. 40 km from the coast). Further south and east the surface of *Sphagnum* mires becomes flat and their vegetation is more influenced by ground water (Tobolski, 2003). Although ombrotrophic bogs are in theory well suited for palaeoecological reconstruction, most of the Baltic bogs in Poland have been drained and some of them are still being exploited (Jasnowski et al., 1968; Herbichowa, 1997; Pawlaczyk et al., 2005). It is nearly impossible to find a completely undisturbed site for studies of the last millennium. Because of artificial lowering of the water table the palaeoecological record was often lost especially in the central parts of the domed peatlands. The peat archive is disturbed mainly for the last 100–200 years of peat accumulation. Furthermore, because of changes in the catchments and surroundings of peatlands, microclimatic conditions were changed. For these reasons the climatic signal may be indistinct at least for the last 100 years.

The general aim of this study was to test if a range of proxies (testate amoebae, pollen, plant macrofossils, tree rings and stable isotopes from *Sphagnum*) could allow inferring a climatic signal from a peat monolith despite the considerable anthropogenic impact on the Pomeranian landscape since the Early Medieval Period. Our more specific aims were to: 1) reconstruct the last millennium palaeoenvironment in a Baltic raised bog and its surroundings, 2) identify the major wet–dry shifts, 3) determine if those events correlate with climate change and human impact, 4) assess the resilience of the Baltic bog ecosystem following human impact, and 5) compare the palaeomoisture signal from the Baltic coast with records from more oceanic regions. This study is the first high-resolution palaeoenvironmental multi-proxy investigation focusing specifically on the last thousand years undertaken in Poland. There are few studies describing human impact in Pomerania over the last millennium and little Holocene palaeohydrological data from peatlands of the region (Skrzypek and Jędrysek, 2000; Żurek et al., 2002; Skrzypek and Jędrysek, 2004).

2. Methods

2.1. Study site and coring

The study site is a Baltic bog — Stążki (N 54 25′ 27.7″; E 18 05′ 00.2″) located in northern Poland ca 35 km from the Baltic sea coast, in the Kaszuby Lakeland, near the highest point (214.6 masl) of a morainic plateau. The morainic plateau is delimited at the south and west by the Łeba river and at the east by the Dębica river. The north-western ribbon depression is filled with waters of the Miłoszewskie and Lewinko lakes. The water from these lakes flows into the Młynówka stream. This morainic plateau is slightly undulating and there are many closed-basin depressions filled by *Sphagnum* mires. Because of uncontrolled peat exploitation many of these have been destroyed and were transformed into meadows or heathlands (Szafrański, 1961).

According to the regional climate classification of Gumiński (1948), the studied area is located in the IV Pomeranian climatic division (Kondracki, 1998). The average annual temperature is +7.7 °C and averages for January and July are respectively −1.2 °C and +16.8 °C. The growing period lasts ca 200 days. The average annual sum of precipitation for Lębork is 690 mm, ranging from 422 mm in dry years (year 1964) to 956 mm in very wet years (year 1998). February and March are the driest months (36 mm) and July the wettest (86 mm). The duration of snow cover is up to 75 days, however, depending on the position of the polar front, the duration and timing is very variable.

Stążki mire has a domed profile with a complex microtopography of hummocks and hollows, typical for raised bogs. The elevation differences between the margin and the highest point in the mire are no more than 1 m but it is very likely that the mire sunk after exploitation and drainage. Based on the vegetation, Stążki is one of the best-preserved Baltic bog on the moraine. However the peripheral lagg no longer exists and boundaries between the mire and adjacent fields are very sharp. The base of the deposit is composed of gyttja indicating a limnogenic origin of this bog. From the west a mineral peninsula encroaches into the mire. In the 19th century ditches were dug along the slope of the dome to drain the peatland. The southern part of the mire is destroyed to a large degree, but north of the mineral peninsula the peatland still possesses the characteristics of a raised bog. Around ca. 1960 the peatland was locally exploited at the southern fringe (some exploitation ponds remain) (Szafrański, 1961), but recently (2004–2006) no peat digging was observed.

The present vegetation of the mire is dominated by *Sphagnum fallax*, *Eriophorum vaginatum* and *Calluna vulgaris*. The exploited parts of the peatland are covered by pine (*Pinus sylvestris*) forest that becomes sparser in the best-preserved and moister central part. We sampled two one-meter peat monoliths with a Wardenaar sampler (Wardenaar, 1987). The first short core (SM1) was taken from the less drained bog part located 40 m from the mire edge. The second core (SM2) used in this study was taken from the central part of the peatland situated near the forested part that is also the highest point of the mire (Fig. 1.). The Troels–Smith method was used to describe the peat in the field. The above-mentioned features and our preliminary examination of cores SM1 and SM2 show that Stążki mire can be considered to be a representative site (and starting point) for

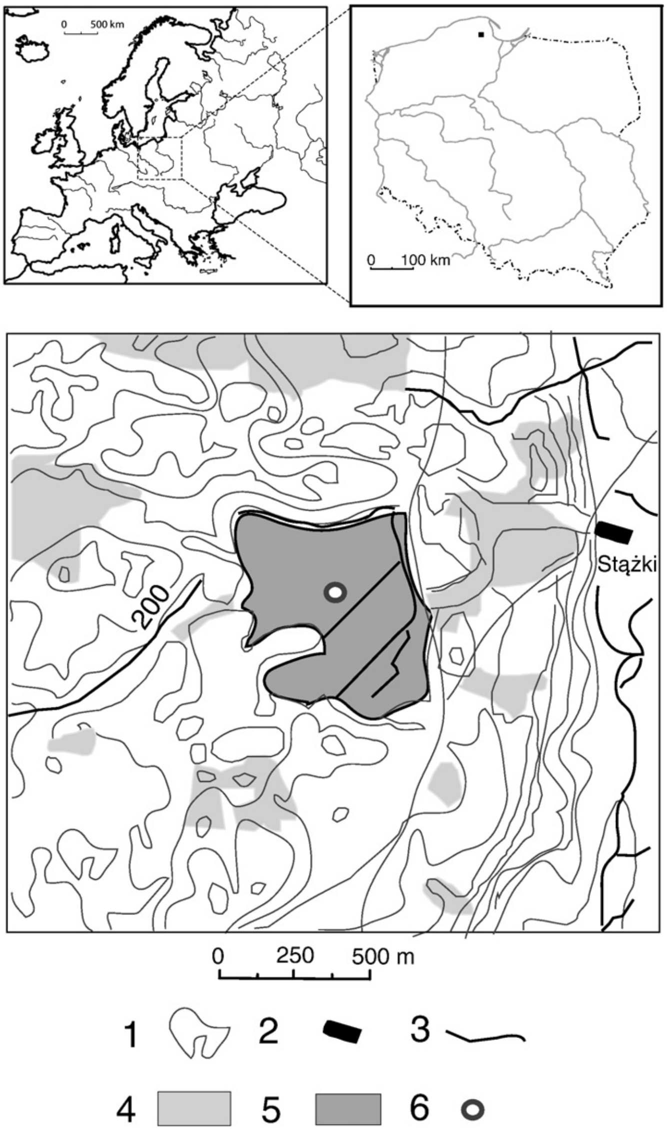

Fig. 1. Setting of the study site. Figure description: 1 — contour lines; 2 — village; 3 — ditch and stream; forest; 4 — forest, 5 — Stążki mire; 6 — coring site.

palaeoclimatological research in northern Poland. The core SM2 was divided into 1 cm slices that were then split for detailed analyses.

2.2. Dating and age–depth model

Several *Sphagnum* stems from nine one-centimetre thick samples were selected for radiocarbon dating (avoiding Ericaeae, and *Carex* rootlets, and other contamination) as these were shown to yield very precise dates (Nilsson et al., 2001; Turetsky et al., 2004). Samples were dated at the AMS facility in Poznań Radiocarbon Laboratory (Goslar et al., 2004) (Table 1B). Seven peat samples were taken from the upper 16 cm of the core for Pb-210 dating. ^{210}Pb was radiochemically extracted from samples (Flynn, 1968) and its radioactivity was measured. The CRS model was used for ^{210}Pb age calculation (Appleby, 2001). Lead dating was realized in the Institute of Geological Sciences of Polish Academy of Sciences in Warsaw (Table 1A). Those dates were also used for construction of the chronology.

The model of peat accumulation is based on calibrated ^{14}C and ^{210}Pb dates. Calibrated ^{14}C dates were projected on the age–depth scale with the method described by Goslar et al. (2005). For construction of age–depth model, we used an algorithm, which maximized the product of probabilities of calendar (calibrated ^{14}C as well as ^{210}Pb) dates (a), minimized the curvature of the age–depth line (b) and (c) minimized deviations of relative changes of the slope of the age–depth line from those suggested by independent indications (in this particular case: by ^{210}Pb data). As these three goals can be conflicting, the quantitative measures of "a", "b" and "c" were weighted appropriately. The same algorithm has already been applied for age–depth modelling of the Saariselka peat profile (Räsänen et al., 2007). As the ^{210}Pb dates of seven samples in Stążki are not independent of one another, the ^{210}Pb data in measure "a" were represented by one date only, while the whole ^{210}Pb chronology was used for defining the shape of the age–depth line in its upper part (measure "c").

Because of the existence of a distinct period of very low peat accumulation around 400 mm depth, the age–depth lines were calculated in two sections separately. In the lower section, only measures "a" (probabilities of calibrated ^{14}C dates) and "b" (curvature) were taken in calculations. In the upper section, two different versions of the age–depth line were calculated. In the simplified version (dotted line in Fig. 2), ^{210}Pb dates were ignored, while the extended version (solid line) incorporated information derived from ^{210}Pb, as described above. As the difference between both versions is small, in further discussion in this paper we use solely the extended age–depth model.

2.3. Stable isotopes

The carbon isotopic composition of *Sphagnum* macrofossils was studied as an independent proxy of past moisture changes in peatland (Price et al., 1997; Ménot-Combes and Burns, 2001; Ménot-Combes et al., 2004; Loader et al., 2007) and the results were compared to the testate amoeba-inferred moisture. For the analysis we selected 30 *Sphagnum* (mainly *S. fuscum*) stems per sample. *Sphagnum* stems proved to be appropriate for those studies (Loader et al., 2007). Samples were taken at each centimetre of the peat monolith. Stems were then washed in distilled water. For each sample about 0.7 mg of stems were was collected. δ^{13}C was measured in the bulk organic matter of the stems. The samples were combusted in the Costech ECS 4010 elemental analyser. The resulting gases were separated by gas chromatography and carbon dioxide was transferred to the Thermo-Electron Delta Plus XP mass spectrometer for δ^{13}C measurement. The

Table 1
Results of dating of SM2 monolith: A — lead dating; B — radiocarbon dating

Sample *N*	Depth [mm]	Age ^{210}Pb [yr]	S.D. [yr]
A			
1	30		5
2	50	16	4
3	80	34	4
4	100	45	6
5	140	90	10
6	150	105	10
7	160	120	15

	Sample	Depth	Age ^{14}C	Material
B				
1	Poz-15776	13.5	115 ± 30 BP	*Sphagnum* stems
2	Poz-15777	20	365 ± 30 BP	*Sphagnum* stems
3	Poz-15778	29.2	310 ± 30 BP	*Sphagnum* stems
4	Poz-15779	37	290 ± 30 BP	*Sphagnum* stems
5	Poz-15780	44.5	1025 ± 30 BP	*Sphagnum* stems
6	Poz-15781	60.5	1100 ± 30 BP	*Sphagnum* stems
7	Poz-15782	70.5	1090 ± 30 BP	*Sphagnum* stems
8	Poz-15784	89.5	1165 ± 30 BP	*Sphagnum* stems
9	Poz-15785	100.5	1245 ± 35 BP	*Sphagnum* stems

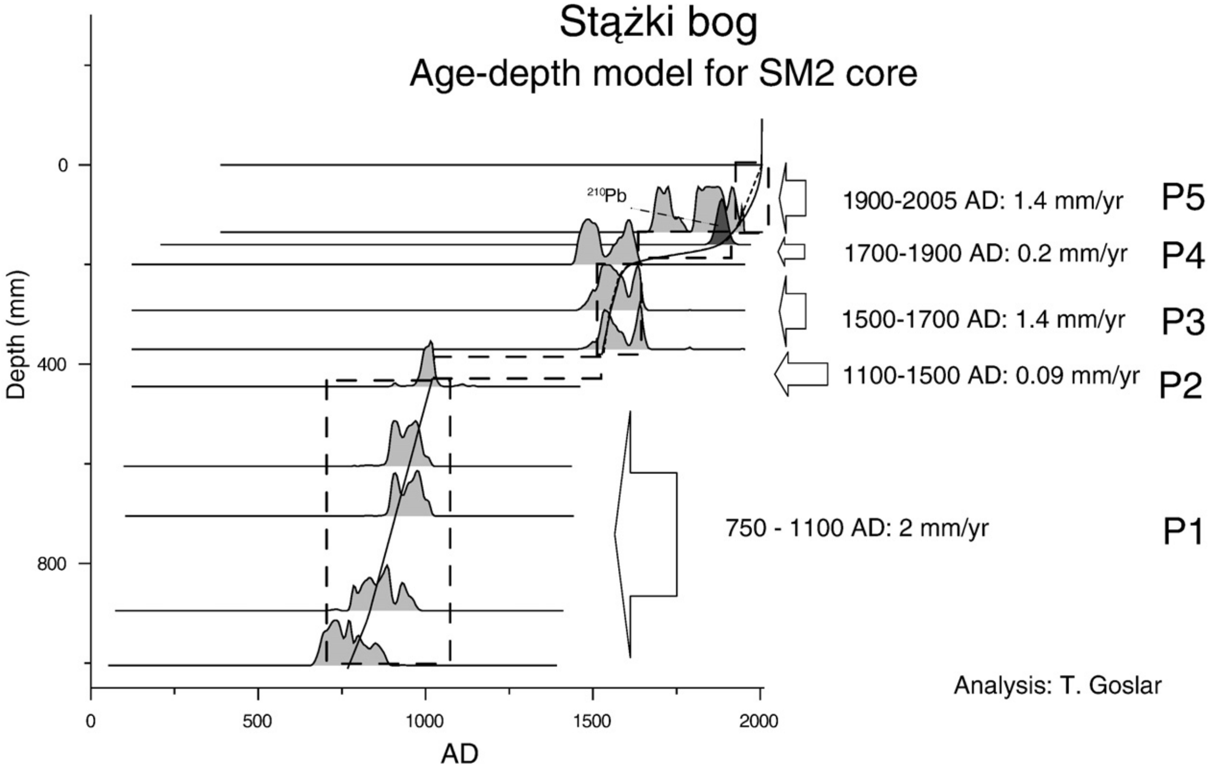

Fig. 2. Chronology of the peat profile in Stążki. The silhouettes show probability distributions of calendar dates, obtained by calibration of individual ^{14}C ages. On the graph, ^{210}Pb dates are represented by one silhouette only, while the full set of 210Pb dates was used as a framework for shape of the ultimate age–depth curve in the computer algorithm.

δ^{13}C values are expressed in ‰ VPDB with an uncertainty equal or better than 0.2‰.

2.4. Testate amoebae, pollen, and plant macrofossils

Core SM2 was divided into 1 cm slices that were then split for the different analyses. Subfossil testate amoebae were extracted from 4 cm^3 samples at 1 cm depth intervals following the sieving and back-sieving procedure described by Hendon and Charman (1997). Testate amoebae were identified and counted to a total of 150 individuals, at 200–400× magnification. Water table depth was inferred from a transfer function from Northern Poland (an expanded version of the model presented by Lamentowicz and Mitchell (2005a).

Samples for pollen analysis were taken every 5 cm. Pollen samples of 2 cm^3 in volume were treated with 10% KOH and then acetolysed (Berglund and Ralska-Jasiewiczowa, 1986; Faegri and Iversen, 1989). In total 500 pollen grains of trees and shrubs (AP) were counted in each sample but in samples where the frequency was very low all pollen grains from two slides 22 × 22 mm were identified and counted. Percentage calculation was based on the sum of pollen grains of trees and upland herbs (AP + NAP). Pollen of Ericaceae, *Calluna vulgaris*, *Vaccinium* and *Andromeda* were excluded from the pollen sum. The percentage pollen diagram was produced with TILIA GRAPH (Grimm, 1992).

Plant macrofossils were analysed at 1 cm intervals. The material was rinsed on 0.25 and 0.5 mm mesh size sieves. The remaining material was identified under the stereoscopic microscope at a magnification of 10–100×. One slide from each sample was examined under the microscope at 200–400× magnification to determine the peat composition. Macrofossils were identified with the use of available guides (Katz et al., 1965; Grosse-Brauckmann, 1972, 1974; Katz et al., 1977; Tobolski, 2000). *Sphagnum* was identified to the section level.

2.5. Tree-ring analysis

Cores from 23 Scots pines (*Pinus sylvestris*) scattered on the central part of the mire were sampled with a Pressler increment borer, 1.3 m above the ground level. For every cored sample, measurements of the width of annual rings were made with 0.01 mm accuracy. Matching of individual dendrograms with calendar years and construction of the chronology were made following the classical methods of dendrochronological dating (Zielski and Krąpiec, 2004). The chronology was subjected to indexation, eliminating long-term trends (e.g. age trend), and accentuating the year-to-year variability in widths of the annual tree rings using the Arstan software (Holmes, 1983, 1994).

2.6. Diagrams preparation and numerical analyses

Percentage diagrams of plant macrofossils, pollen and testate amoebae were plotted using Tilia Graph (Grimm, 1992) and C2 (Juggins, 2003). The estimated percentage composition of particular macrofossils (e.g. *Sphagnum* and other mosses) was presented using a

Table 2
Lithological description of monolith SM2 from Stążki mire

Depth (cm)	Troels–Smith system	Description
0–4	Tb4 (Sphag.)	Not decomposed *Sphagnum* peat
4–6	Th2, Tb1, Sh1 (Sphag.) (Erioph.)	Slightly decomposed *Sphagnum*-herbaceous peat with *Eriophorum*
6–9	Tb4 (Sphag.)	Not decomposed *Sphagnum* peat
9–20	Tb1, Sh3	Very decomposed *Sphagnum* peat
20–30	Tb3, Sh1 (Sphag.)	Moderately decomposed *Sphagnum* peat
30–40	Tb2, Sh2 (Sphag.)	Moderately decomposed *Sphagnum* peat
40–47	Th3,Tb1, Sh+	Moderately decomposed *Eriophorum* peat
47–56	Tb3, Sh1	Slightly decomposed *Sphagnum* peat
56–100	Tb4, Sh1 (Sphag.)	Slightly decomposed *Sphagnum* peat

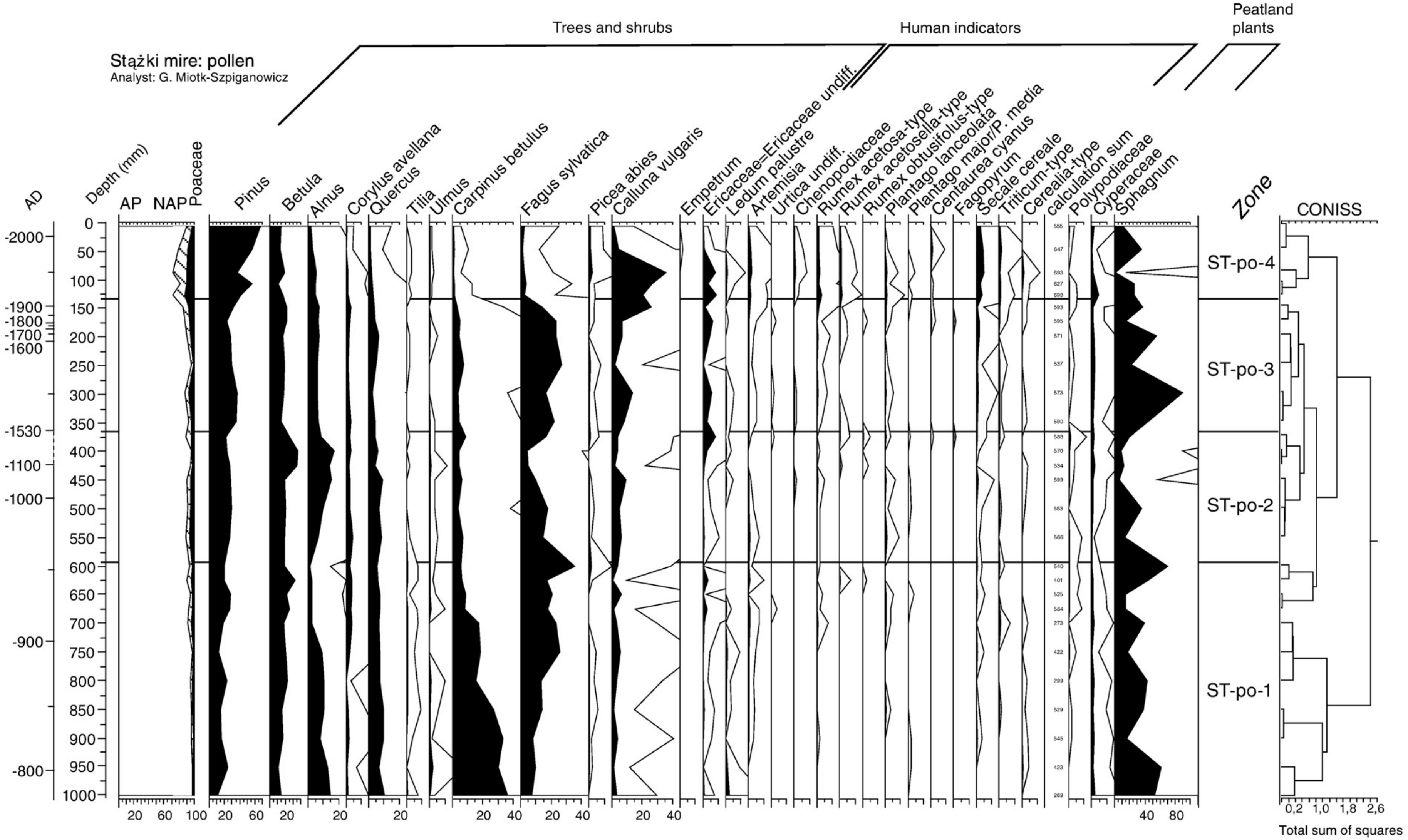

Fig. 3. Percentage pollen diagram for SM2 monolith showing regional vegetation changes in Stążki mire.

five-degree scale. Countable remains (e.g. *Andromeda polifolia* seeds) were presented in absolute numbers. Testate amoeba and pollen diagrams are based on percentage data. We performed stratigraphically constrained cluster analyses (method of incremental sum of squares) on all three data sets independently for quantitative definition of stratigraphic zones using CONISS (Grimm, 1987). For each diagram biostratigraphic zones represent a compromise between numerical (CONISS) and subjective approaches. Each assemblage zone was described in detail, but the summarised mire history is based on phases determined subjectively on the peat accumulation model and the main indicators of change. These phases are, however, in general agreement with results of zonation of particular proxies.

The water table was inferred from testate amoebae using a training set consisting of 123 surface samples taken mainly from natural, not drained *Sphagnum* mires in Pomerania and western Poland (N Poland) (Lamentowicz and Mitchell, 2005b; Lamentowicz et al., in press). Performance of four models was tested: partial least squares (PLS), weighted averaging (WA), tolerance down-weighted averaging (WAtol) and weighted averaging partial least squares (WA-PLS), using the software C2 (Juggins, 2003). The RMSEP (Root Mean Square Error of Prediction) was calculated using the Jacknife cross validation procedure (Crowley, 1992). For depth to the water table (DWT), the model with the lowest RMSEP was provided by the WAtol, with a maximum prediction bias of 8.9 cm and a root mean square error of prediction (RMSEP(jack)) of 4.3 cm (Lamentowicz et al., in press).

3. Results and interpretation

3.1. Peat accumulation, chronology, and lithology

The entire section is dominated by *Sphagnum* peat, mixed in with *Eriophorum* between 4 and 6 cm depth. More decomposed layers occur between 9 and 20 cm and between 30 and 40 cm (Table 2). The projection of calibrated ^{14}C dates on the age–depth scale (Fig. 2) suggests that the peat accumulation history can be divided into five periods: 1) rapid peat growth between ca. AD 750 and 1100 (ca. 2 mm/yr), 2) low peat growth between ca. AD 1100 and 1500 (0.09 mm/yr), 3) rapid peat growth between ca. AD 1500 and 1650 (ca. 1.4 mm/yr), 4) low peat growth between ca. AD 1650 and 1900 (0.2 mm/yr), and 5) rapid peat growth between ca. AD 1900 and present (ca. 1.4 mm/yr). This scenario agrees with the lithology (Table 2) and the biotic proxies (see further).

3.2. Development of the mire

Percentage diagrams for pollen, plant macrofossils, and testate amoebae are presented in Figs. 3, 4 and 6 and a detailed description of biostratigraphic zones for each biotic proxy is presented in Table 3.

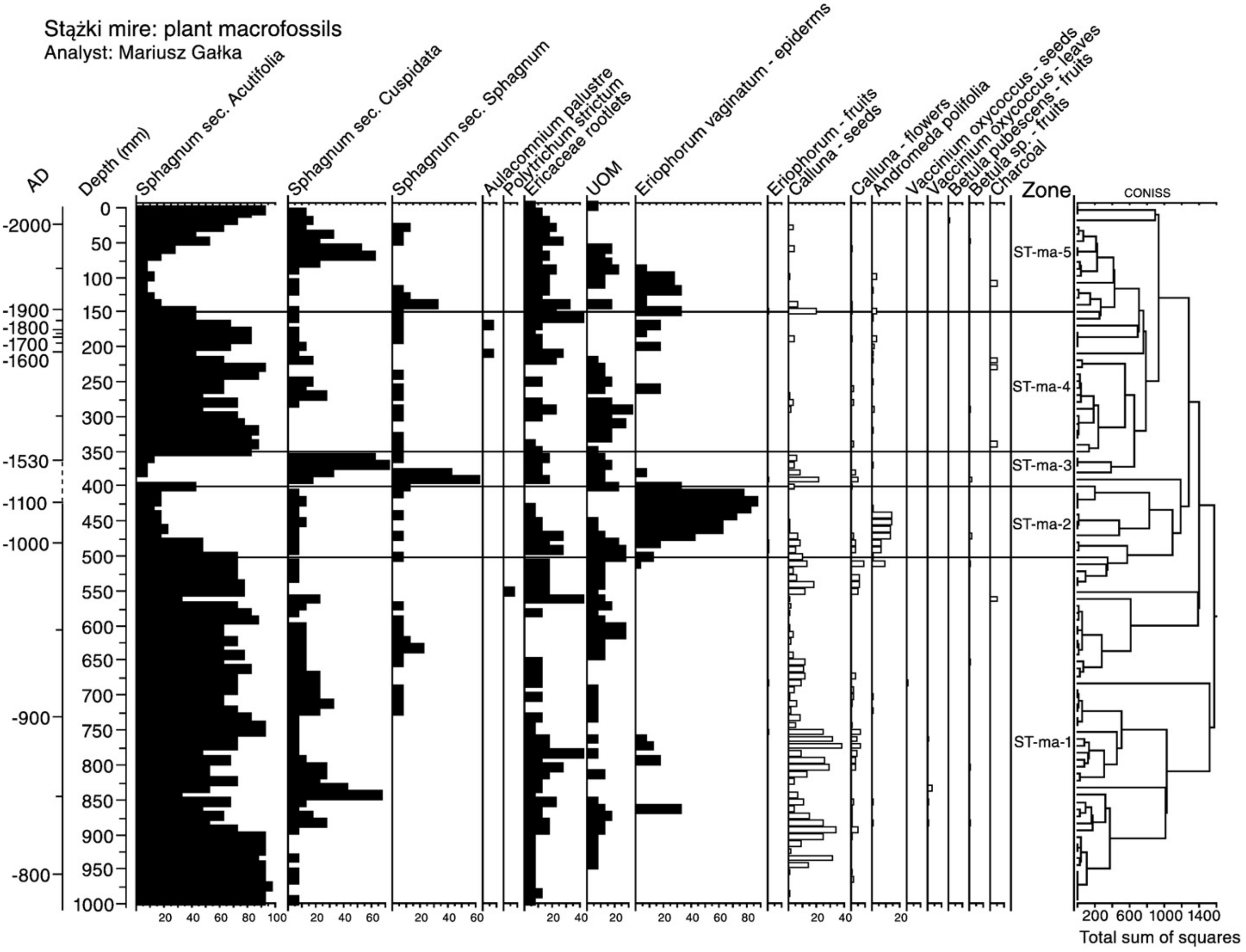

Fig. 4. Plant macrofossils diagram presenting local vegetation changes in Stążki mire.

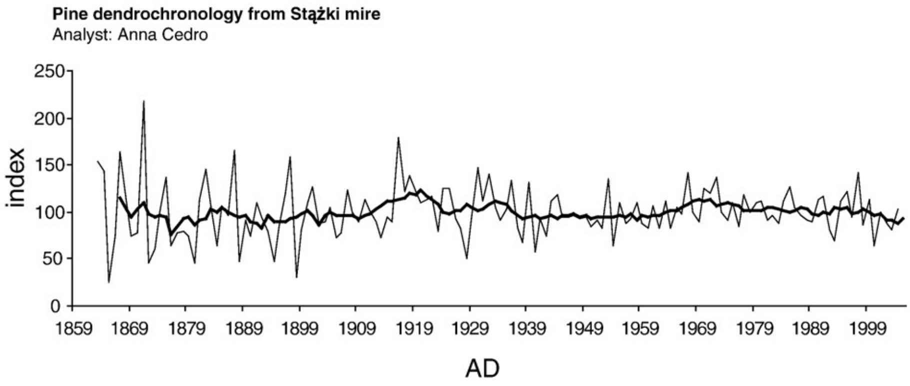

Fig. 5. Index local chronology for Scots pine from Stążki — black line and the 9-year moving average (black bold line).

Based on this data and the lithology, we determined the following main developmental phases of Stążki mire.

Baltic bog phase: ca AD 750–1100 (1010–445 mm): (ST-po-1, ST-po-2, ST-ma-1, ST-ma-2, ST-ta-1, ST-ta-2). During this period of high peat accumulation rate (ca. 2 mm/yr), testate amoebae indicate that the coring site was very moist, except for episodes of lower water table indicated by *Assulina* spp. Until AD 1100 the coring site vegetation was dominated by *Sphagnum* sec. Acutifolia cf. S. *fuscum* (most stem leaves were identified as *S. fuscum*) with admixture of *S.* sec. Cuspidata, and among vascular plants Ericaeae and *Calluna*. Around AD 1100 the mire surface became drier as shown by testate amoebae e.g. increase of *Assulina* spp. and decline of *Hyalosphenia elegans* and *H. papilio*. *Eriophorum vaginatum* indicates water table fluctuations.

During this phase, *Fagus* gradually replaces *Carpinus* as the dominant tree of the forest. Increased concentrations of microscopic charcoal and *Pteridium aquilinum* spores attest for fires in the surroundings. Human influence was insignificant in this period.

Disturbance: ca AD 1100–1500 (445–395 mm): (ST-ma-2, ST-ma-3, ST-ta-3, ST-ta-4). In this phase peat growth was extremely slow ca. 0.09 mm/yr. The profile is characterized by a sharp decline of peat mosses, especially *Sphagnum fuscum* and a domination of *Eriophorum vaginatum*, indicating unstable hydrological conditions. Then *E. vaginatum* disappeared and was replaced by *Sphagnum* sec. *Sphagnum* and afterward by *Sphagnum* sec. Cuspidata. Among testate amoebae *Arcella discoides* suggests fluctuations of the water table. This species occurs in very unstable wet habitats in our modern samples.

Table 3
Description of biostratigraphic zones for each analysed biotic proxy

Zone	AD	Description
Pollen		
ST-po-4	1850–2005	Decline of AP, *Alnus*, *Corylus*, *Quercus*, *Carpinus* and *Fagus*. Increase of *Pinus*, *Artemisia*, Chenopodiaceae, *Rumex*, *Centaurea*. Clear increase of percentage of human indicators. Decrease of value of *Sphagnum* spores.
ST-po-3	1520–1850	Increase in NAP, human indicators and *Fagus*. Continuous decrease of *Carpinus* and *Quercus*. Visible increase in human impact indicators. Peak of charcoal ca 1800. Increase of values of NAP and Poaceae.
ST-po-2	960–1520	Peak of *Alnus* ca 1520. Low and decreasing percentage of *Quercus*. Decline of *Fagus* ca 1500 A.D then its abrupt increase. Two peaks of charcoal and *Sphagnum* decline 1100–1500 Low percentage of human impact indicators. Stable percentage of *Pinus* and *Betula*.
ST-po-1	820–960	High but decreasing percentage of *Carpinus* — abrupt decline ca 920 A.D as well as increase value of *Fagus* — peak ca 950 ⇒ “Exchange” between *Carpinus* and *Fagus*. *Alnus* in decrease — minimum value ca. 950 Low percentage of human impact indicators. Stable percentage of *Quercus* and increase of *Corylus*. Stable percentage of *Pinus* and *Betula*.
Plant macrofossils		
ST-ma-5	1750–2005	Decline of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum*. Abrupt increase in value of *Eriophorum vaginatum* remains between 1800 and 1900 Peak of *Sphagnum* sec. Cuspidata value ca. 1950.
ST-ma-4	1520–1750	Reappearance of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum* and variable percentages of *Sphagnum* sec. Cuspidata, sec. *Sphagnum* as well as *Eriophorum vaginatum*.
ST-ma-3	1500–1520	Disappearance of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum*, maximum of *Sphagnum* sec. *Sphagnum* in the first stage and then *Sphagnum* sec. Cuspidata.
ST-ma-2	990–1500	Zone dominated by *Eriophorum vaginatum* remains. Decline of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum*, *Ericaceae* and UOM. Ca 1300 complete domination of *Eriophorum vaginatum* remains. The largest number of *Andromeda polifolia* in this profile before *Eriophorum* peak.
ST-ma-1	820–990	Domination of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum*. *Sphagnum* sec. Cuspidata value abruptly increase ca. 850 Low percentage of *Eriophorum vaginatum*. Variable value of Ericaceae. High value of *Calluna*.
Testate amoebae		
ST-ta-6	1900–2005	Disappearance of *Archerella flavum* ca 1950 and then reappearance of this species over time. Diversity of species in this zone is high. *Hyalosphenia elegans* appeared in percentage over 20. *Assulina scandinavica*, *Hyalosphenia subflava*, *Euglypha ciliata* and *Physochila griseola* are new for this core.
ST-ta-5	1700–1900	Decline of *Archerella flavum* and domination of *Heleopera petricola*.
ST-ta-4	1560–1700	Max. value of *Archerella wrightianum* ca AD 1520 Decrease of *Arcella discoides* and ca 1600 and increase of *Heleopera petricola* percentage. Increase of *Trigonopyxis arcula* percentage. *Archerella flavum* values decreasing.
ST-ta-3	1050–1560	Dominance of *Arcella discoides* ca. AD 1300 then *A. muscorum* and *A. seminulum* value increase again.
ST-ta-2	970–1050	Disappearance of *Hyalosphenia elegans* and *Hyalosphenia elegans* ca AD 1100 Ca AD 970 *Assulina muscorum* and *A. seminulum* value increase. Appearance of *Archerella wrightianum*.
ST-ta-1	820–970	Variable but very high percentage of *Archerella flavum*. Small increase in *Archerella wrightianum* and *Arcella discoides* ca AD 850. Variable values of *Assulina muscorum*, *A. seminulum*, *Hyalosphenia elegans*, *H. papilio* and *Heleopera sphagni*. *Heleopera petricola* present mainly ca AD 800 and AD 950

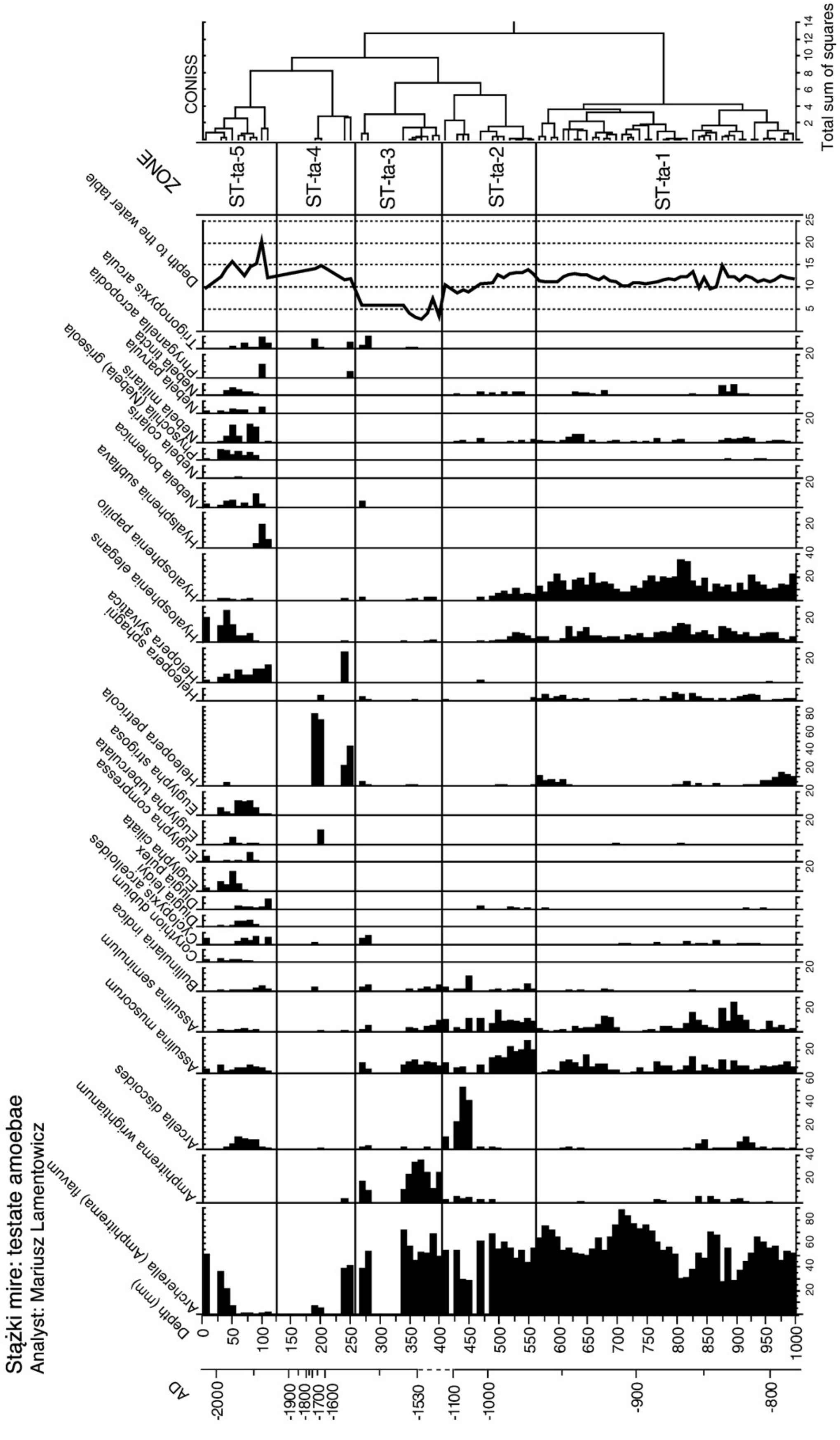

Fig. 6. Testate amoebae percentage diagram with reconstructed depth to the water table curve.

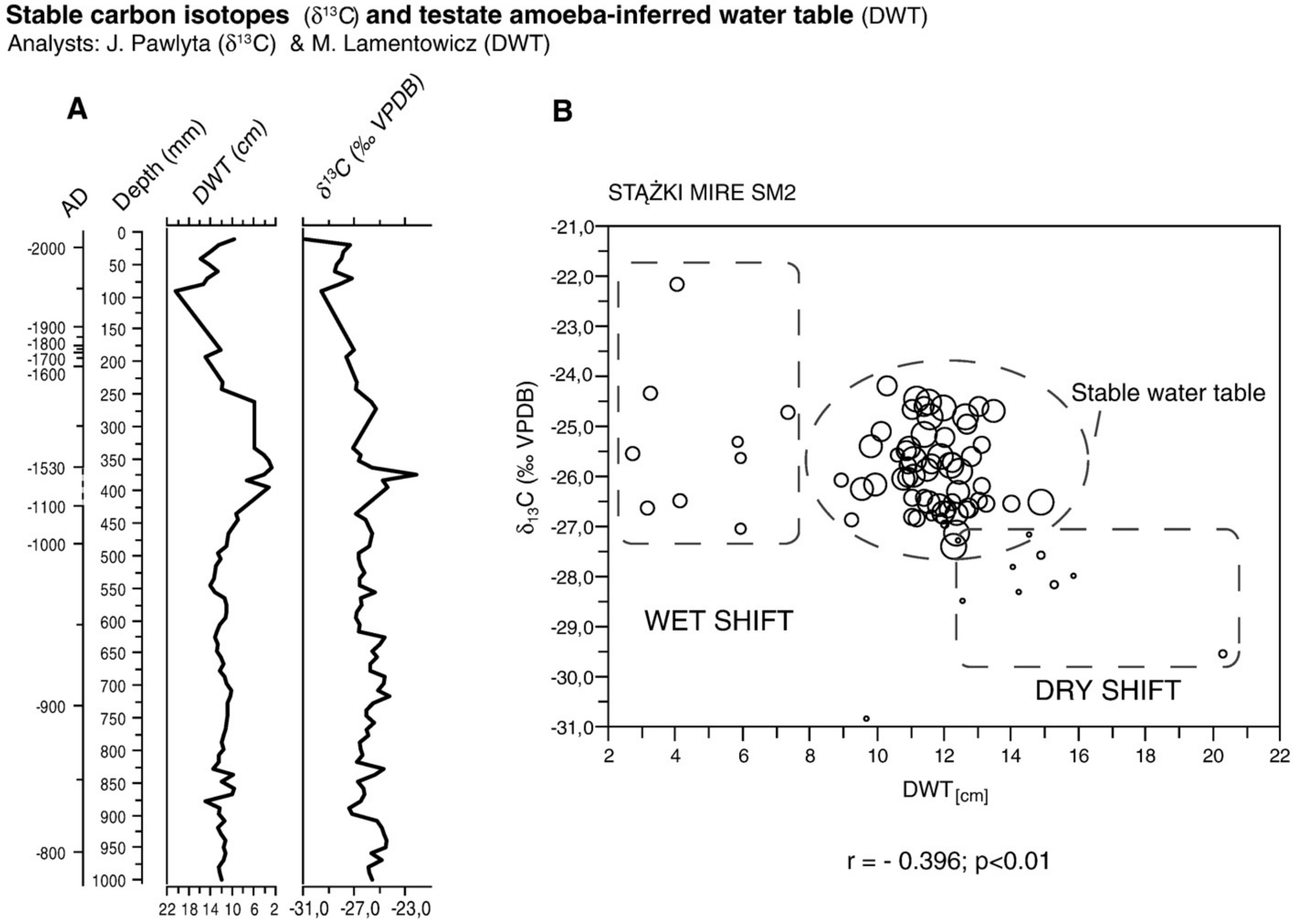

Fig. 7. Comparison of DWT (depth to the water table) inferred from testate amoebae and δ^{13}C measured on *Sphagnum* stems (A); biplot showing the correlation between δ^{13}C and testate amoeba-inferred DWT. The diameter of circles is proportional to the sample depth (B).

In this phase the presence of microscopic charcoal and *Pteridium aquilinum* again attests to fires in the surroundings Stążki bog. At the end of this phase, *Alnus* reached its maximum value (ca 1520) together with *Betula*. After that event *Fagus* started to regenerate but *Alnus* declined. The date AD 1520 is very important because pollen indicators show increasing human activity in the surrounding landscape.

Regeneration (Little Ice Age): ca AD 1520–1700 (395–185 mm): (ST-po-3, ST-ma-3, ST-ma-4, ST-ta-4). Peat accumulation rates increase to 1.4 mm per year. *Eriophorum vaginatum* disappeared and *Sphagnum* expanded with a succession from sec. *Sphagnum*, through sec. Cuspidata to *S. fuscum*. Testate amoebae are dominated by wet indicators (*Amphitrema* and *Archerella*), although *Trigonopyxis* suggests drier conditions at ca. AD 1550. Around AD 1650 all testate amoebae species declined along with *Sphagnum fuscum*. At the end of this phase, *E. vaginatum* appeared again, indicating water table fluctuation, together with Ericaceae indicating dry conditions. This phase ends with a decline of nearly all testate amoebae species and the appearance of *Heleopera petricola* with *T. arcula*.

During this period, *Fagus* expanded. Higher values of *Pinus* and *Calluna* pollen indicate an extension of dry habitats. At the same time human indicators, especially *Secale*, increase.

Human impact and the end of the Little Ice Age: ca AD 1700–1900 (185–145 mm): (ST-po-3, ST-ma-4, ST-ta-5). This generally dry phase with low peat accumulation (ca. 0.2 mm/yr) is characterized by the decline of all testate amoeba wet indicators (*Archerella flavum*, *Hyalosphenia elegans* and *H. papilio*). *Eriophorum vaginatum* and *Calluna vulgaris* suggest a low and fluctuating water table. The maximum value of *Calluna* corresponds with the maximum value of charcoal at the very end of this phase. The decomposition of the peat is high and testate amoebae shell preservation is poor. Agriculture developed during this phase, as indicated by increases of *Secale* and *Centaurea cyanus* pollen abundance.

During this phase pine started to expand on the peatland surface as documented by the dendrochronological analysis (Fig. 5): the oldest pine we observed was established in AD 1820. However, this date actually corresponds to the time when this tree reached a height corresponding today to 130 cm. As pine trees can grow very slowly on wet peatlands, this tree could have been quite old, possibly 100 year old before it reached this height. Pine colonisation is therefore likely to have started in the 18th century already at the time when peat accumulation rates had started to decline.

Disturbance and recovery: ca AD 1900–2005 (145–0 mm): (ST-po-4, ST-ma-5, ST-ta-6)+pine expansion. This phase of relatively high peat accumulation (ca. 1.4 mm/yr) includes the non-compacted acrotelm peat and shows further evidence of disturbance mainly in the first half (AD 1900–1950). The strongest disturbance phase is reflected by the maximum of *Hyalosphenia subflava* accompanied by three other indicators of dry conditions: *Trigonopyxis*, *Phryganella* and *Nebela militaris*. Hydrological conditions on the mire improved very recently: At ca. AD 1950 the mire started to regenerate as attested by an abrupt increase of *Sphagnum* sec. Cuspidata and a decrease of *Eriophorum vaginatum* macrofossils. Testate amoebae too indicate wetter and oligotrophic conditions from ca. AD 1960 onwards.

Single trees of *Pinus sylvestris* occurred on the peatland surface in the first half of the 19th century as an effect of peat exploitation and initial drainage. But the main expansion of pine took place in the last decade of the 19th century in response to more extensive drainage and peat exploitation. The years 1910–1920 and 1929–1937 are characterised characterized by wider tree rings due to the existence of many young trees with strong growth dynamics (Fig. 5). After this period the width of tree rings becomes narrower, suggesting more stable hydrological conditions until the beginning of 1970' when the growth trend again becomes stronger suggesting drier conditions. In the last 30 years however, a trend towards narrower tree rings indicates wetter conditions probably mainly due to the ditches being overgrown and gradually filled in by new *Sphagnum* growth.

Deforestation in the catchment took place at ca. AD 1900 as reflected by the decline of *Fagus* and other deciduous trees in the pollen record. By contrast *Pinus*, *Calluna* and human indicators pollen increase. Since AD 1950 the forest has started to regenerate with *Pinus sylvestris* as the main component.

3.3. Palaeohydrology of the mire: stable isotopes vs. testate amoebae

In this study we used two independent proxies for paleohydrology: δ^{13}C from *Sphagnum* and water table depth inferred from testate amoebae (Fig. 6). A first observation of the two curves (Fig. 7A) suggests that the two data sets show corresponding fluctuations: 1) fluctuations around AD 850, 2) a wet shift with a dry–wet swing at ca. AD 1500–1550, and 3) a decreasing water table until ca. 1970 followed by an abrupt wet shift. The direct comparison of the depth to the water table and δ^{13}C values (Fig. 7B) confirms this relationship. Even though the correlation coefficient for the whole sequence is not very high (−0.396), it is statistically significant ($p<0.01$). This correlation is not significant for the period AD 780–1000 when the range of variation in both data sets is low ($r=-0.176$, $p>0.05$), but the correlation is stronger and more significant in the later period AD 1000–2005 when the variability of both DWT and δ^{13}C values was high ($r=0.68$, $p<0.01$). The cluster of circles in the centre of the diagram represents stable hydrological conditions between AD 750 and 1000 (testate amoeba-inferred DWT: mean = 11 cm, S.D. = 1.1) that are quite typical for the 'living' peat accumulating Baltic bogs. The remaining scattered circles (with the exception of the bottom circle — one sample from the mire surface) show wet or dry shifts in the history of the mire.

4. Discussion

4.1. Development of the mire and major events: human impact vs. climate changes

Baltic raised bogs are located at the southern limit of the range of lowland raised mires in Europe and the bog vegetation is influenced by both oceanic and continental climatic influences therefore Baltic bogs should be especially valuable for climate reconstruction. From 2500 BP human impact is considered to have been the most important factor of change in the vegetation cover in Poland (Ralska-Jasiewiczowa and Latałowa, 1996). However, by contrast, pollen data show that human impact on the bog was moderate until AD 1800. In Pomerania extensive land-use changes took place in the last 200 years with massive deforestation, drainage and exploitation of the raised bogs.

During the last 1250 years of its history, Stążki mire recorded environmental changes that can be related to land-use changes as well as to climatic changes. Hydrological fluctuations appear to be the main driver of the observed ecosystem dynamics and all proxies generally agree for the more important changes (Fig. 8). Our data shows a developmental history that can be divided into five main stages of alternating wet and dry shifts and a general trend for increasing anthropogenic impact. The first part of the archive contains 250 years of continuous accumulation of *Sphagnum fuscum* peat with relatively little change. Following this period, two major dry periods were recorded in the history of Stążki mire [(I) ca. AD 1100–1500 and (II) ca. AD 1650–1900 (–2005)].

The first dry shift (ca. AD 1100–1500) is reflected in all indicators and is most likely due to climate change because the percentage of human indicators is not high during this period although this is a period when human impact became stronger in Pomerania (Latałowa, 1982; Latałowa and Tobolski, 1989). One important forest component, *Carpinus betulus*, disappeared in the upland forest around the Stążki mire and was replaced by *Fagus*. Latałowa and Pędziszewska (2003) reported that between AD 1200 and AD 1700 hornbeam forests extensively covered the morainic plateau of eastern and central Pomerania near the Baltic shore. Our data agree with Latałowa (1982) who observed an abrupt expansion of *Fagus* in the early Medieval period. In the surroundings of Stążki mire the shift from *Capinus* to *Fagus* began ca AD 1200 shortly after the beginning of the dry period. Since there is no evidence of forest clearances in the direct surroundings of Stążki mire climatic change remains the most likely explanation. The lack of charred macrofossils suggests that no local fires occurred. Comparable dry shifts during the climatic optimum of the Medieval Warm Period were recorded elsewhere in Europe (Fagan, 2000; Bertrand et al., 2002; Tiljander et al., 2003; Cook et al., 2004; Jones and Mann, 2004; van der Linden and van Geel, 2006; Weckström et al., 2006) and were related to solar activity (Jirikowic and Damon, 1994; Chambers et al., 1999).

We interpret the dominance of *Eriophorum vaginatum* remains in the peat of this period as an indication of hydrological disturbance. In the region, this species is found in laggs of kettle-hole mires located on sandy out-wash plains in Pomerania, a habitat of considerably fluctuating water tables. Among testate amoebae one particular taxon — *Arcella discoides* — is associated to similar conditions with association with *E. vaginatum*. This species is also found in the uniform assemblages in laggs of kettle-hole mires in Pomerania (Lamentowicz and Mitchell, 2005a). *Arcella discoides* was excluded from the training set because its response to water table depth could not be modelled well and the peculiar ecology of this species caused inconsistency in the reconstruction (higher bias). Nevertheless, *A. discoides* remains an important qualitative indicator of water table fluctuations. The precise ecological requirement of this species therefore deserves more attention.

From ca. AD 1500 to 1650 all proxies indicate wetter conditions. The beginning of this shift occurred during the Little Ice Age and coincides well with data from European lakes (Lotter and Bigler, 2000; Magny, 2004; Blass et al., 2005) and mires (Chiverrell, 2001; Mauquoy et al., 2002a,b). One study from Poland based on stable carbon isotopes also shows a wet event at that time (Skrzypek and Jędrysek, 2000). Polish Baltic bogs development has possibly responded to similar climate changes as Estonian bogs (Sillasoo et al., 2007), where Westerlies also cause wetter conditions while continental climatic influences bring warmer and drier conditions.

The second period of low peat accumulation (ca. AD 1650–1900 (–2005)) can be related to local peat exploitation of the mire that decreased the water table level. Testate amoebae indicate drier conditions starting before AD 1600. The end of the Little Ice Age in Europe is dated to ca. AD 1800–1850 (Grove, 1988; Jones and Mann, 2004) and testate amoebae indicate a further trend to drier conditions at that time. Most probably, mainly the South-Eastern part was exploited from ca AD 1800. This caused a significant water table decrease about ca 150 years. This process was enhanced by ditch digging at the beginning of 20th century. According to information from local people the first drainage was done before World War I and the peatland was still locally exploited in AD 1960 in the southern part as documented by the presence of exploitation ponds (Szafrański, 1961).

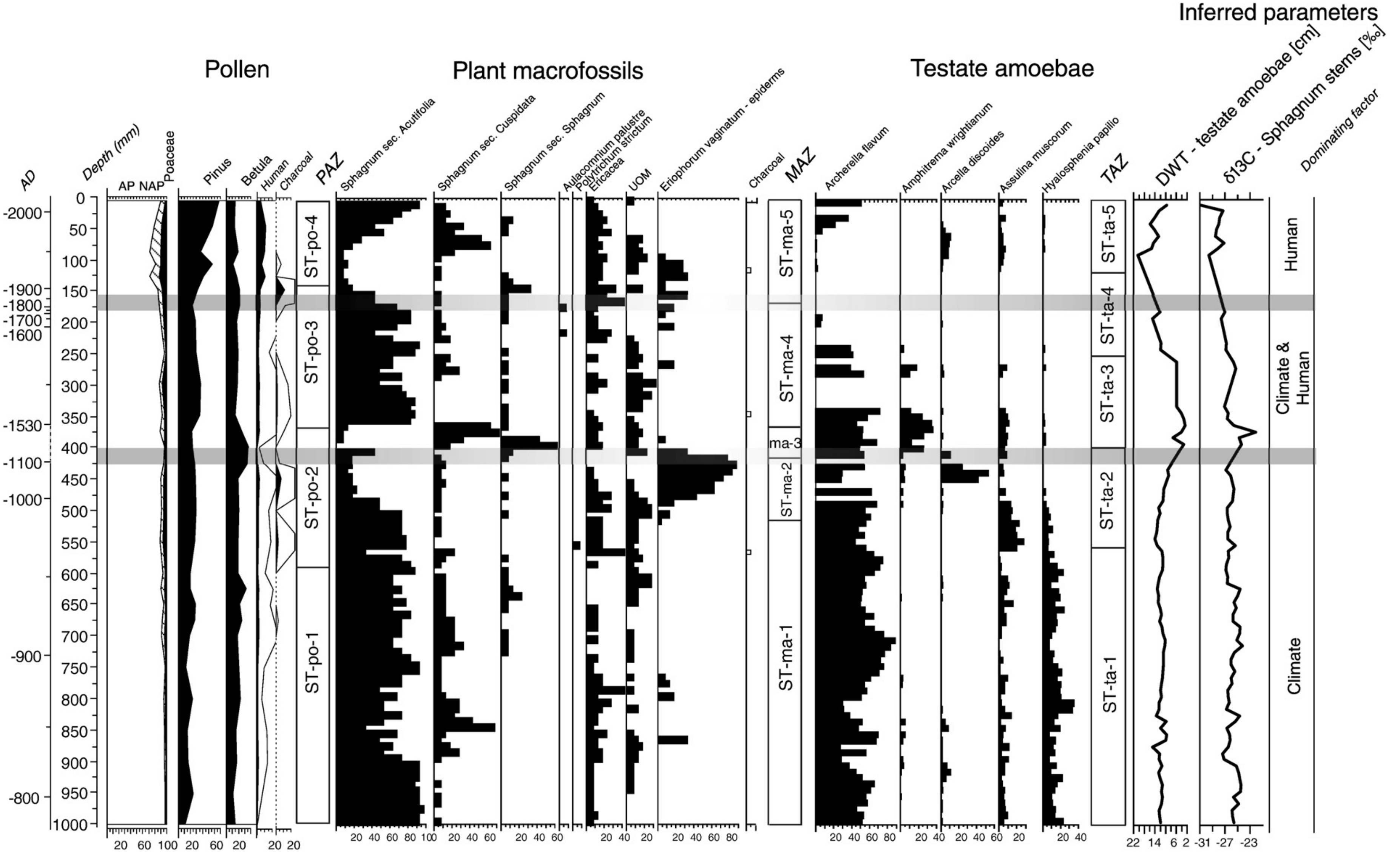

Fig. 8. Composite diagram presenting selected indicators of environmental change for the last 1200 years together with the stable carbon isotope data (δ^{13}C) and the depth to the water table inferred from subfossil testate amoebae.

Dendrochronological analysis of pine trees growing on the mire surface (Fig. 5) further showed that the current pine population on the mire became established by ca AD 1820. But taking into account the likely very slow tree growth to the height of 130 cm (+10–15 cm corresponding to peat accumulation since this date), pine colonisation might have started in the 18th or possibly even 17th century. Pine expansion therefore seems to be directly related with substantial anthropogenic decrease of the water table as was also observed in raised bogs of the Swiss Jura Mountains (Frelechoux et al., 2000a,b). Because the dynamics of pine growth is strongly influenced by drainage, we cannot draw palaeoclimatic conclusions from the tree rings.

The overlying non-compacted part of the acrotelm (accumulated since ca AD 1950) recorded the abandonment of exploitation and filling up of ditches reflected in the record of *Arcella discoides* and later *Archerella flavum* and by *Sphagnum* sec. Cuspidata. Currently the mire surface is covered with *Calluna vulgaris* and scattered pines indicating relatively dry conditions, but the declining growth rate of pine trees indicates that conditions are getting wetter in not disturbed part of the the bog.

Two of our broader goals were to determine if Pomeranian peatlands can be used to infer recent climatic history and if so from which point in time human impact caused the peatlands to become unsuitable for palaeoclimatic reconstruct. Our data show 1) that before AD 1800 both human and climatic signals were recorded and 2) that the effects of local peat exploitation and drainage dominate the palaeoecological signal from ca AD 1800 onwards. Similarly, a recent dendroecological study (Cedro and Lamentowicz, in press) revealed that there is no link between tree ring widths and climatic factors since the establishment of pine on the surface of the bog. Another study on a kettle-hole mire in southern Pomerania showed that this apparently pristine small mire surrounded by forests was also disturbed by human activities (Lamentowicz, 2005; Lamentowicz et al., 2007). Consequently, there are two main limitations to palaeoclimatic reconstruction associated with palaeoecological studies of peatlands in northern Poland: 1) artificial water table decrease caused by peat digging and drainage in ombrotrophic Baltic bogs, and 2) land-use changes (e.g. deforestation, afforestation and agriculture) in the catchment area of peatlands. As we continue to study additional sites we hope to disentangle the effects of human impact and climatic change in the mire.

4.2. Disappearance of Sphagnum fuscum in Pomerania, an analogue to the disappearance of S. austinii (S. imbricatum) in Britain?

Sphagnum fuscum declined in Stążki mire twice at ca AD 1000 and ca AD 1800. The first decline, which took place during a dry phase that we interpret as climate-driven, is synchronous with the extinction of *Sphagnum austinii* in the UK between cal. AD 1030–1400, which was interpreted as due to inter-specific competition between *Sphagnum* species during the 'Early Medieval Warm Period' and the 'Little Ice Age' (Mauquoy and Barber, 1999). *Sphagnum fuscum* has not recovered after the second decline at ca. AD 1800 in agreement with other data from Poland (Jasnowski, 1962). The most likely cause for this decline is a lowering of the water table due to direct human impact (e.g. local peat cutting, drainage). Around 1950, *S. fuscum* was replaced by other *Sphagnum* species (e.g. *S. capillifolum*) of Acutifolia section that tolerate well low water table.

Although peat exploitation was still taking place in the southern fringe of the mire around ca. 1960 (Szafrański, 1961), this may not have had a very significant impact at the coring site. It therefore remains possible that climate change was an additional cause for this disappearance. If climate change indeed played a role, it would have driven to extinction a species that had already became rare due to direct impact on mire. A positive feedback mechanism involving pine trees might also have been involved: It is also likely that drier conditions on the bog were in part amplified by evapotranspiration from the increasing cover of pine trees on the bog, as was observed in peatlands in the Jura Mountains (Mitchell et al., 2001; Freléchoux et al., 2003). Another study of a Baltic bog (Słowińskie Błoto) located 100 km east from Stążki showed a similar dry shift and associated *S. fuscum* extinction (Lamentowicz et al., in preparation). However, Herbichowa (1998) observed that this species had already declined already 500 years ago and is now extinct in Pomeranian Baltic bogs, suggesting an earlier significant human impact in this area. Interestingly, this event again parallels the extinction of *Sphagnum austinii* (Sull. ex Aust.) (=*Sphagnum imbricatum* Hornsch. ex Russow ssp. *austinii* (Sull.) Flatberg) across Wales that was dated to ca 1840 (Hughes et al., 2007).

4.3. Palaeohydrology of the mire: stable isotopes vs. testate amoebae

This study is the first to compare δ^{13}C values from *Sphagnum* and water table depth inferred from testate amoebae. Because the leaves of *Sphagnum* mosses do not contain stomata the isotopic discrimination of carbon is mainly controlled by the thickness of the water film on the leaves. The stable carbon isotope data obtained from *Sphagnum* stems is therefore a proxy for moisture changes at the surface. Higher/less negative values of δ^{13}C indicate higher availability of water for peatmosses (Rice and Giles, 1996; Ménot-Combes et al., 2004; Loader et al., 2007) and hence higher precipitation (or at least a more positive balance between precipitation and evaporation). As testate amoebae also reflect surface wetness these two indicators should yield the same signal. This is indeed the case and especially for the period of greatest fluctuations in both data sest (Fig. 7A and B). The similarity in the patterns of both proxies provides an independent confirmation for the value of each of them. Nevertheless, the correlation is not perfect and this can be due to 1) the imperfect DWT reconstruction from testate amoebae and/or 2) the imperfect relationship between DWT and δ^{13}C of *Sphagnum*, and/or 3) the fact that the thickness of the water film is more directly related to surface moisture than to water table depth.

Acknowledgements

The study was financed with a grant of the Polish Ministry of Science and Higher Education for the project *Climatic changes in Pomerania (N Poland) in the last millennium based on multiproxy high-resolution studies* (No. 2P04G03228) (Principal Investigator — M. Lamentowicz). Financial support is also acknowledged from Swiss NSF (project no. 205321-109709/1 to E. Mitchell). This work was carried out in collaboration with the EU-funded Project MILLENNIUM (017008). Stable isotopes analyses were supported by EC through Marie Curie Actions ToK grant "ATIS" MTKD-CT-2005-029642. We thank Kazimierz Tobolski for the fruitful discussions, Milena Obremska for pollen diagram construction, Łukasz Lamentowicz for help in the field and during sample preparation, and Bas van Geel and an anonymous reviewer from useful comments on the manuscript.

References

Andreev, A.A., Tarasov, P.E., Siegert, C., Ebel, T., Klimanov, V.A., Melles, M., Bobrov, A.A., Dereviagin, A.Y., Lubinski, D.J., Hubberten, H.-W., 2003. Late Pleistocene and Holocene vegetation and climate on the northern Taymyr Peninsula, Arctic Russia. Boreas 32, 484–505.

Appleby, P.G., 2001. Chronostratigraphic techniques in recent sediments. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Changes Using Lake Sediments. Kluwer Academic Publishers, Dordrecht, pp. 171–203.

Barber, K.E., Langdon, P.G., 2007. What drives the peat-based palaeoclimate record? A critical test using multi-proxy climate records from northern Britain. Quaternary Science Reviews 26, 3318–3327.

Behre, K.-E., Hölzer, A., Lemdahl, G., 2005. Botanical macro-remains and insects from the Eemian and Weichselian site of Oerel (northwest Germany) and their evidence for the history of climate. Vegetation History and Archaeobotany 14, 31–53.

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (Ed.), Handbook of Holocene Paleoecology and Paleohydrology. Wiley & Sons Ltd., Chichester-Toronto, pp. 455–484.

Bertrand, C., Loutre, M.-F., Crucifix, M., Berger, A., 2002. Climate of the last millennium: a sensitivity study. Tellus A 54, 221–244.

Blaauw, M., van Geel, B., van der Plicht, J., 2004. Solar forcing of climatic change during the mid-Holocene: indications from raised bogs in The Netherlands. The Holocene 14, 35–44.

Blass, A., Anselmetti, F.S., Grosjean, M., Sturm, M., 2005. The last 1300 years of environmental history recorded in the sediments of Lake Sils (Engadine, Switzerland). Eclogae geol. Helv. 98, 319–332.

Blundell, A., Barber, K., 2005. A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. Quaternary Science Reviews 24, 1261–1277.

Booth, R.K., 2007. Testate amoebae as proxies for mean annual water-table depth in *Sphagnum*-dominated peatlands of North America. Journal of Quaternary Science 23, 43–57.

Booth, R.K., Notaro, M., Jackson, S.T., Kutzbach, J.E., 2006. Widespread drought episodes in the western Great Lakes region during the past 2000 years: geographic extent and potential mechanisms. Earth and Planetary Science Letters 242, 415–427.

Buttler, A., Warner, B.G., Grosvernier, P., Yvan, M., 1996. Vertical patterns of testate amoebae (Protozoa: Rhizopoda) and peat-forming vegetation on cutover bogs in the Jura, Switzerland. New Phytologist 134, 371–382.

Cedro, A. and Lamentowicz, M., in press. Last hundred years dendroecology of Scots pine Pinus sylvestris L. on a raised bog in northern Poland: human impact and hydrological changes. Baltic Forestry.

Chambers, F.M., Ogle, M.I., Blackford, J.J., 1999. Palaeoenvironmental evidence for solar forcing of Holocene climate: linkages to solar science. Progress in Physical Geography 23, 181–204.

Charman, D.J., 1999. Testate amoebae and the fossil record: issues in biodiversity. Journal of Biogeography 26, 89–96.

Charman, D.J., 2002. Peatlands and Environmental Change. John Wiley & Sons, Chichester.

Charman, D., Blundell, A., 2007. A new European testate amoebae transfer function for palaeohydrological reconstruction on ombrotrophic peatlands. Journal of Quaternary Science 22, 209–221.

Charman, D.J., Brown, A.D., Hendon, D., Karofeld, E., 2004. Testing the relationship between Holocene peatland palaeoclimate reconstructions and instrumental data at two European sites. Quaternary Science Reviews 23, 137–143.

Chiverrell, R.C., 2001. A proxy record of late Holocene climate change from May Moss, northeast England. Journal of Quarternary Science 16, 9–29.

Cook, E.R., Esper, J., D'Arrigo, R.D., 2004. Extra-tropical Northern Hemisphere land temperature variability over the past 1000 years. Quaternary Science Reviews 23, 2063–2074.

Crowley, P.H., 1992. Resampling methods for data analysis in computation-intensive ecology and evolution. Annual Review of Ecology and Systematics 23, 405–447.

Esper, J., Wilson, R.J.S., Frank, D.C., Moberg, A., Wanner, H., Luterbacher, J., 2005. Climate: past ranges and future changes. Quaternary Science Reviews 24, 2164–2166.

Faegri, K., Iversen, J., 1989. Texbook of Pollen Analysis. John Wiley & Sons, Ltd.

Fagan, B., 2000. The Little Ice Age. Basic Books, New York.

Flynn, W.W., 1968. The determination of low-levels of polonium-210 in environmental materials. Analytica Chemica Acta 43, 221–227.

Frelechoux, F., Buttler, A., Gillet, F., 2000a. Dynamics of bog-pine-dominated mires in the Jura Mountains, Switzerland: a tentative scheme based on synusial phytosociology. Folia Geobotanica 35, 273–288.

Freléchoux, F., Buttler, A., Schweingruber, F.H., Gobat, J., 2000b. Stand structure, invasion and growth dynamic of bog pine (*Pinus uncinata* var. *rotundata*) in relation to peat cutting and drainage in the Jura Mountains, Switzerland. Canadian Journal of Forest Research 30, 1114–1126.

Freléchoux, F., Buttler, A., Gillet, F., Gobat, J.M., Schweingruber, F.H., 2003. Succession from bog pine (*Pinus uncinata* var. *rotundata*) to Norway spruce (*Picea abies*) stands in relation to anthropic factors in Les Saignolis bog, Jura Mountains, Switzerland. Annals of Forest Science 60, 347–356.

Goslar, T., Czernik, J., Goslar, E., 2004. Low-energy 14C AMS in Poznań Radiocarbon Laboratory. Nuclear Instruments and Methods B, 5–11.

Goslar, T., Engstrom, D.R., Van der Knaap, W.O., 2005. Comparison of AMS ^{14}C and ^{210}Pb dates of a modern peat profile. 10th International Conference on Accelerator Mass Spectrometry. Berkley, California, 38 pp.

Grimm, E.C., 1987. CONISS: a fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13, 13–35.

Grimm, E.C., 1992. TILIA/TILIA Graph. Version 1.2. Illinois State Museum. Springfield, Illinois.

Grosse-Brauckmann, G., 1972. Über pflanzliche Makrofossilien mitteleuropäischer Torfe. I. Gewebereste krautiger Pflanzen und ihre Merkmale. Telma 2, 19–55.

Grosse-Brauckmann, G., 1974. Über pflanzliche Makrofossilien mitteleuropäischer Torfe. II. Weitere Reste (Früchte und Samen, Moose u. a.) und ihre Bestimmungsmöglichkeiten. Telma 4, 51–117.

Grove, J.M., 1988. The Little Ice Age. Routledge.

Gumiński, R., 1948. Próba wydzielenia dzielnic rolniczo-klimatycznych w Polsce. Przegląd Meteorologiczno-Hydrologicznych, 1.

Hall, V.A., Mauquoy, D., 2005. Tephra-dated climate- and human-impact studies during the last 1500 years from a raised bog in central Ireland. The Holocene 15, 1086–1093.

Hendon, D., Charman, D.J., 1997. The preparation of testate amoebae (Protozoa: Rhizopoda) samples from peat. The Holocene 7, 199–205.

Herbichowa, M., 1997. Rozwój, współczesna roślinność oraz problemy ochrony torfowisk bałtyckich. In: Fałtynowicz, W., Latałowa, M., Szmeja, J. (Eds.), Dynamika i ochrona roślinności Pomorza. Bogucki Wydawnictwo Naukowe, Gdańsk-Poznań, pp. 125–134.

Herbichowa, M., 1998. Ekologiczne studium rozwoju torfowisk wysokich właściwych na przykładzie wybranych obiektów z środkowej części Pobrzeża Bałtyckiego. Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk.

Holmes, R.J., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. 43, 69–78.

Holmes, R.J., 1994. Dendrochronology Program Library. Users Manual. University of Arizona, Tucson.

Hughes, P.D.M., Lomas-Clarke, S.H., Schulz, J., Jones, P., 2007. The declining quality of late-Holocene ombrotrophic communities and the loss of *Sphagnum austinii* (Sull. ex Aust.) on raised bogs in Wales. The Holocene 17, 613–625.

Jasnowski, M., 1962. Budowa i roślinność torfowisk Pomorza Szczecińskiego. Szczec. Tow. Przyj. Nauk, Wydz. Nauk Rol-Przyr., 10, 1–339.

Jasnowski, M., Jasnowska, J., Markowski, S., 1968. Ginące torfowiska wysokie i przejściowe w pasie nadbałtyckim Polski. Ochrona Przyrody 33, 69–124.

Jirikowic, J.L., Damon, P.E., 1994. The medieval solar activity maximum. Climatic Change 26, 309–316.

Jones, P.D., Mann, M.E., 2004. Climate over past millennia. Rev. Geophys. 42 pp.

Juggins, S., 2003. C2 User Guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation. University of Newcastle, Newcastle upon Tyne, UK.

Kalis, A.J., Merkt, J., Wunderlich, J., 2003. Environmental changes during the Holocene climatic optimum in central Europe — human impact and natural causes. Quaternary Science Reviews 22, 33–79.

Katz, N.J., Katz, S.V. and Kipiani, M.G., 1965. Atlas opredelitel' plodov i semyan vstretchayushchikhsya v chetvertinnykh otuocheniyakh SSSR. Izd. Nauka, Moskva.

Katz, N.J., Katz, S.V., Skobiejeva, E.I., 1977. Atlas rastitielnych ostatkov v torfach. Nedra, Moskva.

Kondracki, J., 1998. Regional Geography of Poland (in Polish). PWN, Warszawa.

Lamentowicz, M., 2004. Origin and development of natural and seminatural peatlands in Tuchola Forest Inspectorate. Department of Biogeography and Palaeoecology. PhD thesis. Adam Mickiewicz University (in Polish), Poznań.

Lamentowicz, M., 2005. Origin and development of natural and seminatural peatlands in Tuchola Forest Inspectorate (in Polish). Prace Zakładu Biogeografii i Paleoekologii UAM Poznań, vol. 5. Bogucki Wydawnictwo Naukowe, Poznań.

Lamentowicz, M., Mitchell, E.A.D., 2005a. The ecology of testate amoebae (Protists) in *Sphagnum* in north-western Poland in relation to peatland ecology. Microbial Ecology 50, 48–63.

Lamentowicz, M., Mitchell, E.A.D., 2005b. Testate Amoebae (Protists) as Palaeoenvironmental Indicators in Peatlands. Special Papers, vol. 16. Polish Geological Institute.

Lamentowicz, M., Tobolski, K., Mitchell, E.A.D., 2007. Palaeoecological evidence for anthropogenic acidification of a kettle-hole peatland in northern Poland. The Holocene 17, 1185–1196.

Lamentowicz, M., Obremska, M., Mitchell, E.A.D., in press. Autogenic succession, land-use change, and climatic influences on the Holocene development of a kettle hole mire in Northern Poland (Northern Poland). Review of Palaeobotany & Palynology. doi:10.1016/j.revpalbo.2008.01.009 printed online.

Lamentowicz, M., Milecka, K., Gałka, M., Cedro, A., Pawlyta, J., Piotrowska, N., Lamentowicz, Ł. and van der Knaap, W.O., in preparation. Climatic change and human disturbance in Pomerania (N Poland) since AD 800: a multi-proxy high resolution study from ombrotrophic mire.

Latałowa, M., 1982. Major aspects of the vegetational history in the eastern Baltic coastal zone of Poland. Acta Palaeobotanica 22, 47–63.

Latałowa, M., Tobolski, K., 1989. Type region P-u: Baltic shore. Acta Palaeobotanica 29.

Latałowa, M., Pędziszewska, A., 2003. Zbiorowiska leśne z udziałem grabu (*Carpinus betulus*)i buka (*Fagus sylvatica*) na Wysoczyźnie Gdańskiej w późnym Holocenie. Wstępne wyniki badań. In: Gołębiewski, R. (Ed.), Ewolucja pojezierzy i pobrzeży południowobałtyckich. Fundacja Rozwoju Uniwesytetu Gdańskiego, Gdańsk, pp. 95–100.

Lavoie, C., Zimmermann, C., Pellerin, S., 2001. Peatland restoration in southern Quebec (Canada): a paleoecological perspective. Ecoscience 8, 247–258.

Loader, N.J., McCarroll, D., Knaap, W.O.v.d., Robertson, I., Gagen, M., 2007. Characterizing carbon isotopic variability in *Sphagnum*. The Holocene 17, 403–410.

Lotter, A.F., Bigler, C., 2000. Do diatoms in the Swiss Alps reflect the length of ice-cover? Aquatic Sciences 62, 125–141.

Magny, M., 2004. Holocene climate variability as reflectedby mid-European lake-level fluctuations andits probable impact on prehistoric human settlements. Quaternary International 113, 65–79.

Mauquoy, D., Barber, K.E., 1999. Evidence for climatic deteriorations associated with the decline of *Sphagnum* imbricatum Hornsch. ex Russ. in six ombrotrophic mires from northern England and the Scottish Borders. The Holocene 9, 423–437.

Mauquoy, D., Engelkes, T., Groot, M.H.M., Markesteijn, F., Oudejans, M.G., van der Plicht, J., Van Geel, B., 2002a. High-resolution records of late-Holocene climate change and carbon accumulation in north-west European ombrotrophic peat bogs. Palaeogeography, Palaeoclimatology, Palaeoecology 186, 275–310.

Mauquoy, D., van Geel, B., Blaauw, M., van der Plicht, J., 2002b. Evidence from northwest European bogs shows ‘Little Ice Age’ climatic changes driven by variations in solar activity. The Holocene 12, 1–6.

Ménot-Combes, G., Burns, S.J., 2001. Carbon isotopes in ombrogenic peat bog plants as climatic indicators: calibration from an altitudinal transect in Switzerland. Organic Geochemistry 32, 233–245.

Ménot-Combes, G., Combes, P.-P., Burns, Stephen J., 2004. Climatic information from δ13C in plants by combining statistical and mechanistic approaches. The Holocene 14, 931–939.

Mitchell, E.A.D., van der Knaap, W.O., Leeuwen, J.F.N., Buttler, A., Warner, B.G., Gobat, J.M., 2001. The palaeoecological history of the Praz-Rodet bog (Swiss Jura) based on pollen, plant macrofossils and testate amoebae (Protozoa). The Holocene 11, 65–80.

Mitchell, E., Charman, D., Warner, B., in press. Testate amoebae analysis in ecological and paleoecological studies of wetlands: past, present and future. Biodiversity and Conservation. doi:10.1007/s10531-007-9221-3.

Nilsson, M., Klarqvist, M., Bohlin, E., Possnert, G., 2001. Variation in ^{14}C age of macrofossils and different fractions of minute peat samples dated by AMS. The Holocene 11, 579–586.

Pawlaczyk, P., Herbichowa, M., Stańko, R., 2005. Ochrona torfowisk bałtyckich. Wydawnictwo Klubu Przyrodników, Świebodzin.

Price, G.D., McKenzie, J.E., Pilcher, J.R., Hoper, S.T., 1997. Carbon-isotope variation in *Sphagnum* from hummock-hollow complexes: implications for Holocene climate reconstruction. The Holocene 7, 229–233.

Ralska-Jasiewiczowa, M., Latałowa, M., 1996. Poland. In: Berglund, B.E., Birks, H.J.B., Ralska-Jasiewiczowa, M., WrightJr. Jr., H.E. (Eds.), Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley, Chichester, pp. 403–472.

Räsänen, S., Froyd, C., Goslar, T., 2007. The impact of tourism and reindeer herding on forest vegetation at Saariselka, Finnish Lapland: a pollen anałytical study of a high resolution peat profile. The Holocene 17, 447–456.

Rice, S.K., Giles, L., 1996. The influence of water content and leaf anatomy on carbon isotope discrimination and photosynthesis in *Sphagnum*. Plant, Cell & Environment 19, 118–124.

Rydin, H., Jeglum, J., 2006. The Biology of Peatlands. Oxford University Press.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walkerk, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.

Schoning, K., Charman, D.J., Wastegård, S., 2005. Reconstructed water tables from two ombrotrophic mires in eastern central Sweden compared with instrumental meteorological data. The Holocene 15, 111–118.

Sillasoo, Ü., Mauquoy, D., Blundell, A., Charman, D., Blaauw, M., Daniell, J.R.G., Toms, P., Newberry, J., Chambers, F.M., Karofeld, E., 2007. Peat multi-proxy data from Männikjärve bog as indicators of late Holocene climate changes in Estonia. Boreas 36, 20–37.

Skrzypek, G., Jędrysek, M.O., 2000. Climatic variation in the last millennium in Poland: δ^{13}C peat profiles. In: Obrębska-Starkel, B. (Ed.), Reconstructions of climate and is modelling. Institute of Geography of the Jagiellonian University, Cracov, pp. 131–136.

Skrzypek, G., Jędrysek, M.-O., 2004. ^{13}C/^{12}C Ratio in Peat Cores: Record of Past Climates.

Szafrański, F., 1961. Polodowcowa historia lasów obszaru na północ od Wysoczyzny Staniszewskiej. Badania Fizjograficzne nad Polską Zachodni 8, 91–131.

Tarasov, P.E., Brovkin, V., Wagner, M., 2005. What drives the climate: man or nature? PAGES News 13, 24–25.

Tiljander, M., Saarnisto, M., Ojala, A.E.K., Saarinen, T., 2003. A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajarvi, central Finland. Boreas 26, 566–577.

Tobolski, K., 1987. Holocene vegetational development based on the Kluki Reference Site in the Gardno-Łeba Plain. Acta Paleobotanica 27, 179–222.

Tobolski, K., 2000. Przewodnik do oznaczania torfów i osadów jeziornych. PWN, Warszawa.

Tobolski, K., 2003. Torfowiska, na przykładzie Ziemi Świeckiej. Towarzystwo Przyjaciół Dolnej Wisły, Świecie.

Turetsky, M.R., Manning, S.W., Wieder, R.K., 2004. Dating recent peat deposits. Wetlands 24, 324–356.

Väliranta, M., Korhola, A., Seppä, H., Tuittila, E.-S., Sarmaja-Korjonen, K., Laine, J., Alm, J., 2007. High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitative approach. The Holocene 17, 1093–1107.

van der Linden, M., van Geel, B., 2006. Late Holocene climate change and human impact recorded in a south Swedish ombrotrophic peat bog. Palaeogeography, Palaeoclimatology, Palaeoecology 240, 649–667.

Wardenaar, E.C.P., 1987. A new hand tool for cutting peat profiles. Canadian Journal of Botany 65, 1772–1773.

Warner, B.G., Charman, D.J., 1994. Holocene changes on a peatland in northwestern Ontario based on fossil testate amoebae (Protozoa) analysis. Boreas 23, 270–279.

Weckström, J., Korhola, A., Erästö, P., Holmström, L., 2006. Temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. Quaternary Research 66, 78–86.

Zielski, A., Krąpiec, M., 2004. Dendrochronologia. PWN, Warszawa.

Żurek, S., 1993. Zmiany paleohydrologiczne w mokradłach. Przegląd Geograficzny 64, 75–95.

Żurek, S., Pazdur, A., 1999. Zapis zmian paleohydrologicznych w rozwoju torfowisk Polski. W: Geochronologia górnego czwartorzędu Polski. In: Pazdur, A. (Ed.), Geochronologia górnego czwartorzędu Polski, Gliwice, pp. 215–228.

Żurek, S., Michczyńska, D., Pazdur, A., 2002. Time record of palaeohydrological changes in the development of mires during the late glacial and holocene, north Podlasie lowland and Holy Cross mts. Geochronometria 21, 109–118.