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CLIMATE CHANGE AND HUMAN IMPACT IN THE SOUTHERN BALTIC DURING THE LAST MILLENNIUM RECONSTRUCTED FROM AN OMBROTROPHIC BOG ARCHIVE

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Abstract

We present the last millennium of history of a peatland located in northern Poland. Our results are based on two replicate monoliths taken from a Baltic raised bog. We applied a high-resolution approach and radiocarbon dating to the peat material to obtain a detailed palaeoenvironmental reconstruction. To reconstruct past peatland moisture, we used three proxies: testate amoebae, plant macrofossils and pollen. Despite different peat accumulation and extensive hiatus in the formerly studied core, both monoliths show a similar pattern of changes. However, the core from this study provides us with more detailed data on *S. fuscum* disappearance which correlates well with the data from the other Baltic bog, Słowińskie Błoto. Our research shows that pristine Baltic bogs can be dated to AD 1350. Słowińskie Błoto palaeohydrology confirms AD 1300 as the beginning of the hydrological disturbance. In the case of the Stążki and Słowińskie Błoto bogs, the Little Ice Age (LIA) is recorded between AD 1500 and AD 1800. However, this climatic change might have been blurred by human impact. In the case of the Baltic bogs, their reference virgin state can be dated to AD 1200. After this date, we observed increasing human impact and climatic instability connected with the LIA. However, between AD 1800 and 1900, bogs were wet, most possibly due to climatic forcing. This fact suggests that despite human impact, recent peat deposits can still reflect climate. Our research provided information related to the time of existence, location and characteristics of the natural/pristine state. High-resolution peatland palaeoecology is crucial for restoration activities, e.g., rewetting and environmental management. The palaeohydrological context (supported by other proxies) of the last 1000 years provides a reliable answer to the question: 'To rewet or not to rewet?'

Key words: Baltic bog; last millennium; multi-proxy; Poland; peatlands; raised bog

INTRODUCTION

A recent effort in the study of past global changes is reconstructing recent climatic change with the highest possible precision. Many different archives (*e.g.* tree rings, lakes, ice cores) are being used in high resolution to infer any palaeoclimatic signal (Charman 2007, McCarroll 2010). Tree rings and laminated sediments are very precise sources of the palaeoclimatic signal; however, each proxy has its pros and cons. By using a wide array of archives, we can obtain a fuller picture of past change.

Diverse scientific consortia (*e.g.* MILLENNIUM) have been intensively studying past change. However, there are also many researchers who are focused on modern processes (Dise 2010). Understanding modern ecosystems is crucial to effective quantitative reconstructions. Furthermore, experimental investigations provide a better look at ecosystem functioning. Consequently, if we want to understand modern ecosystems better, we should look into the past.

Peatlands are very important archives of past change. They are a source of information about past hydrological conditions and carbon storage. Peatlands stored *ca.* one-third of the atmospheric carbon in the Holocene period (Frolking, Roulet 2007, Gorham 1991, Turunen *et al.* 2002). Most of the Holocene peatlands (and other wetlands) remained intact.

Two hundred years ago, however, they began to be disturbed intensively. As a result, nearly all the European peatlands are disturbed (Joosten, Clarke 2002, Minayeva, Sirin 2009). Because drained and exploited peatlands are a source of carbon dioxide and their biodiversity is decreasing, they are currently being restored in different parts of the world (Erwin 2009). Palaeoenvironmental studies are a prerequisite for generating reliable conservation plans, and not many peatlands possess a high-resolution multiproxy study that could be the basis for decision-making.

Raised bogs in Eastern Europe are underused archives of climate change and human impact. Most scientific activities have concentrated on the ombrotrophic peatlands of northwestern Europe. In particular, British bogs' ecology and palaeoecology have been described very widely. However, there is not a lot of data published in peer-reviewed journals on Eastern European raised bogs. High resolution well dated multiproxy studies are particularly important to better understand high-frequency palaeoclimatic signal from the peat archive. Good chronological precision is prerequisite for the regional palaeoclimatic comparisons. Two of the sites in central Polish Pomerania possess such data for the past 1,200 years (De Vleeschouwer *et al.* 2009, Lamentowicz *et al.* 2008, Lamentowicz *et al.* 2009). Those publications partly fill the gap in the data on the last millennium of environmental change, and they are a reference for further investigations in the same peatlands and the other sites in central Polish Pomerania. Replicate coring is a reliable method of validating former interpretations (Charman *et al.* 1999, Hendon *et al.* 2001). Analysis of at least two cores can confirm or improve previous interpretations. The next step in the development of the coring network is to reconstruct regional climatic change (Blundell *et al.* 2008, Charman *et al.* 2009). Nevertheless, data from replicate multiproxy and high-resolution cores are very rare for the southern Baltic region.

Most of the Baltic raised bogs in northern Poland are protected by law, and they are also Natura 2000 sites (Herbichowa *et al.* 2007). Furthermore, they have been restored within the framework of the Life EU project (Herbichowa *et al.* 2007). However, an issue concerning reference conditions for restoring peatlands remains. For most of the raised bogs, such a long-term ecological perspective does not exist. Willis and Birks (2006) have already stressed that palaeoecological records can reduce much of the uncertainty surrounding the question of what is 'natural' and provide important guidance for long-term management and conservation. Consequently, we need such perspectives to understand the present state, and the last millennium is a key/threshold period to better understand the present state of a raised bog in the context of climate change and human impact.

In this study we want to address four research questions:

– What are the patterns of hydrological variability in Baltic bogs over the last millennium?

– What are the relative influences of human activities and climate change on these patterns?

– Can this knowledge be used for the conservation and management of Baltic bogs?

– Which reference should be used for defining restoration projects for these bogs?

STUDY SITE

We investigated a Baltic bog, Stążki (N 54° 25' 27.7''; W 18° 05' 00.2''), situated in northern Poland *ca.* 35 km from the coast. It is located on the Kashubian Lakeland on the morainic plateau (214.6 m a.s.l.) 13 km northwest of Kartuzy. The morainic plateau is slightly undulating, and there are many depressions without run-off filled with peatlands. Many of them were destroyed and transformed into meadows or forests (Szafrański 1961).

The Stążki mire has a plateau profile that is typical for ombrotrophic Baltic bogs. Elevation differences between the margin and the highest point in the mire are no more than one meter. The Stążki bog possesses characteristic features of the raised bog: it is dome-shaped with hummocks and hollows. Boundaries between the mire and the adjacent fields are very sharp, and the lagg actually transformed into meadows. The mire is located near the culmination of the moraine. In the nineteenth century, the peatland was partly exploited and drained.

The mire's vegetation is dominated by *Sphagnum fallax*, *S. magellanicum*, *Baeothryon cespitosum,* and *Eriophorum vaginatum*. *Calluna vulgaris* occurs in considerable abundance, which suggests a rather low and fluctuating groundwater table. The exploited parts of the peatland are covered by pine forest that becomes sparser in the best-preserved northeastern part of the mire. The peatland is also partly covered by the pine forest due to drainage and local peat exploitation (Cedro, Lamentowicz 2008).

According to the climatic regionalisation of Gumiński (1948), the average annual temperature is +7.7°C. January is the coldest month with an average temperature of –1.2°C, and the warmest month is July with an average temperature of +16.8°C. The vegetation season has *ca.* 200 days. The average annual precipitation for Lębork is 690 mm. In dry years, it is 422 mm (year 1964), and in very moist years, it accounts for 956 mm (year 1998). Snow cover is present up to 75 days a year; however, due to the oceanic-polar air, the timing is variable. (Data source – Institute of Meteorology and Water Management.)

METHODS

Fieldwork

Two one-metre peat monoliths were taken with a Wardenaar sampler (Wardenaar 1987). The first short core (SM1) was taken from a less-drained part of the bog located 40 m from the mire's edge. Core (SM2), already published (Lamentowicz *et al.* 2008), was retrieved from the central part of the peatland (Fig. 1.). In the laboratory, the SM2 and SM1 cores were divided into one-centimetre slices that were then split for particular analyses. The two cores were analysed with the same methodology. In this study, we present the results from core SM1.

Dating and age-depth model

Several *Sphagnum* stems from five one-centimetre thick samples were selected for radiocarbon dating, as these were shown to yield very precise dates (Nilsson *et al.* 2001). Sam-

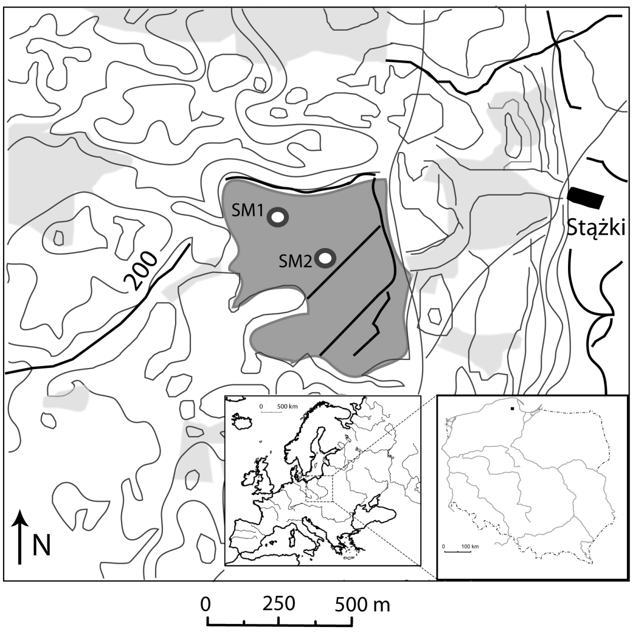

Fig. 1. Location of the study site.

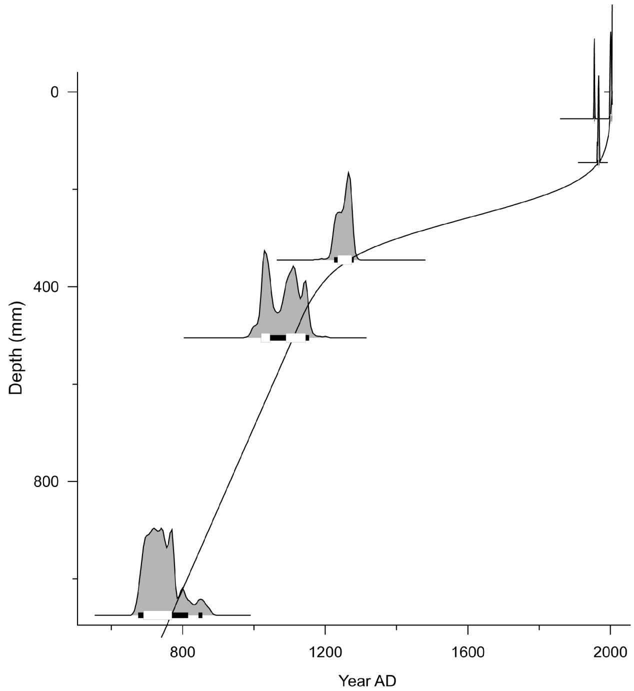

Fig. 2. Age-depth model of SM1 monolith.

ples were dated at Radiocarbon Facility of the Scottish Universities Environmental Research Centre (SUERC) (Table 1). The age-depth model (Fig. 2) was constructed as described in Lamentowicz *et al.* (2008). Calibrated ^{14}C dates were projected on the age-depth scale using the method described by Goslar *et al.* (2005). To construct the age-depth model, we used an algorithm to maximise the product of probabilities of calendar dates (a), minimised the curvature of the age-depth line (b) and (c) minimised deviations of relative changes of the slope of the age-depth line from those suggested by independent indications. As these three goals can conflict, the quantitative measures of 'a','b' and 'c' were weighted appropriately. The same algorithm has been applied for age-depth modelling of the Saariselka peat profile (Räsänen *et al.* 2007).

Pollen, plant macrofossils and testate amoebae

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, Ralska-Jasiewiczowa 1986, Faegri, 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 22x22 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. Percentage pollen diagram were produced with TILIA GRAPH (Grimm 1992).

Plant macrofossils of 4 cm^3 were analyzed 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 (Grosse-Brauckmann 1972, 1974, Katz *et al.* 1965, 1977, Tobolski 2000, Hölzer 2010). *Sphagnum* was identified to the section level.

Table 1

Radiocarbon dates of samples from the profile SM1

Depth (cm)	Laboratory code	^{14}C Age/ ^{14}C activity	68.2% Calibrated range	95.4% Calibrated range
5–6	SUERC-14693	109,31±0,48 pMC	1996AD (68.2%)	2000AD (95.4%)
14–15	SUERC-14697	158,58±0,68 pMC	1964AD (68.2%) 1970AD	1962AD (95.4%) 1973AD
34–35	SUERC-14698	765±35 BP	1225AD (68.2%) 1277AD	1212AD (95.4%) 1288AD
50–51	SUERC-14699	970±35 BP	1020AD (26.6%) 1049AD 1084AD (31.2%) 1124AD 1137AD (10.4%) 1151AD	998AD (0.7%) 1002AD 1012AD (94.7%) 1158AD
107–108	SUERC-14700	1260±35 BP	686AD (68.2%) 776AD	668AD (89.0%) 830AD 836AD (6.4%) 868AD

Bog surface wetness was quantitatively reconstructed from subfossil testate amoebae on the basis of the existing training set from northern Poland using weighted averaging model with the classical deshrinking (Lamentowicz *et al.* 2008). Sample-specific errors of reconstruction were generated with the bootstrap procedure. Easily decomposing taxa (*e.g. Euglypha*) were included in the reconstruction (Swindles, Roe 2007), however, they do not affect reconstruction performance (Mitchell *et al.* 2008). Samples taken at one-centimetre intervals were prepared from 4 cm^3 peat samples according to the sieving and back-sieving procedure described by Hendon and Charman (1997). Testate amoebae were counted to a total of 150 individuals at a magnification of 200-400 times. The identification was based on the available literature (Charman *et al.* 2000, Clarke 2003, Grospietsch 1958, Ogden, Hedley 1980).

Zonation was constructed based on a constrained cluster analysis with CONISS software (Grimm 1987). Common zones were determined qualitatively on the basis of each proxy and chosen taxa from each proxy group. Then, palaeohydrological phases were determined.

RESULTS

All applied proxies allowed for reconstructing regional vegetation change along with the local palaeohydrology to reflect climate change and human activities. Four main stages of the development were determined that reveal general environmental changes in the peatland and its surroundings during the past 1,250 years. Particular proxies are in Figure 3 (pollen), Figure 4 (plant macros) and Figure 5 (testate amoebae). Curves of the chosen taxa from the each proxy are summarised in Figure 6. Assemblage zones for each proxy are characterised in Table 2.

SM1: AD 750 – 1050 (Pristine Baltic Bog) *[SM1-po-1, SM1-po-2; SM1-m-1, SM1-m-2; SM1-ta-1, SM1-ta-2, SM1-ta3]*

During the first stage, the groundwater table was high and stable with a small dry shift *ca.* AD 940. The peat was accumulating very rapidly, which supports the inference from the proxies. Testate amoebae and plant macrofossils remain in a good agreement. Furthermore, *Carpinus betulus* and *Hyalosphenia elegans* dropped *ca.* AD 820. *Arcella discoides* suggests a minor hydrological disturbance *ca.* AD 820 that is also indicated by the decomposed peat. Until 1050, the peatland remained very wet, but it was not flooded. Pollen human indicators (also reflected in NAP increase) suggest minor local deforestation and other human activities; however, they did not take place in the direct vicinity of the peatland. *Sphagnum*, most probably *S. fuscum* (identification based on the stem leaves), a stable peat component especially from AD 980, was the main peat-forming species.

SM2: AD 1050-1350 (Instability) *[SM1-po-3; SM1-m-2, SM1-m-3; SM1-ta-4, SM1-ta-5]*

This zone starts with a dry shift indicated by *Assulina muscorum, A. seminulum* and *Bullinularia indica*. During this shift, *Archerella flavum*, *Hyalosphenia papilio* and *H. elegans* decreased. NAP increase at the beginning of SM4 suggests local clear-cutting and cultivation. However, human impact decreased and remained low throughout this zone. *Sphagnum* cf. *fuscum* still dominates; however, section *Sphagnum* appeared *ca.* AD 1100, indicating a change in the local vegetation. Over time, the dry shift changed into a wet shift before the next dry shift (*ca.* AD 1200 – shown by *Trigonopyxis arcula*) appeared. This date marks the beginning of the hydrological instability. However, it also reflects considerable change in the surrounding vegetation triggered by deforestations during the medieval period.

SM3: AD 1350-1950 (Disturbance) *[SM1-po-3, SM1-po-4; SM1-m-3, SM1-m-4; SM1-ta-5, SM1-ta-6, SM1-ta-7]*

This stage marks significant forest transformation and clear-cutting. At the beginning of the zone, *Betula*, *Alnus*, *Fagus* and *Carpinus* decline in percentage, while there is a gradual increase of *Pinus*. Plant macrofossilss revealed a substantial transformation of the local vegetation caused by the hydrological instability that can be linked to the change in the regional vegetation. The height of this dry shift is dated to AD 1730. Among testate amoebae, *Bullinularia indica* indicates very dry conditions. This species occurred alternatively with *Amphitrema wrightianum* (pool species), suggesting fluctuations in the groundwater table. Remains of *Eriophorum vaginatum* and the decomposed peat show unstable hydrological conditions. Furthermore, *Sphagnum* cf. *fuscum* declined along with the peat accumulation rates. This taxon was replaced with the *Sphagnum* sec. Sphagnum. There is an increase in human indicators and a decrease in AP (Arboreal Pollen), particularly from AD 1500 when wider deforestations took place. This period ends with the wet shift starting in AD 1800.

SM4: AD 1950-2000 (Disturbance/Regeneration) *[SM1-po-4; SM1-m-4; SM1-m-5; SM1-ta-7, SM1-ta-8]*

The final and most recent phase of peatland development shows very different patterns in the proxies. *Sphagnum* cf. *fuscum* disappeared completely, and it was replaced with *Sphagnum* sec. Cuspidata (the most possibly *Sphagnum fallax*), which can be interpreted as a rather drying and eutrophication trend with two pronounced dry shifts. Among shrubs, the Ericaceae indicate dry conditions, and *Eriophorum vaginatum* indicates hydrological instability that is confirmed by *Arcella discoides*. Furthermore, *Archerella flavum* shows a big drop and its minimum. In the upper, most recent part, testate amoebae show a trend toward regeneration as indicated by *A. flavum* and *Hyalosphenia elegans*.

DISCUSSION

Peatland history, environmental change and replicate coring

According to all curves compared in this discussion, six palaeohydrological phases were determined that also reflect the ‘naturalness’ of the bog and surrounding landscape. We compared the obtained DWT (depth to the water table) re-

Table 2

Description of biostratigraphic zones for each biotic proxy analysed

Zone	yr AD	Description
		Pollen
SM1-po-4	1380-2000	Distinctive turnover of the dominating taxa. Increased role of the cultivated plants (*Secale, Triticum, Fagopyrum*) and other human indicators such as: *Centaurea cyanus*, *Artemisia*, *Rumex* and *Plantago lanceolata. Fagus*, *Carpinus*, *Betula* and *Alnus* decreased at the bottom of the zone. *Pinus* increase in percentage along with grass pollen. Furthermore, there is distinctive increase in *Calluna* and *Cyperaceae*.
SM1-po-3	1060-1380	Decrease of *Fagus* and increase of *Betula*. Decrease of human indicators. Increase and stable *Alnus*. Decrease in *Calluna* and *Sphagnum*.
SM1-po-2	780-1060	Distinctive decrease of *Carpinus* along with increasing % of *Fagus* (distinctive exchange of species) and stable *Quercus*. Increase of *Betula* and *Pinus*. Diminishing role of *Alnus*. At the end of the zone increase of human indicators. *Sphagnum* spores more abundant, especially in the middle of the zone. Low abundance of *Alnus* pollen.
SM1-po-1	750-780	Large abundance of *Fagus* and *Carpinus*, stable *Quercus*, *Pinus* and *Betula*. Small percentage of NAP, *Ulmus* and *Tilia*. Decreasing *Alnus* along with increasing % of *Corylus*.
		Plant macrofossils
SM1-ma-5	1960-2000	*Sphagnum* sec. *Cuspidata* is dominating. *Eriophorum vaginatum* has an increase between the maximum values of *Sphagnum* sec. Cuspidata.
SM1-ma-4	1500-1960	Time when the meaning of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum* decreases rapidly. The number of *Sphagnum sec.* Sphagna grows up to maximum. *Eriophorum vaginatum* remains appear for the first time.
SM1-ma-3	1150-1500	Domination of *Sphagnum* sec. *Acutifolia* cf. *Sphagnum fuscum. Sphagnum sec.* Sphagna appearance. The phase is also characterized by almost complete lack of *Calluna vulgaris* remains.
SM1-ma-2	920-1150	Time of almost complete domination of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum.* Considerable abundance of *Andromeda polifolia.*
SM1-ma-1	800-920	Zone of *Sphagnum* sec. Acutifolia cf. *Sphagnum fuscum* domination.
		Testate amoebae
SM1-ta-8	1960-2000	Distinctive decrease in *Archerella flavum* percentage. Species richness increases. Shift from *Bullinularia indica-Archerella flavum* community to assemblages with *Euglypha* spp., *Difflugia* spp., *Physochila griseola*, *Assulina muscorum* and *Arcella discoides*.
SM1-ta-7	1780-1960	Beginning of the zone with domination of *Bullinularia indica*, *Assulina muscorum* and *A. seminulum. Archerella flavum* % is gradually decreasing; however *Amphitrema wrightianum* is also present. A pronounced turnover in testate amoebae communities begins in this zone.
SM1-ta-6	1580-1780	Disappearance of nearly all taxa. Domination of *Bullinularia indica* together with *Archerella flavum*.
SM1-ta-5	1180-1580	Abrupt fluctuations of various species. Again increase in *Trigonopyxis arcula* and *Arcella discoides*. Disappearance of both *Hyalosphenia* species. *Archerella flavum* shows instability. Appearance of *Amphitrema wrightianum* in the top part of the zone.
SM1-ta-4	1060-1180	Decreasing *Hyalosphenia papilio* and *H. elegans*. Increase and fluctuations of: *Assulina muscorum*, *A. seminulum* and *Nebela militaris*. *Trigonopyxis arcula* shows an abrupt increase at the bottom of the zone.
SM1-ta-3	880-1060	Considerable increase in *Hyalosphenia papilio*, decrease in *Archerella flavum*. Constant *Arcella catinus* and appearance of *Trigonopyxis arcula*.
SM1-ta-2	760-880	Increase in *A. flavum* (up to 80%), decrease of *H. papilio* and fluctuations of *H. elegans*. Increase of *Arcella discoides* in the top of the zone.
SM1-ta-1	750-760	Domination of *Archerella flavum* together with *Hyalosphenia elegans* and *H. papilio*. Minority of *Heleopera sphagnii* , *Arcella catinus, Nebela militaris* and *Nebela tincta*

construction to other data already published from Stążki (Lamentowicz *et al.* 2008) and Słowińskie Błoto (De Vleeschouwer *et al.* 2009, Lamentowicz *et al.* 2009). Actually, there is no another bog besides Słowińskie Błoto that could be useful for regional palaeohydrological comparisons. However, we initially applied replicate sampling to the Stążki bog (Lamentowicz *et al.* 2008), and the first core (SM2) has already been described. This core had an extensive hiatus between AD 1000 and AD 1500, which, in the end, did not allow for precise inferences. However, we detected similar patterns in the proxies in both cores. Furthermore, the data from SM1 is complementary; it improves reconstructions of vegetation change and hydrology during the last millennium.

Our study shows that a pristine Baltic bog can be dated to AD 1350 when the rapid peat accumulation of *Sphagnum* cf. *fuscum* is recorded (Figure 7, Phase 1). However, the disturbance started earlier as the gap in the testate amoebae record began in AD 1200 and suggests a lag in the response of the vegetation. Słowińskie Błoto palaeohydrology also confirms AD 1350 as the time of the hydrological disturbance (De Vleeschouwer *et al.* 2009). However, the atmospheric soil dust flux started to increase *ca.* AD 1200, which supports the signal in the testate amoebae from SM1. Both peatlands (Słowińskie Błoto and Stążki) behaved synchronously hydrologically when we take SM1 into account, while SM2 seems to be too disturbed to clearly record the transitions between peatland hydrological states.

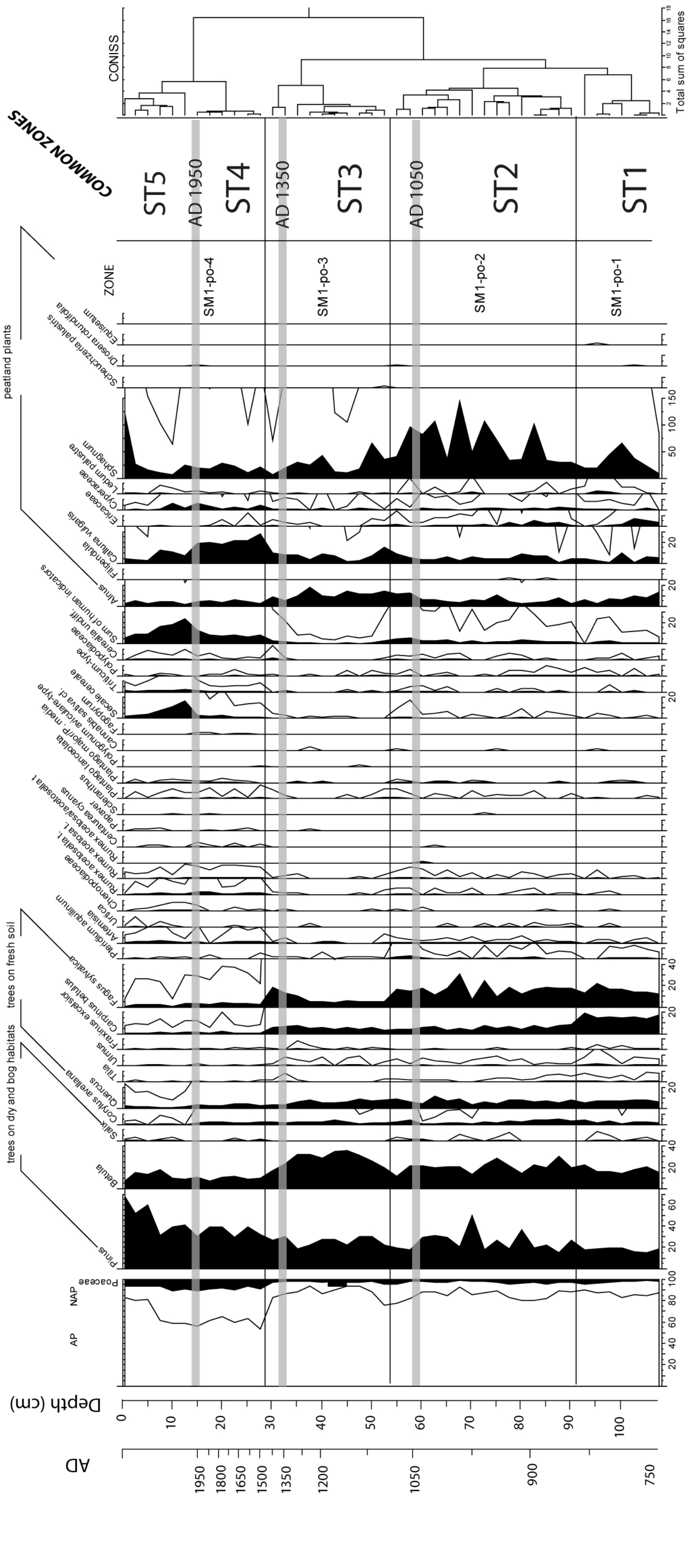

Fig. 3. Percentage pollen diagram. Dendrogram generated in CONISS is a basis for the zonation.

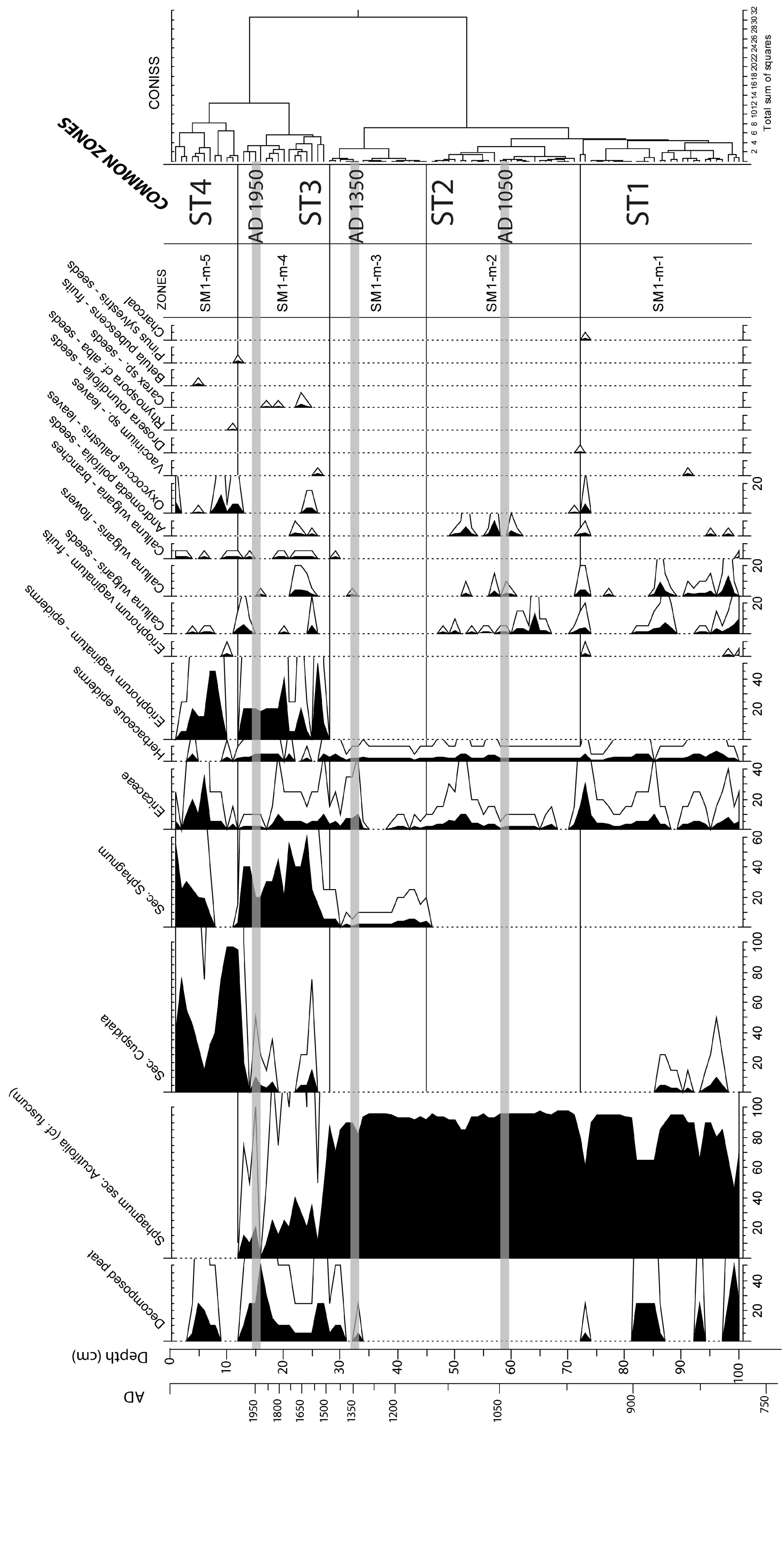

Fig. 4. Plant macrofossils diagram. Dendrogram generated in CONISS is a basis for the zonation.

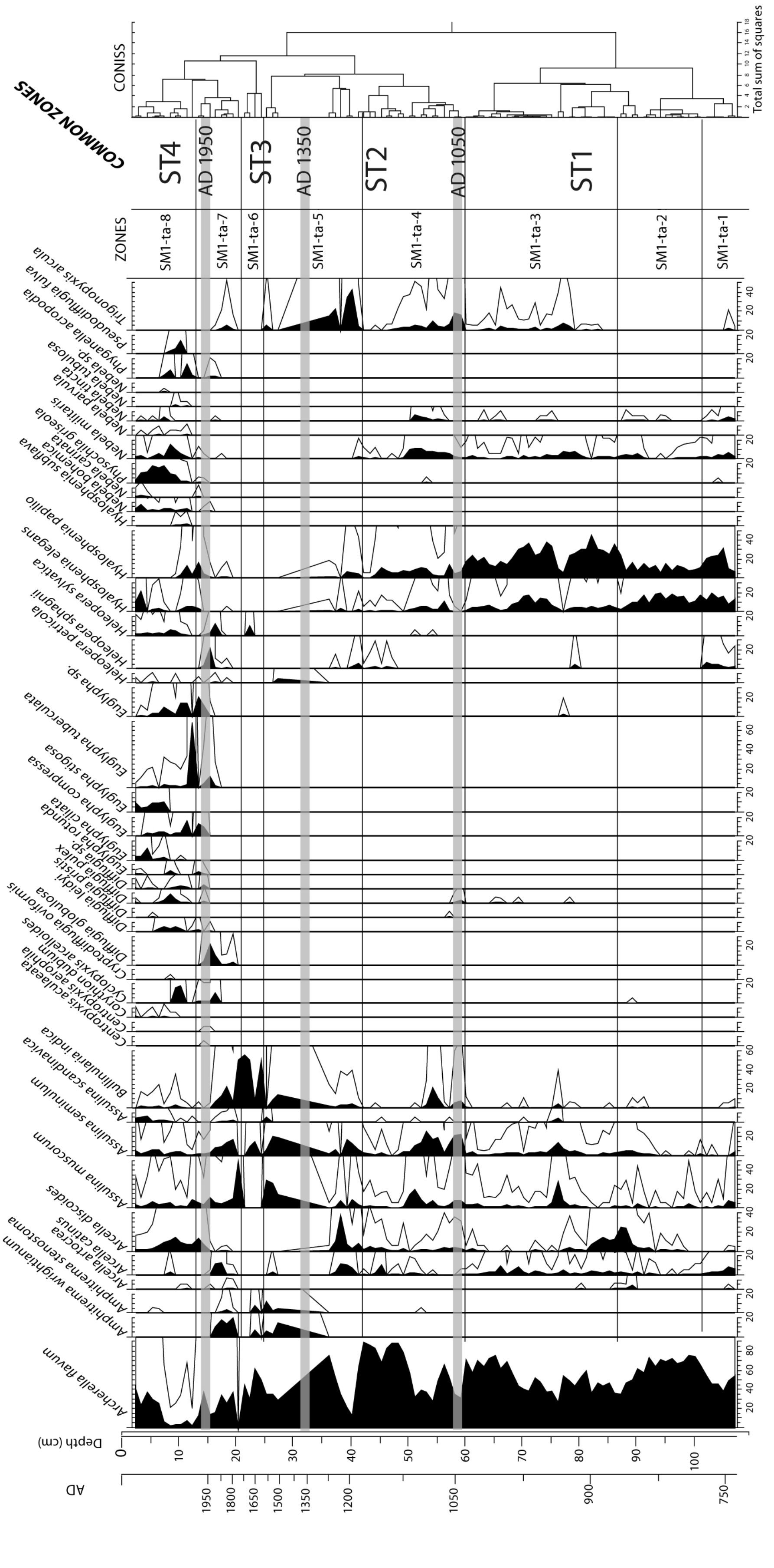

Fig. 5. Percentage testate amoebae diagram. Depth to the water table reconstruction is presented in Figure 6.

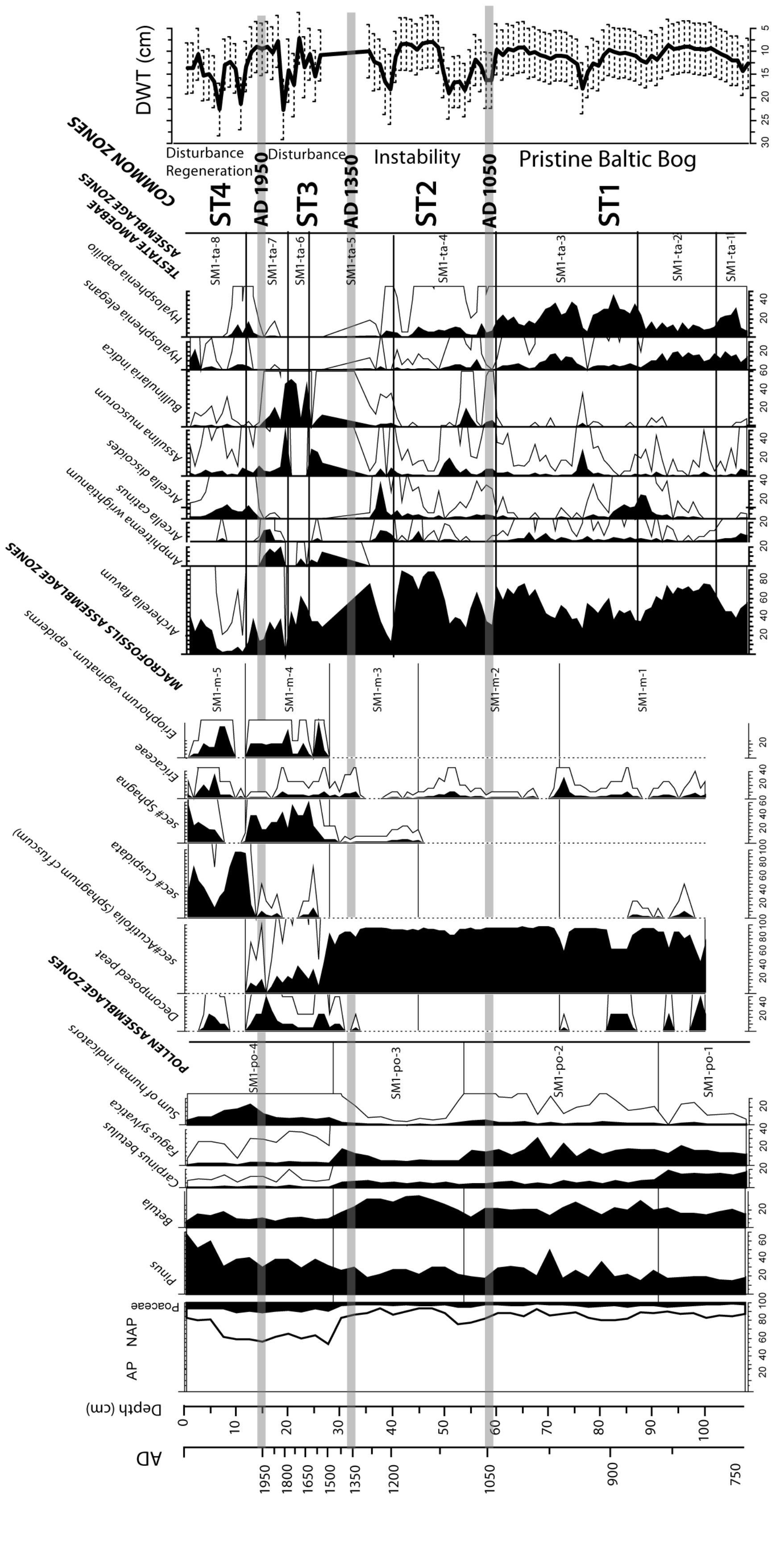

Fig. 6. Summary diagram showing selected testate amoebae, pollen, plant macrofossils and quantitative water table reconstruction.

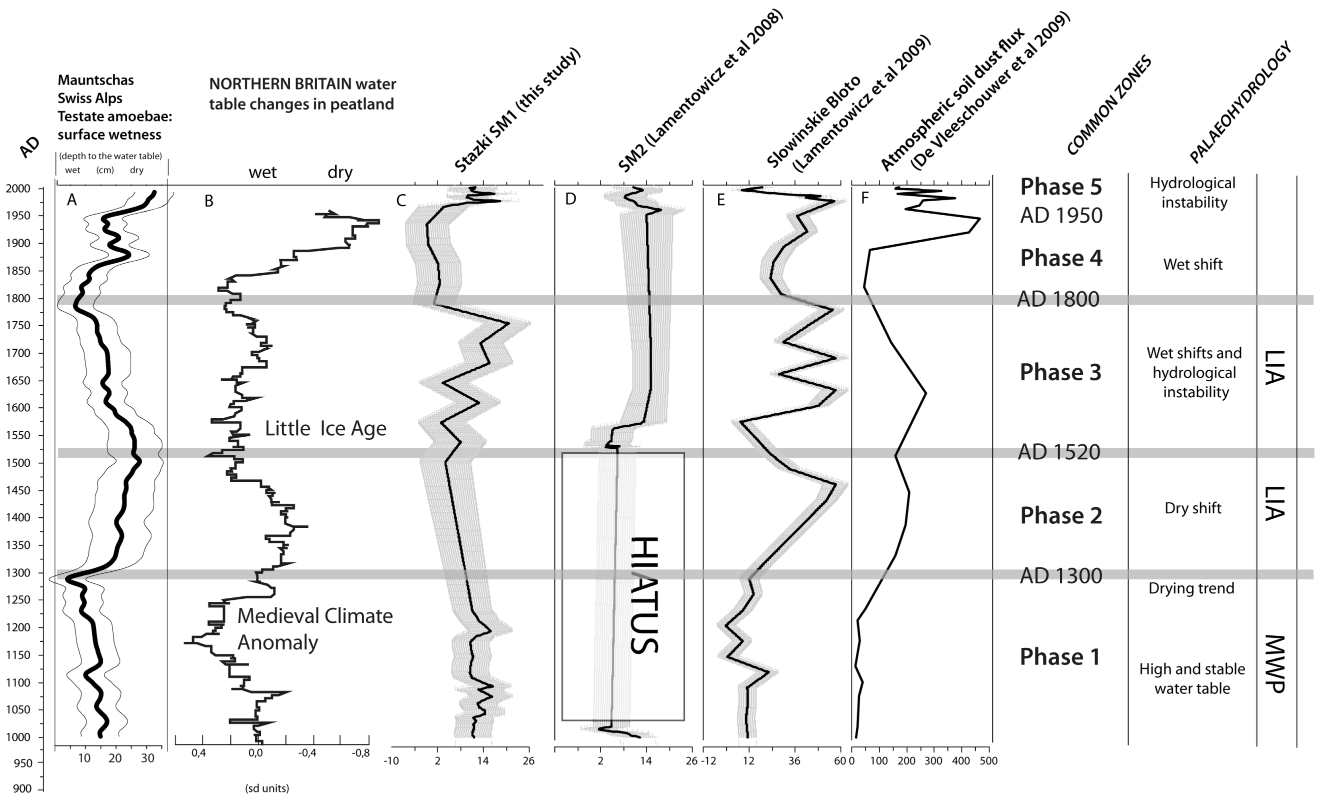

Fig. 7. Comparison of palaeohydrological change in two Baltic bogs (Stążki and Słowińskie Błoto) represented by DWT curves with: A – Mauntschas peatland (Swiss Alps) (van der Knaap *et al.* in press), B – Water table change in N Britain (Charman *et al.* 2006), C – Stążki, this study SM1 , D – Stążki, former study SM2 (Lamentowicz *et al.* 2008), E – Słowińskie Błoto (Lamentowicz *et al.* 2009) and F – ASD flux from Słowińskie Błoto (De Vleeschouwer *et al.* 2009). Common zones representing similar hydrological phases are described.

We assume that the raised bogs are not dependent on the catchment processes; however, deforested landscape and mineral input from the open soils can transform peatlands' chemistry and vegetation. We revealed that AD 1350 (phase 2, Fig. 7) marks *Sphagnum fuscum* decline in Baltic bogs. This species has been considered the most important peat-forming component, and its disappearance might be related to *Sphagnum austinii* decline in Western Europe (Hughes *et al.* 2007). However, in the case of the Stążki bog, *Sphagnum fuscum* was present for 7,000 years (Gałka *et al.* in preparation, Gałka, unpublished data); therefore, this is only a partial analogue. The question is whether the disturbance had climatic or anthropogenic origin. This question is often asked in many publications (Finsinger *et al.* 2010, Magny *et al.* 2008, Müller *et al.* 2011, Sjögren, Lamentowicz 2008). In the case of bogs in the southern Baltic, we need to collect more sites in a west-east gradient, especially in the case of the last millennium, including major disturbances that started in the medieval period.

Phase 2 (AD 1300-1520) was determined to emphasise the dry shift in Słowińskie Błoto (Lamentowicz *et al.* 2009) that is actually blurred in the Stążki bog where there is a very low concentration of testate amoebae. Despite this gap, there is good agreement between the sites when we look at the plant macros. Furthermore, there is also an increase in ASD, suggesting soil erosion.

Phase 3 (AD 1520-1800) is related to the Little Ice Age climatic deterioration. In the case of the studied raised bogs, a response of increased hydrological instability can even be interpreted as the dry shift. Among pollen indicators, *Calluna vulgaris* is the species that suggests relatively dry conditions. At the beginning of this period, the surface of the bogs was wet in three cores. The first core from Stążki (SM2) (Lamentowicz *et al.* 2008) shows a slow accumulation rate from *ca.* AD 1600. In this study, the wiggles of the DWT curve from SM1 are comparable with those from Słowińskie Błoto (Lamentowicz *et al.* 2009), which suggests a regional climatic forcing. There is also an increase of ASD, suggesting increased storminess and transport of mineral matter from open soils (De Vleeschouwer *et al.* 2009). However, this increase could mostly be caused by local deforestation.

Phase 4 (AD 1800-1950) is very intriguing, as it began during the time of the Industrial Revolution and increasing exploitation of nature. This is the twilight of *Sphagnum* cf. *fuscum* in Baltic bogs, and it was replaced by *Sphagnum* section Cuspidata, most probably *S. fallax* co-occurring with *Eriophorum vaginatum*. The increased water table in the peatlands between AD 1800 and 1900 is surprising. This wet shift might have climatic origin if we assume that the Stążki bog was an ombrotrophic bog completely independent from the catchment. The same shift was recorded in the Słowińskie Błoto bog and, interestingly, ASD (Atmospheric Soil Dust) also decreased (De Vleeschouwer *et al.* 2009, Lamentowicz *et al.* 2009). Then, in AD 1900, ASD abruptly increased, and the water table decreased in the mire. The wetness shifts during the last 200 years are very interesting, and we expect to obtain more data from the new sites to confirm these trends. There is a gradual change in Słowińskie Błoto, and a more stable and abrupt change at Stążki. In fact, 1950 marks the period when water tables decreased in both peatlands. However, this decrease might have been connected with peatland dehydration due to ditch digging that is very visible in Słowińskie Błoto.

In Phase 5 (AD 1950-2000) the water table in Stążki decreased, most probably as an effect of the ditch digging. A synchronous shift was observed in the Słowińskie and Stążki bogs (Fig. 7); however, in the middle of this period, a wet shift took place that might have been an effect of the self-regeneration resulting from the ditches infilling. Restoration practices (ditch blocking) started at the beginning of the twenty-first century; therefore, we rather exclude the presence of this signal.

SM1 core vs. SM2 core

Water table reconstruction was based on a jack-knifed weighted averaging model (Birks 1995) of 80 subfossil samples in SM2 and 98 samples in SM1. The mean values of reconstructed DWT are very similar: SM2 (10.6 cm, s.d. = 3.2 cm) and SM1 (11.3 cm, s.d. = 3.7 cm). Water table fluctuations are shifted in time because of the different sensitivity and resilience of particular parts of the mire to allogenic (climatic and human) changes. This is apparent at *ca.* AD 1800 when SM2 shows a decreasing trend in the water table, while, conversely, in SM1, the water table abruptly increased and then decreased *ca.* AD 1950 as the consequence of drainage. Monolith SM2 seems to possess a more sensitive record because it was sampled from the central part of the bog. The SM1 site has been moister during its history, probably because it is located near the part of the mire that has not been impacted by humans. Dry shifts in the peat record are present in both cores. In SM1, dry shift appeared *ca.* 100 years later than in SM2. Wet shifts between 1500 and 1800 (represented by *Amphitrema wrightianum*) are distinct in both cores.

Despite different peat accumulation and an extensive hiatus in SM2, both cores show a similar pattern in past vegetation. There is a shift from *Sphagnum* cf. *fuscum* to sec. Cuspidata. However, SM1 provide us with more detailed data on the *S. fuscum* disappearance and correlates well with the data from Słowińskie Błoto.

Climatic and human impact signal in Baltic bogs

This look at the peat archives actually leads to the reconstruction of past climatic changes in the southern Baltic region. Phases determined from the two Baltic bogs show synchronous changes in both studied mires. Despite that, we cannot reconstruct temperature and precipitation quantitatively, but we can provide possible general climatic changes in northern Poland, especially for the timing of events such as the Little Ice Age and the Medieval Warm Period in Poland, which is very inspiring and stimulating for further work. In the case of the Stążki and Słowińskie Błoto bogs, the Little Ice Age started around AD 1500 and ended in AD 1800; however, it might have been blurred by human impact, especially in the second half. Anthropogenic changes in the bogs might be caused not only by the peat exploitation but also by the change in the hydrochemistry connected with the deposition of the mineral matter on the surface of the bogs, *e.g.* reflected in ASD flux (De Vleeschouwer *et al.* 2009).

Palaeohydrological reconstructions from the British Isles possess some similarities with our record. Little Ice Age hydrological instability that is visible in Stążki was also recorded in *e.g.* Dead Island and Slieveanorra bogs (Swindles et al., 2010). Furthermore, the Northern record established by Charman *et al.* (2006) shows dry phase from AD 1300 to AD 1500 (Fig. 7). This pattern is similar to Baltic bogs that also showed not stable hydrological conditions starting from *ca.* AD 1300. Moreover, despite the different biogeographical setting there is a striking similarity in water table changes between Słowińskie Błoto, Stążki and Mauntschas mire located in Swiss Alps (van der Knaap *et al.* in press). All three profiles show wet conditions until AD 1300, drying trend afterwards and then wet trend from *ca.* AD 1500 with the wet shift between AD 1750 and AD 1850. Then, the high water table was identified *ca.* AD 1800 when mentioned sites and bogs of N Britain, revealed very close pattern (Fig. 7). Lack of synchroneity in compared peat records might be due to autogenic/site specific factors or reflecting the spatio-temporal variations in past human impact and climate change (Swindles *et al.* 2011).

Przybylak *et al.* (2006, 2005) suggest that the past Polish climate (particularly in the last millennium) is still not well known. However, it has been guessed that the first part of the last millennium was warm and the second part colder (Przybylak 2007). Moreover, Przybylak (2007) also states that there was more than average precipitation in the 12th century (and particularly the second half thereof) and in the first halves of the 16th and 18th centuries. Furthermore, the second half of the 13th century and first half of the 19th were drier than average. Such a pattern would fit our data when wet conditions prevailed in both discussed mires until AD 1300. After that, we had a dry shift until AD 1500, which was followed by hydrological instability. However, bog surface wetness unfortunately reflects neither precipitation nor temperature in the continental climate. DWT is driven both by the temperature and precipitation and, finally, is an effect of evapotranspiration (Charman 2002). Charman (2007) also suggests that summer water table deficits that we reconstruct from peatlands are determined by summer precipitation in mid-latitude oceanic peatlands and that summer temperature plays a greater, but still subsidiary role, in higher latitude, continental settings. The observational study from the Linje mire would support this statement (Słowińska *et al.* 2010).

Archives such as tree rings (Koprowski *et al.* 2010) are very valuable as a source of palaeoclimatic information, but they provide mostly high-frequency data. Peatlands are sources of lower-frequency palaeohydrological information that might be used for modelling past climatic changes (Booth *et al.* 2010, Lamentowicz *et al.* 2010b). Polish peatlands are still underused in this context; however, the palaeoecological work is progressing (Lamentowicz *et al.* 2010a). Among the various proxies, testate amoebae are the most promising group that provide an opportunity to reconstruct past wetness quantitatively (Lamentowicz, Obremska 2010, Mitchell *et al.* 2008). The ecological background is still being studied, and our understanding of testate amoebae ecology and taxonomy is improving (Charman *et al.* 2007, Payne *et al.* 2011). The number of people working with this proxy is rapidly increasing.

Implications for the conservation biology

Long-term ecological data are crucial for effective environmental management and nature conservation. The more precise the data are, the more relevant the conservation plan. The applied aspect of such data is very often overlooked. Holocene-length, low-resolution studies are very important in understanding the origin of the site and the general features of its development. However, high-resolution (at least decadal) time series reconstructed from recent peat tell us precisely when the pristine state still existed and when the disturbance began. Consequently, we can determine reference conditions useful for nature conservation. Even if we cannot reach reference conditions, we can estimate the state of preservation of a site and potential activities that can bring us closer to the reference state of an ecosystem.

Stążki bog was partly drained and exploited on the margins and it would deserve active nature conservation now. However, restoration to the pristine state is rather not possible. In the case of the studied Baltic bogs, their reference virgin state can be dated to *ca.* AD 1200. After this date, we observed increasing human impact (deforestation) and climatic instability connected with the LIA. However, between AD 1800 and 1900, bogs were wet, most possibly due to a climatic forcing. This fact suggests that despite human impact, recent peat deposits can still reflect climate and they could accumulate peat actively in appropriate climatic conditions.

Without the Holocene perspective, however, we would not be sure that the peat core covering the last millennium is sufficient to estimate the pristine state. Therefore, a long-core study from the Stążki bog (Lamentowicz *et al.* 2010a, Gałka *et al.* in prep) was also used as the long-term perspective for the short monoliths. The same basis for the Słowińskie bog data of Herbichowa (1998) was used as background. The next important issue is replicate coring, which is crucial to achieving an appropriate reconstruction quality. This approach was particularly important in the case of the Stążki bog, where we updated and improved our reconstruction and avoided a hiatus. In the Słowińskie bog, the proxies in two analysed cores showed very similar trends (De Vleeschouwer *et al.* 2009, Lamentowicz *et al.* 2009). Hydrochemistry is very difficult to reconstruct, but we provide palaeohydrological reconstructions. Values of the groundwater table inferred from testate amoebae can be used a target water table for further restoration. In cases where restoration cannot be fully realised, the hydrological status of a peatland could be estimated. This can be achieved through precise monitoring of the peatland ecosystem and a quantitative water table reconstruction to provide reference conditions. An observational system with piezometers was constructed in several peatlands (Słowińska *et al.* 2010), but there are problems with sustaining it as a continuing study.

CONCLUSIONS

We can highlight the following common patterns in the Stążki and Słowińskie bogs:

– High and stable water level AD 800–1200: stable Baltic bogs.

– Drought AD 1200–1500.

– Hydrological instability AD 1500–1800.

– Wet phase AD 1800–1900.

– Low water table AD 1950 (drainage and cutting).

– Regeneration after AD 1950.

–Humans affected those peatlands, but more in the later stage ca 1900.

Regarding nature conservation, we state that:

– A palaeoclimatic and *multiproxy* palaeoenvironmental context is indispensable for a good understanding of peatland ecosystems.

– Our research provides information about the reference conditions – the natural/pristine state and what, where and when.

– High-resolution peatland palaeoecology is crucial for restoration activities, *e.g.* rewetting and environment management.

– The palaeoecological context is expected to provide reliable information for the peatland ecosystem management.

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