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Always on the tipping point – A search for signals of past societies and related peatland ecosystem critical transitions during the last 6500 years in N Poland

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ABSTRACT

We explored past critical transitions in a peatland located in N Poland using a densely dated (× 44 ^{14}C dates and ×26 ^{210}Pb), high-resolution multi-proxy profile. A 6500-year record was supported by a very robust age-depth model. Changes in land use, climate and carbon sequestration in northern Poland were investigated using a range of biotic proxies. We determined critical transitions in the development of the mire which were dependent upon extrinsic drivers. The trophic status of the mire shifted several times during the last 6.5 millennia. The pattern of changes suggests that it was very sensitive to different changes in the peatland basin. We identified several factors which may have driven transitions between the bog and fen state as a response to catchment hydrology changes largely driven by human impact which overlapped with periods of climate change. We determined the vegetation threshold in relation to microcharcoal which could be related to fire intensity. Based upon microcharcoal and pollen analyses, the local plant community threshold for fire intensity was estimated to be ca 7500 microcharcoal particles/cm^2/year. We discovered that this level was also an important tipping point for the divergence between plants positively (e.g. human indicators and *Carpinus betulus*) or negatively related (e.g. *Quercus*) related to fires. This local threshold was related to ecological changes related to the emergence and fall of subsequent human communities. The first pollen grains indicating human activities in the deposits are dated to ca. 6000 cal. BP. The strongest signal comes from the Neolithic, the Bronze Age, the Pre-Roman Period and the Roman Period. These past societies exploited natural resources and deforested the landscape while actively using fire. We inferred a distinct human influence since ca. 5000 cal. BP (the Neolithic) until the Early Middle Ages with strong evidence during the Bronze Age and Roman Period which demonstrates the high importance of the area until the transition from the tribe period to the Polish state. The peatland possibly recorded several climatic shifts, however the climate change signals were modified by human impacts which actively changed the environmental conditions.

1. Introduction

Global changes connected with climate crisis, pollution and landscape fragmentation have affected terrestrial ecosystems and their carbon balance over a wide range of timescales (Chapin et al., 2000; Mack et al., 2003; Ellis et al., 2013). Different kinds of

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disturbances are an effect of long-term human activities which gradually increased since the Neolithic (Ellis, 2015; Blockley et al., 2018; Stephens et al., 2019). Progressive land use change and deforestation has triggered the creation of novel ecosystems (Corlett, 2015; Ellis, 2015). Virgin forests which covered the central-eastern part of Europe disappeared in the Early Middle Ages (Williams, 2000; Kaplan et al., 2009). Nevertheless, before this dramatic process, different past communities used natural resources and left traces in palaeoecological archives (Zolitschka et al., 2003; Starkel, 2005; Kołaczek et al., 2016; Roberts et al., 2018). Various disturbances to forest structures increased their level of openness at the transition into the Neolithic, Medieval as well as the Anthropocene which is proposed to begin from the era of nuclear weapons testing (Williams et al., 2015; Ellis, 2017). Therefore, current landscapes carry legacies of these past transformations (Vanniere et al., 2015; Słowiński et al., 2019).

Peatlands are important carbon sinks (Borren et al., 2004; Vasander and Kettunen, 2006; Yu, 2006; Gallego-Sala et al., 2018) and have accumulated up to about a third of the global soil carbon during the Holocene (Gorham, 1991; Turunen et al., 2002). This stored carbon (250–455 Pg of carbon) is equivalent to about 25–50% of the current atmospheric CO_2 burden (Frolking and Roulet, 2007). Understanding how early human impacts affected carbon accumulation in peatlands is an important issue today because many peatlands are affected by human disturbance in terms of enhanced nutrient deposition and drainage.

Various environmental changes generate signals driven by both extrinsic and intrinsic factors in peatlands (Birks and Birks, 1980; Seddon et al., 2011; Williams et al., 2011). Large peatlands are usually more resilient than small basins to various environmental disturbances (Lamentowicz et al., 2008b). Therefore, small sites potentially contain a more sensitive record of local environmental signals driven by climate and/or human impacts. Peatlands cross critical transitions in different trophic states and hydrological conditions (Jassey et al., 2018; Jassey et al., 2018). Such transitions are usually connected with substantial climatic shifts, landscape opening, fires or pollution (Barber, 1981; Hughes and Barber, 2003; Fialkiewicz-Koziel et al., 2015). As a result, ecosystems might cross a tipping point (TP) with no return to the previous ecological conditions (Lenton et al., 2008). After the transition, the structure and food chain of the ecosystem changes along with significant modifications of the carbon flux (Jassey et al., 2013, 2018).

Organic deposits stored in lakes and peatlands are important palaeoenvironmental archives (Tobolski, 2003; Booth et al., 2010b). Along with sediments' accumulation there is a signal of environmental changes stored in the organic matter (Birks and Birks, 1980; Charman, 2002). Peatlands (that are built of organic matter) have been used to better understand past climate, carbon accumulation and human impact in different parts of the world (Yu et al., 2010; Swindles et al., 2016; Gallego-Sala et al., 2018; Kołaczek et al., 2018). Raised peat bogs have predominantly been the focus of palaeoclimatic research as they have a direct connection with the atmosphere (Barber, 1981; Barber and Charman, 2003; Charman et al., 2006; Booth, 2010; van Bellen et al., 2018). However, other types of peatlands (e.g. poor fens, kettle-hole mires and spring fens) have also been used to reconstruct past environmental changes as well as human-environmental relationships across a wide range of timescales (Payne, 2010; Hájkova et al., 2012). Fens provide information about changing catchment conditions, and they are closer to lakes in terms of their archive records, given that they grow in closed depressions and peat does not emerge above the surrounding landscape. The changing trophic status of fen ecosystems is closely connected with the ground water and mineral input from the surrounding areas (Lamentowicz et al., 2009a; Płóciennik et al., 2015). The hydrology of fens is also strongly dependent upon the plant cover of their basins, and even moderate disturbance during periods of local deforestation can affect their nutrient composition and the position of local ground water tables (Lamentowicz et al., 2007; Woodward et al., 2014).

Central Eastern Europe (including northern Poland) has been the focus for a wide range of palaeoecological research (Hjelmroos, 1981; Tobolski, 1982; Latałowa, 1989; Bogaczewicz-Adamczak, 1990; Miotk-Szpiganowicz, 1992; Goslar et al., 1999; Tylmann, 2015). Initially studies of peat and lake deposits were undertaken at a low resolution and focused upon pollen and plant macrofossil analyses spanning the Late Glacial period and the Holocene (Wodziczko and Thomaschewski, 1932; Tobolski, 1983; Latałowa and Tobolski, 1987). During the last two decades high-resolution studies started to appear which aimed to apply several proxies simultaneously to infer past environmental changes from the peat archive mostly during the last millennium (Lamentowicz et al., 2008a, 2011; Marcisz et al., 2015; Kołaczek et al., 2018). This high-resolution strategy then started to be applied to longer time scales (Lamentowicz et al., 2015; Gałka et al., 2017). However, studies based upon Polish palaeoenvironmental archives before 2015 do not include quantitative analyses of macro and micro charcoal (the proxy of fires ignited the most possibly by human when accompanied by pollen human indicators) which is crucial to understand how the archaeological data reflects past human impacts (Marcisz et al., 2015, 2019).

In this study we explore past critical transitions which can be defined as the state at which an ecosystem becomes more fragile until a relatively small disturbance triggers a regime shift (Carpenter and Scheffer, 2009; Scheffer, 2009; van Nes et al., 2016). We chose a fen adjacent to a varved lake as well as a time span of ca 6500 years BP to explore environmental changes and the impacts of archaeological cultures from the Late Mesolithic to modern times. We assume that climate change is an important driver of peatland development, however there is also the possibility that some climatic shifts may overlap with anthropogenic signals.

We hypothesised that the majority of the transitions identified in the peat archive during the last 6500 years were driven by cascading effects of past human societies which affected the functioning of the mire ecosystem and peat carbon accumulation rates. We wanted to define the pollen-based vegetation fire threshold (expressed by microcharcoal influx) which led to considerable changes in the local vegetation. For this purpose, a sensitive, small basin chosen for this study was the most promising archive to explore critical transitions related to extrinsic drivers (Dupont, 1986; Mauquoy and Barber, 2002). Palaeoenvironmental reconstructions were based upon testate amoebae, plant macrofossil, carbon and pollen/non-pollen microfossil analyses. To compare our proxy data with archaeological data we performed dense (ca. one ^{14}C date per 10 cm, and one ^{210}Pb date per 1 cm in the topmost sections), high-resolution AMS radiocarbon dating of the peat core. Furthermore, the mire is adjacent to a laminated lake which creates the promising perspective of calibration of both records in the future.

To test if past societies were the main driver of environmental changes, we compared proxy records to the local and regional archaeological data sets. We aimed to: a) identify drivers of the critical transitions in the peatland ecosystem recorded in the peat profile, and b) identify possible climate signals and their impacts on distinct critical transitions in the peatland ecosystem, and c) determine the regional vegetation threshold in relation to fires.

2. Study site

Głęboczek is a small (less than 1 ha) kettle hole adjacent to the varved Lake Głęboczek in the northern part of the Tuchola

Pinewoods (Fig. 1). The peatland is covered by the birch and pine forest with collapsed dead trees. The vegetation is dominated by *Sphagnum* spp, *Carex* spp and shrubs. The area is close to the Pomeranian ice margin of the Weichselian Glaciation dated between 17,000 and 16,000 cal. BP (Marks, 2012). The surficial geology is mostly composed of glacial till and glaciofluvial outwash plain deposits. Lake basins were formed after the melting of dead ice blocks in subglacial channels or in kettle holes (Kordowski et al., 2014). The climatic conditions in this area are characterised by a warm summer transitional climate. Monthly mean temperatures range from −2.5 °C in January to 17 °C in July. Total annual precipitation reaches 590 mm with distinct summer maxima (82 mm in July and 70 mm in August) (Kozłowska−Szczęsna, 1993; Woś, 1999). The study area is a typical polygenetic young glacial landform with a rich array of melting forms/depressions (Słowiński et al., 2014). The Głęboczek mire basin enters into a cascade of lakes and peatlands in the Czechowskie lake catchment (Ott et al., 2017). The Tuchola Pinewoods is the largest forest complex in Poland. Given that the Tuchola Pinewoods contains poor soil which developed on fluvioglacial sediments (Blaszkiewicz et al., 2015), agriculture was not widely undertaken in the region.

3. Methods

3.1. Core retrieval, sampling, and carbon acumulation rate

The 4-m core was sampled in March 2016. Using a Wardenaar sampler the top 1 m was recovered. The remaining part of the profile was extracted using an INSTORF sampler (1-m-long and 8 cm diameter) corer specially designed for this study. The samples were then transported to the laboratory where they were stored frozen.

Material for bulk density, loss on ignition (LOI_{550}) and peat carbon accumulation rates (CAR) analyses was drilled from the frozen peat core using an empty drill which produced a peat pellet of known volume (Suppl. Fig. 2). This served to achieve a continuous 2-cm sampling resolution. Then each sample was dried, weighed, burnt at 550 °C for 12 h, and weighed again (Heiri et al., 2001). For each depth increment, the accumulation rate derived from the peat-core chronology was multiplied with the ash-free bulk density measurement and multiplied by 50% to represent carbon accumulation rates (Loisel et al., 2014).

The fresh (not frozen) material was subsampled for each proxy and dated/analysed at a range of resolutions. The upper 1 m was sampled every 1 cm for lead dating (^{210}Pb), samples for AMS radiocarbon dating (^{14}C) were taken every 10 cm. Pollen, microcharcoal and testate amoebae were sampled every 5 cm and plant macrofossils samples were extracted every 5 cm up 150 cm, and then ever 10 cm in the bottom part of the core. Samples for macrocharcoal analysis were continuously sampled every 1 cm.

3.2. Absolute chronology

The absolute chronology was based upon 44^{14}C AMS dates (Table 1) and 26 ^{210}Pb dates for two sections of the profile: (i) 400−28 cm − a Bayesian age-depth model based on 39 ^{14}C AMS dates (Table 1), (ii) 28−0 cm - 26 ^{210}Pb dates and validated by 4 ^{14}C AMS dates.

^{14}C AMS dates were provided by the Poznań Radiocarbon Laboratory (Poland) (Table 1). The age-depth model was calculated using the OxCal 4.3 software (Bronk Ramsey, 1995) applying the *P_Sequence* function with parameters: $k_0 = 0.6$, $log_{10}(k/k_0) = 1$, and interpolation = 1 cm (Bronk Ramsey, 2008; Ramsey and Lee, 2013). The IntCal13 atmospheric curve was used as the calibration dataset (Reimer et al., 2013). Four ^{14}C dates, i.e. Poz-92755, Poz-89550, Poz-92754, and Poz-89543, which are significantly different from neighbouring ones were excluded prior to the age-depth modelling. Moreover, the topmost ^{14}C date was calibrated using the BombNH1 calibration curve. The profile sections potentially indicate changes in peat accumulation rates (PAR) which were introduced to the model as boundaries (*Boundary* command). These were as follows: (i) 400 cm − the bottom of the profile, (ii) 200 cm − transition between peatland and telmatic deposits inferred from biotic proxies, (iii) 100 cm − transition between lacustrine and peatland deposits inferred from biotic proxies and (iv) 28 cm − top of the model, the presence of a layer with abundant amorphous organic matter and macrocharcoal which may indicate evidence for a local fire and/or dry phase contributing to the hiatus.

The activity of ^{210}Pb was determined as an activity of its daughter radionuclide ^{210}Po (half-life 138 days). Peat samples of 0.5−0.7 g were spiked with ^{208}Po as a yield tracer and digested using a concentrated mixture of HNO_3, HCl and H_2O_2. ^{210}Po was autoplated onto Ag disks after reduction of Fe^{3+} (Fiałkiewicz-Kozieł, 2014; Marcisz et al., 2015; Mróz et al., 2017). The activities of ^{208}Po and ^{210}Po were counted by alpha particle spectrometers with semiconductor, passivated silicon detectors. Excess ^{210}Pb (unsupported) activities were measured as total ^{210}Pb activity minus supported ^{210}Pb activity. The supported level was calculated by using the mean ^{210}Pb activity for the bottom layers (7 Bq/kg). The CRS (Constant Rate of Supply) model was used to estimate the age of this peat core.

To improve the readability of the following sections, the μ (mean) value of the modelled date was rounded to the nearest decade for the section between 400 and 28 cm (expressed as cal. BP − years before AD 1950). The ages of the samples above 28 cm are expressed as unrounded values. The PAR (unit: $cm/yr)_t$ was calculated from the OxCal 4.3 derived age-depth model (400−28 cm) and the ^{210}Pb chronology (28−0 cm).

3.3. Pollen, non-pollen palynomorphs and microscopic charcoal

A total of 80 samples (2 cm^3 in volume, sampled every 5 cm), were prepared using standard laboratory procedures for palynological analysis (Berglund and Ralska-Jasiewiczowa, 1986). Samples were treated with 10% HCl to dissolve carbonates and heated in 10% KOH to remove humic compounds. Next, acetolysis was applied for 2.5 min. Pollen, cryptogam spores, and selected non-pollen palynomorphs (NPPs) were counted under a binocular microscope until the total pollen sum (TPS) in each sample reached at least 500. Pollen grains were identified with the assistance of atlases and keys (Moore et al., 1991; Beug, 2004; van Geel and Aptroot, 2006). The results of the palynological analysis were expressed as percentages calculated on the basis of the ratio of an individual taxon to the TPS, i.e., the sum of AP (arboreal pollen) and NAP (non-arboreal pollen) excluding aquatic and wetland plants including Cyperaceae, and cryptogams. For better readability some pollen taxa which are human impact indicators were grouped into: cultivated land indicators and major ruderals (Behre, 1981; Poska et al., 2004; Gaillard, 2013).

Microscopic charcoal particles (diameter: 10−100 μm) were counted from the same slides as pollen and NPPs (Tinner and Hu, 2003) until the number of charcoal particles and *Lycopodium* spores, counted together, exceeded 200 (Finsinger and Tinner, 2005). The calculations of microscopic charcoal accumulation rate (MIC) follow the formula proposed by (Davis and Deevey, 1964) i.e. $MIC = C_t \times PAR$, in which C_t is the concentration of charcoal particles (unit: particles/cm^3)(Tinner and Hu, 2003).

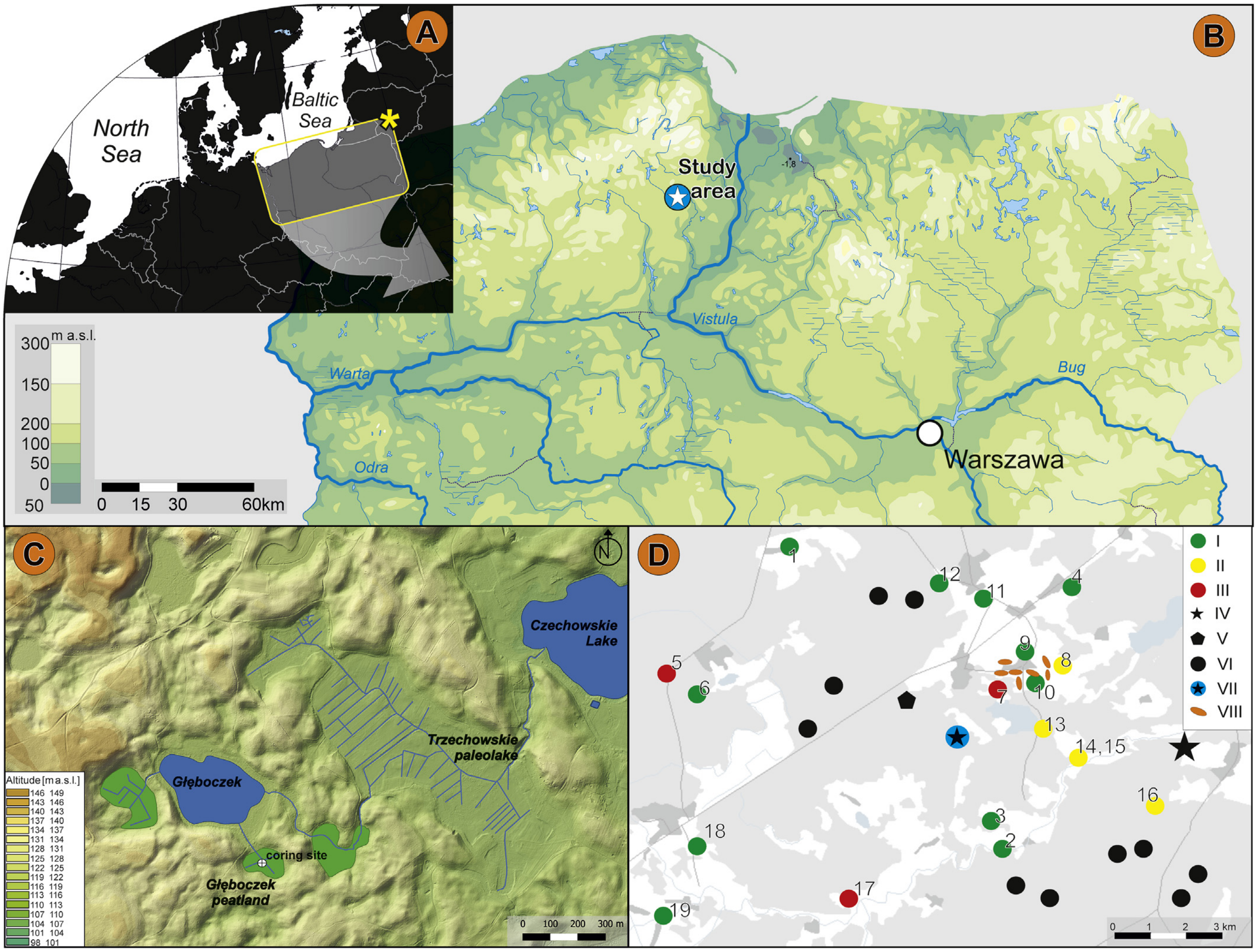

Fig. 1. Location of the study site and other adjacent important wetlands possessing palaeoecological reconstructions, A) Europe, B) N Poland, C) Lidar terrain model, D) Distribution of archaeological sites in the Głęboczek peatland surroundings (see Suppl Table 1.): I - the site without known location, II - the site with approximate location, III - the site with exact location, IV - barrow necropolis, V - alleged place of exploitation, VI - charcoal piles, VII - Głęboczek site location, VIII - sites recorded during field surveys in the vicinity of Iwiczno village (Stone Age – 2, 3, 7, 14; Bronze Age Period – 10, 12, 17; Early Iron Age – 1, 4, 6, 8, 11; Roman Period – 18, 19; Early Middle Ages – 15; Late Middle Ages – 9; Modern Period – 5, 17).

3.4. Macroscopic charcoal

For macroscopic charcoal analysis, 1 cm^3 sediment samples were prepared following the method described by Whitlock and Larsen (2002). Particles divided into two fractions (100–500 μm and >500 μm) were counted under stereoscope at 40 × magnification. Macroscopic charcoal influx (proxy for local fires (Conedera et al., 2009)) or accumulation rates (MAC, particles/cm^2/yr) were calculated using the charcoal concentrations and the peat accumulation rate.

3.5. Plant macrofossils

The macrofossil composition of the ~5 cm^3 peat samples was determined by warming each sample in 5% KOH, followed by sieving (mesh diameter 125 μm). Macrofossils were scanned using a binocular microscope (10 × –50 × magnifications) and identified using an extensive reference collection of type material (Mauquoy and van Geel, 2007). Volume percentages were estimated for all components with the exception of seeds, *Betula* spp. catkin scales, *Eriophorum vaginatum* spindles, *Carex* spp. nutlets, *Chara* oospores and *Sphagnum* spore capsules, which were counted and expressed as the number (n) present in each subsample.

3.6. Testate amoebae

80 samples (2 cm^3 in volume) for testate amoeba TA) analysis were sampled from the same depths as for pollen and microscopic charcoal analyses. Peat samples were washed under 0.3-mm sieves following the method described by (Booth et al., 2010a). TA were analysed under a light microscope between 250 × and 400 × magnification, with a minimum of 150 tests per sample where possible (Payne and Mitchell, 2008). Several keys and taxonomic monographs (Grospietsch, 1958; Ogden and Hedley, 1980; Meisterfeld, 2001a, 2001b; Clarke, 2003; Mazei and Tsyganov, 2006) as well as internet resources (Siemensma, 2019) were used to achieve the highest possible taxonomic resolution. The results of the TA analysis were used for the quantitative water table depth reconstructions.

Table 1
List of radiocarbon dates from Głęboczek peatland with the description of the plant material dated.

n	LabID - number	Depth [cm]	Age [14C BP]	Error [14C years]	Calibrated ages [cal. BP] (2σ range - 95.4%)	Material dated
1	Poz-89651	9,5	112.6	0.32 pMC	−7 (4.1%) -8 −43 (91.3%) - 45	*Pinus* needles 3 pc, *Betula* sp. fruit scale 5 pc = pieces, *Betula* sp. winged nutlet 16 pc.
2	Poz-103688	15,5	114	0.28 pMC	−7 (4.7%) -8 −40 (90.7%) - 43	*Sphagnum* stem fragments 8 pc
3	Poz-89528	19,5	105	30	269 (27.3%) 213 194 (0.7%) 189 147 (67.4%) 13	pine needle fragment, *Sphagnum* stem fragment, charcoal 6 pc, bark fragments 4 pc
4	Poz-103604	25,5	355	30	497 (44.5%) 420 411 (50.9%) 315	*Sphagnum* stem fragments 8 pc
5	Poz-89529	29,5	680	30	680 (60.4%) 634 596 (35.0%) 561	*Sphagnum* stem fragments 22 pc
6	Poz-89530	39,5	860	30	901 (9.9%) 866 826 (2.0%) 814 800 (83.5%) 695	*Sphagnum* stems 22 pc
7	Poz-89532	49,5	1185	30	1226 (1.8%) 1212 1183 (88.3%) 1050 1029 (5.3%) 1001	*Sphagnum* stem fragments 34 pc
8	Poz-89533	59,5	1265	30	1285 (89%) 1172 1159 (1.9%) 1145 1139 (1.5%) 1124 1111 (2.8%) 1088	*Sphagnum* stems 30 pc
9	Poz-89534	69,5	1310	30	1295 (68.0%) 1223 1213 (27.4%) 1181	*Sphagnum* stem fragments 40 pc
10	Poz-89536	79,5	1435	30	1380 (95%) 1295	*Sphagnum* stems 20 pc
11	Poz-89537	89,5	1620	30	1569 (95.4%) 1412	*Sphagnum* stems 30 pc
12	Poz-89538	99,5	1605	30	1555 (95.4%) 1412	*Sphagnum* stems 15 pc
13	Poz-89549	101	1640	30	1615 (75.8%) 1514 1504 (3.8%) 1478 1465 (15.9%) 1416	*Carex* sp. seed 1 pc, charcoal fragments, *Sphagnum* stems fragments
14	Poz-89548	110	1785	30	1816 (62.5) 1686 1679 (32.9%) 1618	charcoal - few dozens of small pieces
15	Poz-89547	120	1835	30	1855 (95.4%) 1705	charcoal 10 pc, *Carex* sp. seeds 3 pc
16	Poz-89546	130	1945	30	1970 (1.8%) 1960 1951 (93.6%) 1822	*Sphagnum* stem 1 pc, charcoal pieces, *Betula* sp. winged nutlet 1 pc, *Carex* sp. seeds 2 pc
17	Poz-89544	140	2165	30	2308 (44.7%) 2223 2210 (46%.0%) 2098 2089 (4.6%) 2061	bark fragment
18	Poz-89543	150	2480	30	2723 (94.9%) 2431 2390 (0.5%) 2383	*Carex* sp. seeds 17 pc
19	Poz-89542	160	2170	30	2309 (92.9%) 2105 2083 (2.5%) 2065	*Carex* sp. seed 1 pc, charcoal fragments
20	Poz-89541	170	2255	30	2345 (35.1%) 2297 2265 (60.3%) 2157	Charred *Carpinus* sp. seed
21	Poz-89540	180	2450	35	2705 (25.5%) 2629 2620 (16.4%) 255 2547 (53.5%) 2360	Charcoal pieces, seed 1 pc
22	Poz-89539	190	2880	30	3141 (2.0%) 3125 3110 (2.2%) 3093 3080 (88.8%) 2922 2907 (2.4%) 2888	*Rubus* sp. seeds 6 pc
23	Poz-99653	200	3040	40	3361 (94.5%) 3143 3090 (0.9%) 3083	*Carex* sp. seeds 7 pc, *Sphagnum* stem 1 pc, charcoal
24	Poz-92754	210	2550	30	2750 (54.9%) 2693 2635 (9.9%) 2614 2593 (30.6%) 2500	Leaves
25	Poz-89550	220	3935	35	4514 (7.4%) 4481 4445 (80.0%) 4248	*Carex* sp. seeds 2 pc, charcoal fragments
26	Poz-89645	230	3380	30	3695 (95.4%) 3565	*Sphagnum* stems fragments 5 pc, charcoal
27	Poz-89646	240	3895	30	4417 (95.4%) 4244	*Sphagnum* stem fragment 1 pc, *Carex* sp. seed 1 pc, charcoal
28	Poz-89647	250	3900	35	4425 (95.4%) 4235	*Sphagnum* stems 20 pc
29	Poz-89649	260	3950	35	4519 (21.5) 4463 4451 (73.9%) 4289	*Sphagnum* stems 20 pc
30	Poz-89650	270	4135	35	4822 (93.0%) 4568 4556 (1.5%) 4548 4542 (0.9%) 4537	*Sphagnum* stems 10 pc
31	Poz-92755	280	4710	40	5582 (27.7%) 5506 5488 (21.1%) 5438 5420 (46.5) 5321	Charcoal
32	Poz-92756	290	4400	35	5258 (0.5%) 5249 5232 (0.4%) 5226 5214 (3.3%) 5189 5055 (91.2%) 4859	*Sphagnum* stems fragments (very small), *Carex* sp. seeds 3 pc, charcoal, bark fragment

(*continued on next page*)

Table 1 (*continued*)

n	LabID - number	Depth [cm]	Age [14C BP]	Error [14C years]	Calibrated ages [cal. BP] (2σ range - 95.4%)	Material dated
33	Poz-92757	300	4550	35	5319 (37.7%) 5213 5191 (57.7%) 5052	*Carex* sp. achene, bark fragment, needle fragment
34	Poz-92758	310	4625	35	5466 (70.9%) 5345 5335 (24.5%) 5297	Brown moss stem 1 pc, needle fragment, *Carex* sp. seed 1 pc
35	Poz-92759	320	4770	30	5590 (93.1%) 5465 5347 (2.3%) 5333	Needle fragments, bark fragment
36	Poz-92761	330	4795	35	5599 (95.4%) 5468	Brown moss stems fragments 15 pc
37	Poz-92762	340	4970	30	5858 (51%) 5828 5751 (90.3%) 5606	Brown moss stems fragments 20 pc
38	Poz-92763	350	5170	40	5999 (86.9%) 5885 5820 (8.5%) 5760	brown mosses stems fragments 15 pc, *Carex* sp. seeds 2 pc
39	Poz-92764	360	5240	40	6178 (8.7%) 6148 6120 (21.9) 6039 6032 (64.8%) 5917	*Sphagnum* stems fragments 8 pc, *Carex* sp. seed 1 pc, charcoal
40	Poz-92765	370	5350	40	6272 (10.0%) 6238 6217 (85.4%) 6001	brown mosses stems fragments 15 pc
41	Poz-92766	380	5430	40	6303 (93.4) 6180 6143 (2.0%) 6126	brown mosses stems fragments 15 pc
42	Poz-92920	390	5540	40	6405 (95.4%) 6284	*Sphagnum* & brown mosse stems fragments 20 pc
43	Poz-83944	399	5630	40	6487 (95.4%) 6314	*Sphagnum* stems
44	Poz-83943	400	5760	40	6659 (94.8%) 6465 6458 (0.6%) 6454	*Sphagnum* stems

3.7. Numerical analyses and graphical output

Threshold Indicator Taxa ANalysis (TITAN) was used to estimate the plant community (expressed as pollen percentages) thresholds to the reconstructed fire activity (see Baker and King (2010) for a full description of the method). Briefly, TITAN identified the optimum changing point of every plant taxon frequency and abundance along the MIC gradient using bootstrapping and permutation tests to assess the uncertainty of every changing point (Baker and King, 2010). TITAN detects changes in species distributions (taxon that increase [normalised z + scores] or decrease [normalised z-scores] in abundance) along a gradient and assesses synchrony among species responses as evidence for community thresholds. The quality and estimation of the critical tipping point area in a plant community (representing trees, shrubs and human indicators) was tested using 1000 permutations and 150 bootstrap replicates (resampling with replacement) using the *TITAN2* R package (Baker and King, 2010). The reconstruction of statistically significant fire peaks/episodes, background charcoal and fire frequency was undertaken using contiguous macroscopic charcoal data in the application CharAnalysis using local threshold, lowess smoother robust to outliers and a 1000 yrs smoothing window (Higuera et al., 2010) (Suppl. Fig. 1).

The relationships between pollen relative abundance (%), NPPs (%) and environmental variables (MIC influx, MAC influx (two size groups), CAR and DWT) were assessed using redundancy analysis (RDA). The chosen pollen and NPPs (representing trees, shrubs and human indicators) data were Hellinger transformed (Legendre and Gallagher, 2001) prior to the analysis. The significance of the model, axes and of each explanatory variable included in the model was tested using 999 permutations. Calculations were performed using the *vegan* package (Oksanen et al., 2017) using R software (Team, 2018).

Quantitative reconstruction of the TA-based depth to water table (DWT) and pH reconstructions were performed in C2 software (Juggins, 2003), using a training set developed for northern Poland by (Lamentowicz and Mitchell, 2005; Lamentowicz et al., 2008b). The local training set was used to avoid biogeographical and taxonomic bias (Lara et al., 2015; Singer et al., 2015).

Diagrams with palaeoecological proxy data were plotted using C2 (Juggins, 2003) or Tilia graph (Grimm, 1992) software. To adjust the description of the proxy data we divided each diagram into zones based upon the pollen and NPP spectra, as these proxies represent the broadest spatial set of environmental changes. Zonation was performed using constrained cluster analysis (CONISS) applied in the *rioja* package (Birks and Gordon, 1985; Bennett, 1996; Juggins, 2017; Juggins, 2017, 2017). To draw the synthesis figure, DataGraph was used (MacAskill, 2012). The final graphical output was edited using Affinity Designer (affinity.serif.com).

3.8. Archaeological chronology

Archaeological periods were based upon the chronology established for the Polish territory by Kaczanowski and Kozłowski (1998). We took however into account the cultural specificity of the Tuchola Pinewoods (see: Grzelakowska, 1989a; Grabarczyk, 1992, 1997). To determine the main occupation phases of the Głęboczek area, archaeological and historical sources are necessary. However, with the exception of medieval and modern glasswork archaeological studies, systematic archaeological surveys are not available (Olczak, 1984), due to the high level of afforestation which prevents field walking. The Polish National Record of Archaeological Sites (PNRAS/Archeologiczne Zdjęcie Polski in Polish, Mazurowski, 1980; Barford et al., 2000) was not undertaken in the study area. For this reason, all known sites in Głęboczek surroundings are accidental discoveries among which many are loose finds. Information on archaeological sites are based on publication survey and the data from the Voivodship Monuments Protection Office (VMPO) in Gdańsk and Archaeological Museum in Gdańsk (AMG) (Suppl Table 1).

4. Results and interpretation

4.1. Absolute chronology and peat accumulation rates

The age-depth model (Fig. 2) revealed a reliable model agreement index (A_{model}) equal to 62.9% (>60%; Bronk Ramsey, 2008). The results of the age-depth modelling show that the section of the profile dated only by ^{14}C (400–28 cm) spans the period from 6590 ± 50 to 630 ± 40 cal. BP. The σ error of the modelled age ranged between ca. 10 (ca. 2330–2320 cal. BP) and 110 years (ca. 4000–3900 cal. BP). The peat accumulation rate (PAR) ranged between 0.002 and 0.13 cm/yr. The lowest PAR values characterised the section of 239–230 cm (ca. 4190–3710 cal. BP), which indicates the possible presence of depositional gap(s). Moreover, between 230 and 200 cm (ca. 3710–3210 cal. BP) two outlier ^{14}C dates were identified, which might be evidence for physical disturbance to these peat layers.

The unsupported ^{210}Pb activities ranged between 15 ± 4 to 579 ± 15 Bq/kg in the section of 28–0 cm and the highest value occurs at 2 cm depth. The unsupported ^{210}Pb presents a relatively well-defined exponential decrease with core depth. Supported levels of ^{210}Pb were calculated by using the mean activity of bottom layers of peat core and equel 7 Bq/kg. The CRS modelling revealed that the 28-0 cm section of peat profile spans period AD 1871+/-24 - 2016.. The average accumulation rate for the profile is 0.33 cm/yr (0.09–0.89 cm/yr).

In the section between 20 and 0 cm there is a good fit between the ^{14}C and ^{210}Pb dates; however, between 28 and 20 cm there is a discrepancy between the results of the two dating methods.

4.2. Forest and peatland ecosystems changes

Bulk density and LOI results are presented in Fig. 2. Figs. 3–5 present diagrams of the pollen, non-pollen palynomorphs (NPPs), plant macrofossils and TA, respectively. Fig. 6 presents records of microscopic charcoal, macroscopic charcoal and peat carbon accumulation rates (CAR). The reconstructed number of significant fire episodes and inferred fire frequency is presented in Suppl. Figure. 1 and the summary is presented in Fig. 9.

4.2.1. Stage G1 – ca. 6500-5500 cal. BP (400-321 cm): Peatland phase (archaeological chronology: Neolithic)

Bulk density and LOI remained relatively stable during this phase. Carbon Accumulation Rates (CAR) decreased from ca 5750 cal. BP to ca. 30 g C/cm^2/yr and then reached a maximum of ca 70 g C/cm^2/yr at ca. 5500 cal. BP. Macroscopic plant remains reveal *Sphagnum magellanicum* (>80%) dominated peat at ca. 6500 cal. BP, which then decreased along with Undifferentiated Monocots (MU). *Sphagnum* sec. Acutifolia appeared with *S.* sec. *Cuspidata*. *Drepanocladus* remains and domination of *Carex* (>80%) rootlets suggest a change towards a fen state during this period. Palynological data revealed the presence of a wet fen as inferred by the presence of *Thelypteris palustris* and Filicales spores. Single sporomorphs of *Potamogeton* and *Botryococcus* indicate short-term inundation events.

TA abundance fluctuated with dominance of *Assulina muscorum*, *Assulina seminulum* and *Phryganella acropodia*, which alternated with *Centropyxis aculeata*. We also recorded the presence of the wet indicators *Hyalosphenia papilio* and *Archerella flavum*. The reconstructed depth-to-water table (DWT) was unstable in this phase, varying between 10 and 15 cm, reaching a maximum of 3 cm at 6255 cal. BP, and decreasing to 25 cm at the end of the phase.

Pollen data show that *Betula* and *Pinus sylvestris* were the main components of the forest revealing opposite optima. Additional components were *Corylus avellana* and *Quercus*. The damp fen may have been overgrown by *Alnus*. Two episodes with an occurrence of cultivated plants (at ca. 6070 and 5600 cal. BP) might suggest minor agricultural activity.

The microcharcoal accumulation rates (MIC) increased gradually until ca. 5800 cal. BP and then dropped and its sum remained low until the top of the zone. The macrocharcoal accumulation rates (MAC) are characterised by numerous peaks suggesting local fires, with the largest peak of MAC (sum of both fractions) reaching 439 particles/cm^2/yr at ca 5510 cal. BP. In total, eight significant charcoal peaks were identified during this phase and the inferred fire

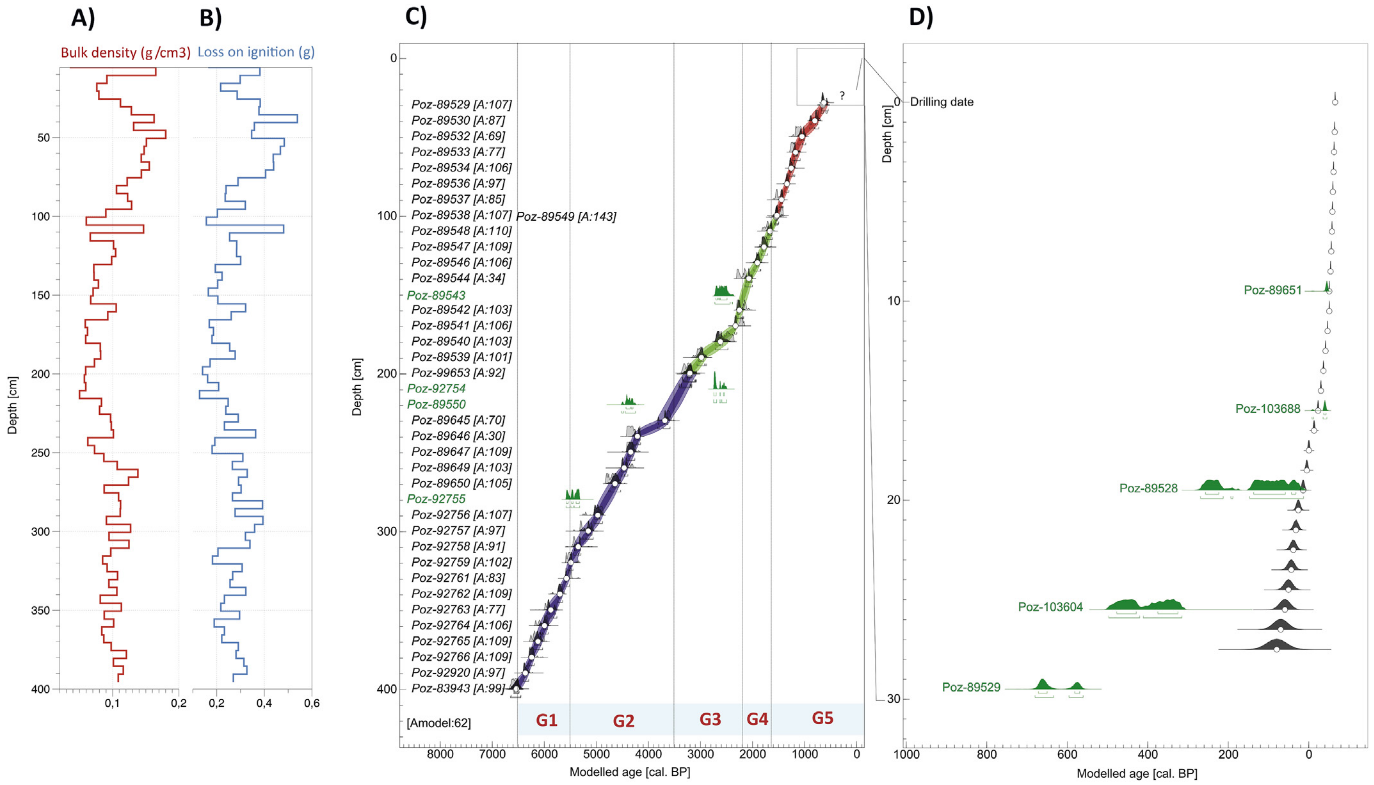

Fig. 2. Results of analyses of the bulk density and loss on ignition (LOI) (A) & (B) respectively. Age-depth model based on 44 radiocarbon dates and 210 Pb measurements (C) & (D) respectively.

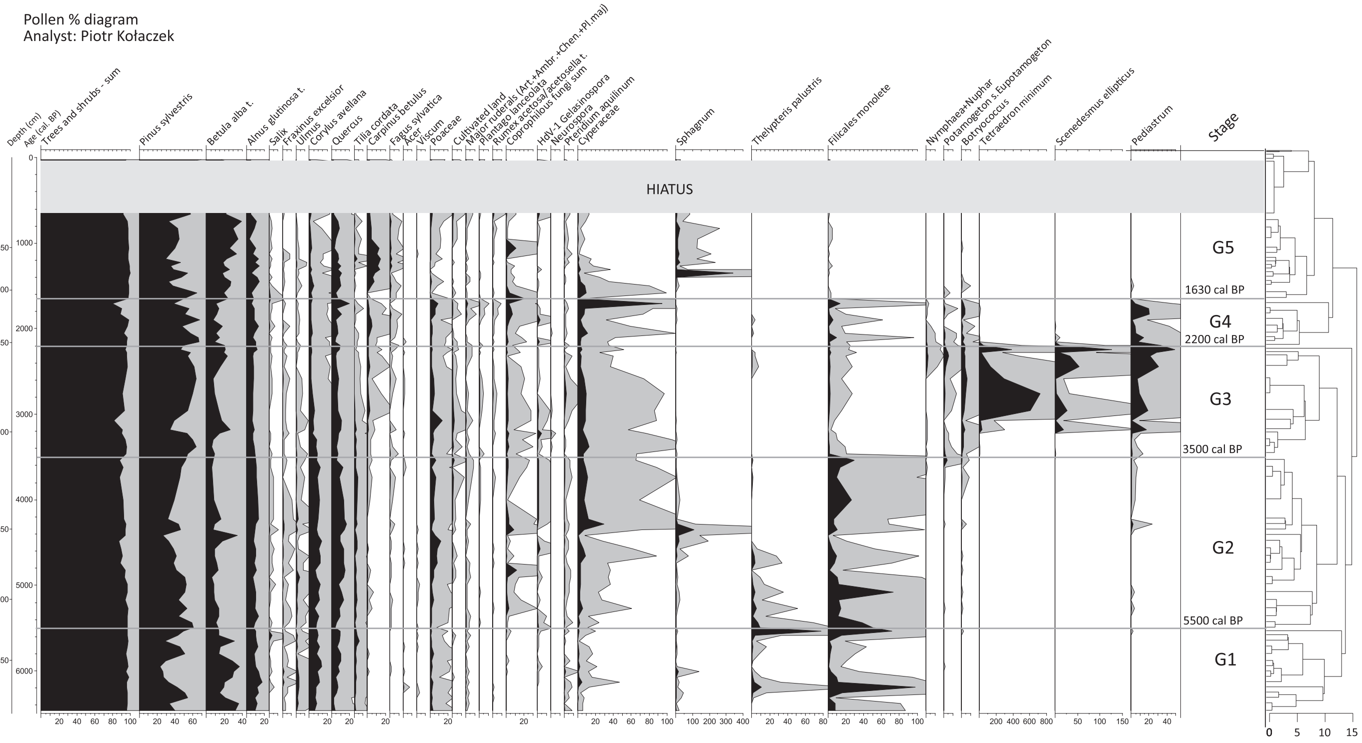

Fig. 3. Pollen % diagram. Zonation based on CONISS performed in the "rioja" R package (Juggins, 2017). Pollen-based zones were used for other proxies to describe particular stages of development of the mire.

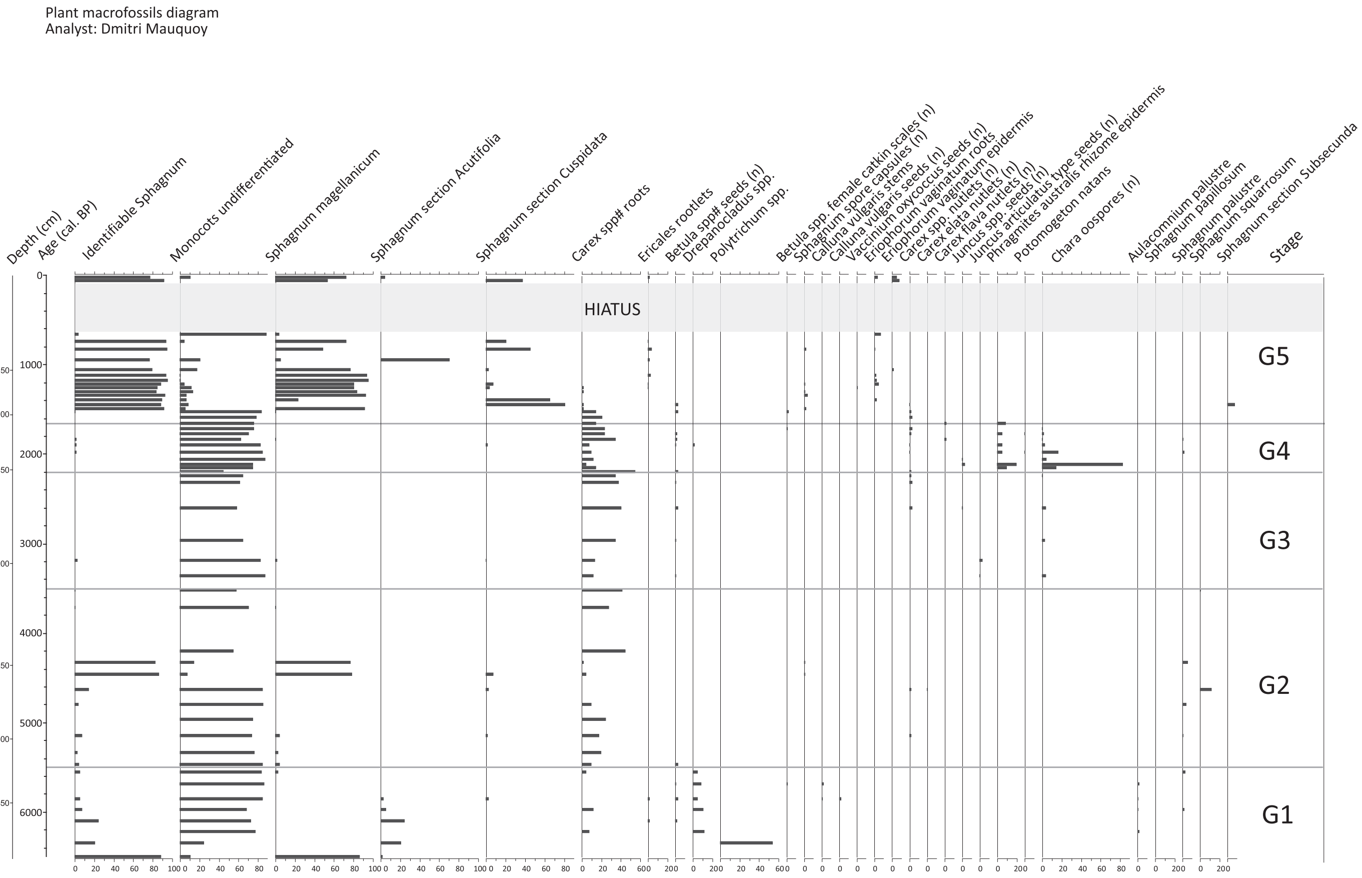

Fig. 4. Plant macrofossil diagram (zonation based on the pollen data).

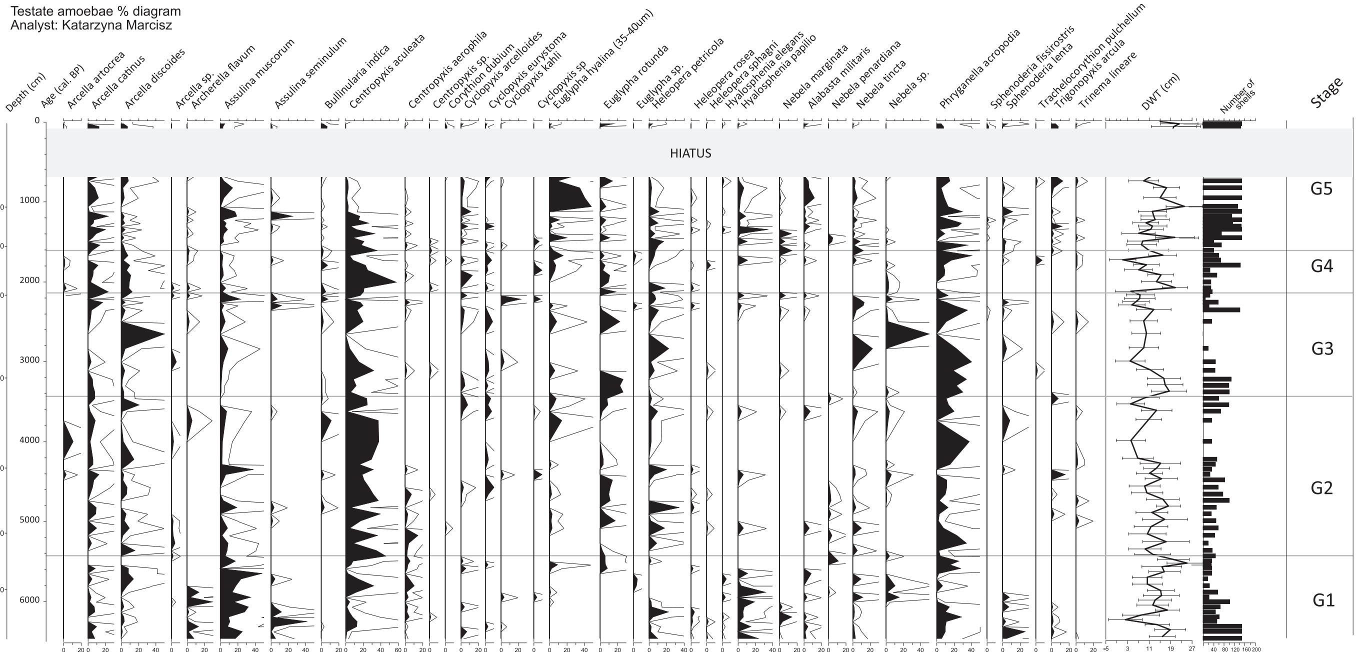

Fig. 5. Testate amoebae % diagram with the quantitative estimates of the depth to the water table (zonation based on the pollen data).

frequency (IFF; episodes/1000 yr) revealed a mean of 5–10 fire episodes per millennium. High IFF suggests an anthropogenic origin of the recorded fires (Suppl. Fig. 1).

4.2.2. Stage G2 – ca. 5500-3500 cal. BP (321-218 cm): Peatland phase (Neolithic - Bronze Age)

CAR values oscillated around 30 g C/cm^2/yr, but then abruptly decreased at ca. 4200 cal. BP to 11 g C/cm^2/yr until ca. 3800 cal. BP, when again CAR abruptly increased. The plant macrofossil record shows an increase in content of *Carex* rootlets and unidentified remains of MU. However, *Carex* retreated and *Sphagnum* started to "engineer" the peatland habitat between ca. 4800 and 4200 cal. BP (600 years) suggesting a probable water table decrease, possible cooling and habitat acidification, which preceded the event with low carbon accumulation rates (Fig. 9). This is also seen in an increase of the *Sphagnum* spore percentages at ca. 4350 cal. BP and a simultaneous decrease of *Thelypteris palustris*. *Botryococcus* and *Pediastrum* occur at irregular intervals reflecting inundations, however, they both appear continuously in small numbers at the top of the zone.

Amongst the testate amoebae, *Centropyxis aculeata* alternated with *Phryganella acropodia*. Water table depth at the fen fluctuated close to 12 cm and started to increase to 6 cm at ca. 4200 cal. BP with a shallowest water table depth of 4.3 cm at ca. 4000 cal. BP. The presence of *Arcella discoides* might suggest water table instability, however, the absence of open water indicators suggests that any inundation was intermittent.

Pollen suggests a continuous and increasing human presence in the vicinity of the site from ca. 5000 cal. BP. The date marks the presence of cultivated fields and suggests the beginning of intensified human impact. An increase in Poaceae percentages since ca. 4500 cal. BP suggest local deforestation and/or growing populations of grasses (i.e. *Phragmites australis*) on the fen surface. An increase in coprophilous fungi percentages during this stage may reflect an intensification of pastoral activity as well as more frequent visits by herbivorous and/or omnivorous animals. Simultaneously, Stage G2 is the time of *Quercus* spread which declined toward ca. 3500 cal. BP. *Carpinus betulus* occurred intermittently until ca. 4500 cal. BP, then from 4200 cal. BP it was a continuous component of the surrounding forests.

MIC and MAC values were lower than in zone G1, with increases at ca. 5000-4730, 4500, 4200, 4120-4050 and 3860-3500 cal. BP. During these phases nine significant fire episodes have been reconstructed and suggest local fires, which might be connected with human impact during the Late Neolithic and Early Bronze Age.

4.2.3. Stage G3 – ca. 3500-2250 cal. BP (218-159 cm): Telmatic/inundation phase (SB2-SA1, Bronze Age – Hallstatt Period - Older Pre-Roman Period)

During this stage CAR decreased from ca. 3500 to 3000 cal. BP to a minimum value of 14 g C/cm^2/yr, then CAR gradually increased to 97 g C/cm^2/yr at ca. 2320 cal. BP. Domination of Monocots and *Carex* rootlets in the peat suggests a wet fen phase. *Chara* oospores regularly occur and indicate local inundation. The presence of *Tetraedron minimum*, *Botryococcus* and *Pediastrum* suggest longer periods of peatland inundation. Permanently open water, as indicated by the pollen of Nymphaeaceae and *Potamogeton* subgen. *Eupotamogeton*, appeared from ca. 2600 cal. BP. However, the plant macrofossil composition and lithology suggest more terrestrial conditions with dynamic hydrological changes.

Testate amoeba communities were dominated by *Phryganella acropodia*, *Euglypha rotunda*, and *Centropyxis aculeata*. At ca. 2600 cal. BP *Arcella discoides* was present in high values for a short time. However, during this phase the sample testate amoebae concentrations were very low and it was impossible to reach a sum of 150 counted shells. TA inferred water tables were lowest at the beginning of the phase, but rose and reached ~6 cm at ca. 3000 cal. BP. Until the end of the phase DWT was a little lower but did not fall below a depth of 11 cm. We assume that low TA concentrations are an effect of prolonged peatland inundation.

P. sylvestris woodlands dominated during Stage G3. At ca. 3100 cal. BP (beginning of the wet phase), they retreated rapidly and it was associated with a spread of *Betula* and an increase in openness as revealed by a peak of Poaceae pollen. During this stage

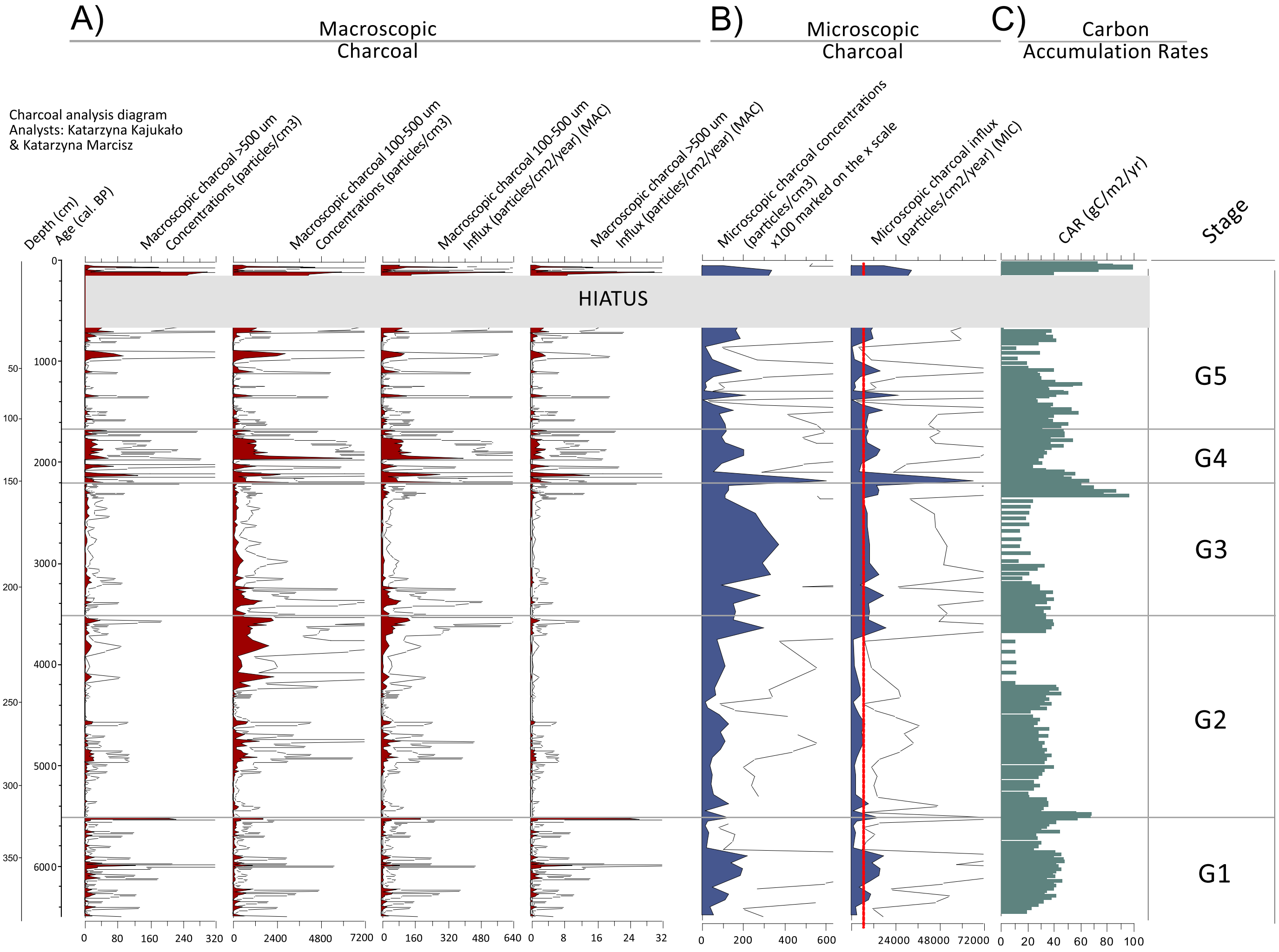

Fig. 6. Concentration and influx of the macroscopic charcoal (A), microscopic charcoal (B), and peat carbon accumulation rates (C). Red line delimits the vegetation community threshold in relation to MIC (microscopic charcoal influx). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

C. betulus became a more important component in the woodlands. A stable presence of cultivated land pollen indicators suggests locally intensive human impact, therefore humans may have been responsible for the *P. sylvestris* retreat. During this stage *Tilia cordata* and *C. avellana* also gradually retreated.

In Stage G3 the MIC influx records high and stable values of ca. 10,000 particles/cm^2/yr. The higher abundance of microscopic charcoal suggests extra-local fires, which may be connected with forest clearance at ca. 3200-3100 cal. BP (a decrease in percentages of arboreal pollen and increases in cultivated land/ruderal taxa). The highest values of macroscopic charcoal were also recorded at the beginning of the zone and three fire episodes are noted at ca. 3360 and 3210 cal. BP. Later fire activity decreased, and the following peak was recorded at the end of the zone, at ca. 2274 cal. BP.

4.2.4. G4 — ca. 2250-1630 cal. BP (159-107 cm): Telmatic/inundation phase (Younger Pre-Roman Period - Roman Period - Migration Period)

CAR decreased from the former maximum value for the profile to 24 g C/cm^2/yr, and then gradually begun to increase and oscillated around 40 g C/cm^2/yr. Dominance of Monocots, *Carex* rootlets and *Phragmites australis* in the peat profile points to a submerged fen habitat. Open water is indicated by the presence of *Potamogeton* macrofossils and *Chara* oospores. The occurrence of *Pediastrum* and *Botryococcus* as well as pollen of Nymphaeaceae and *Potamogeton* subgen. *Eupotamogeton* reinforces this inference. *Sphagnum* leaves are sparse. *Pediastrum* declined at ca. 1850 cal. BP; however, traces of open water were present until the end of the phase.

The testate amoebae record shows a domination of *Centropyxis aculeata* (maximum at ca 2000 cal. BP). This record suggests that *C. aculeata* might be regarded as an important indicator of eutrophication (Lamentowicz and Mitchell, 2005). However, in stages G3 and G4 the low concentrations of testate amoeba might confirm inundation events. The continuous presence of *Arcella discoides* suggests water table fluctuations (Lamentowicz et al., 2009b). The reconstructed DWT shows instability/water table fluctuations, however, as in stage G3 the TA concentrations were very low and the TA-inferred DWT reconstruction is highly tentative for this stage.

Considerable fluctuations of *P. sylvestris* and *Betula* were recorded. Cultivated field indicators decreased at the beginning of the stage. However, the rapid increase in coprophilous fungi abundance at ca. 1850 cal. BP with a peak at ca. 1630 cal. BP which is simultaneous with human indicators of cultivated plants and major ruderals and a distinct decline in arboreal pollen, suggests an increase in landscape openness related to intense human activity. Increased human impact was preceded by an optimum of *C. betulus* at ca. 2000–1900 cal. BP which then decreased considerably. However, *Quercus* recorded a short-term optimum which corresponds with the declining *C. betulus* trend. Finally, the spread of *P. sylvestris* and *Betula* at the end of the stage contributed to the retreat of *Quercus* and *C. betulus*.

This stage was characterised by the highest charcoal accumulation rate, including both MIC and MAC, between ca. 2250-1730 cal. BP. During this time period MIC reached 66,493 particles/cm^2/yr at ca. 2160 cal. BP. Moreover, high mean values (20,000 particles/cm^2/yr) were noted throughout the phase until ca. 1500 cal. BP suggesting continuous extra-local fires. The local burning signal expressed by high values of MAC shows that the surroundings of the Głęboczek mire might have experienced severe local fires. Five significant fire episodes were recorded at ca. 2170 cal. BP (256 particles/cm^2/yr), 2015 cal. BP (82.8 particles/cm^2/yr), 1920 cal. BP (487.8 particles/cm^2/yr), 1680 cal. BP (83.4 particles/cm^2/yr) and 1650 cal. BP (94 particles/cm^2/yr). These fires may have been related to activities of former human societies and burning of the local forests. The MIC patterns are strikingly similar to changes in CAR, with a prominent decrease at ca 2000 cal. BP.

4.2.5. G5 – ca. 1500 cal. BP-to the present (107-0 cm) - hiatus: ca. 630-110 cal BP (29.5–27.5 cm): Sphagnum/Carpinus phase (Migration Period - Middle Ages – Modern Period)

CAR recorded high values with a decreasing trend to ca 12 g C/m^2/yr between 900 and 800 cal. BP and then gradually increased above the hiatus from 40 to 550 g C/m^{2}yr at the top of the profile. The latter pattern reflects the acrotelm-catotelm relations typical of the active topmost *Sphagnum* peat layers.

Sphagnum abruptly expanded in this stage suggesting oligotrophy, and lower water tables in the catchment as well as the nearby lake. *Sphagnum magellanicum* and *Eriophorum vaginatum* indicate locally ombrotrophic conditions. *Carex* rootlets virtually disappeared. Between ca. 1500-1100 cal. BP, testate amoebae communities were dominated by *Centropyxis aculeata, Arcella catinus* and *Phryganella acropodia*, with water table depths oscillating between 11 and 16 cm. Since ca. 1100 cal. BP *C. aculeata* gradually decreased, and *Euglypha hyalina* abruptly begun to dominate the assemblages (along with forest cutting). At the same time *Assulina muscorum* and *A. seminulum* recorded a small peak at ca. 1100 cal. BP. This date marks a sudden decrease in local water table depths, which is unstable until the end of the phase, showing abrupt former changes in the mire hydrology.

The pollen record reveals distinct changes and forest regeneration between ca. 1500 cal. BP and 1000 cal. BP when *C. betulus* recorded an optimum in the forests. Since ca. 1000 cal. BP most of the tree taxa including hornbeam retreated with a simultaneous increase of human impact based upon the pollen indicators of cultivated land and ruderal habitats (Fig. 3).

Microscopic charcoal influx is much lower in this phase, with distinct increases at ca. 1450 cal. BP, 1300 cal. BP, and 1050 cal. BP and in the top section. MAC is low with the lowest background charcoal recorded. However, five distinct significant fire episodes and one insignificant were recorded in regular intervals between ca. 1300 and 700 cal. BP. The most recent fire episode – the only insignificant charcoal peak – is connected with the highest peak of MAC during the last century, which is also mirrored by MIC.

4.3. Fires and critical transition in the vegetation – RDA and TITAN analyses

Redundancy analysis (p = 0.019) of the pollen percentage and environmental variables connected with the water table, carbon and fire revealed that DWT (p = 0.026), was the most important variable driving the vegetation structure (Fig. 7). MAC (fraction: 100–500 μm) was close to significance (p = 0.062). The ordination biplot shows that low water tables appear to control the abundance of *Sphagnum* (spores), as well as trees and shrubs. Simultaneously, algae (indicating inundations) such as *Scenedesmus ellipticus*, *Tetraedron minimum* and *Pediastrum* sp. appeared to be correlated to MAC (fraction: 100–500 μm) and MIC. *Betula* appeared to be positively associated with the increase in CAR.

Using TITAN, we identified 13 pollen taxa and groups of taxa (out of 15) which indicate a significant changing point along the MIC gradient (Fig. 8A). As a result, vegetation community composition showed an important taxa turnover at a MIC of ca. 7500 part./cm^2/yr (Fig. 8b) indicating a community-level tipping point. Mostly tree taxa (e.g. *Tilia*, *Ulmus* and *Quercus*) revealed negative (z-) responses to fires. Positive responses were recorded for *Carpinus betulus*, *Pinus sylvestris*, *Plantago lanceolata*, *Rumex acetosa/acetosella* and anthropogenic indicators (major ruderals and cultivated field indicators).

5. Discussion

5.1. Critical transitions, hydrological dynamics and peat carbon accumulation rates

We summarised the most important proxy data inferred from the Głęboczek core and compared them to archaeological data (Fig. 9). The site crossed different critical transitions and was always

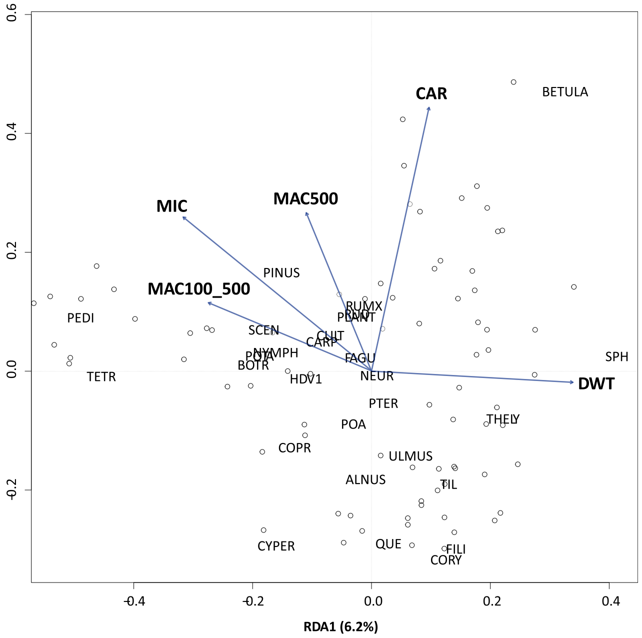

Fig. 7. Redundancy analysis based on the chosen taxa pollen and non-pollen palynomorphs (%) vs accumulation rates (PAR) and influx of the macro- (MAC500 - size >500 μm, MAC100_500 - size 100–500 μm), micro-charcoal (MIC) and depth to the water table (DWT). The Model was significant overall p = 0.003, first axis was significant p = 0.004, two explanatory variables were significant: MAC MAC100_500 p = 011 and MIC p = 0.016. (Taxa abbreviations: PINUS - *Pinus sylvestris*, BETULA - *Betula alba* t. ALNUS - *Alnus glutinosa* t. ULMUS - *Ulmus*, CORY - *Corylus avellana*, QUE - *Quercus*, TIL - *Tilia cordata*, CARP - *Carpinus betulus*, FAGU - *Fagus sylvatica*, POA - Poaceae, CULT - Cultivated plants, RUD - *Ruderals*, RUMX - *Rumex acetosa/acetosella*, COPR - Coprophilous fungi, HDV1 - *Gelasinospora*, NEUR - *Neurospora*, PTER - *Pteridium aquilinum*, CYPER - Cyperaceae, SPH - *Sphagnum*, THELY - *Thelypteris palustris*, FILI - *Filipendula*, NYMPH - Nymphaeaceae, POTA - *Potamogeton*, BOTR - *Botryococcus*, TETR - *Tetraedron minimum*, SCEN - *Scenedesmus ellipticus*, PEDI - *Pediastrum*).

unstable in its development. The small Głęboczek basin experienced periods of intense human impact, however it was also possibly affected by different climatic events during the last 6500 years. Oligotrophication and subsequent eutrophication regime shifts through time are connected with flooding and human impacts.

We identified four major critical transitions in the local hydrology and composition of the local peat-forming vegetation: 1) 5.9 cal BP *Sphagnum* decline, 2) ca. 4.2 cal. BP. second *Sphagnum* decline after the peak at ca. 4.5 cal BP., 3) Wet and eutrophic phase between 3300 and 1650 cal. BP, and an abrupt *Sphagnum* encroachment around ca. 1600 cal. BP. On the other hand we inferred a local fire threshold (ca. 7500 part./cm^2/yr) represented by the microcharcoal influx (MIC) which was highly important for the divergence of fire related taxa in the area. To our knowledge this is the first time that such an environmental reconstruction has been made for this part of Europe. The fire threshold is only based upon the data for this site and similar calculations should be attempted for other regions. A similar approach from Poland, which focused upon water table depth changes and the plant macrofossil record has recently been published (Lamentowicz et al., 2019). The study revealed a tipping point value of the ground water table that is critical for the functional shift below ca. 12 cm (DWT) in the *Sphagnum* peatland ecosystem. Identification of the ecological tipping points and critical transitions at different temporal and spatial scales is highly important (Lenton et al., 2008; Scheffer et al., 2012) for active nature protection and the management of wetland ecosystems as it creates a consistent functional target for ecological restoration (Doncaster et al., 2016; Jassey et al., 2018; Lamentowicz et al., 2019).

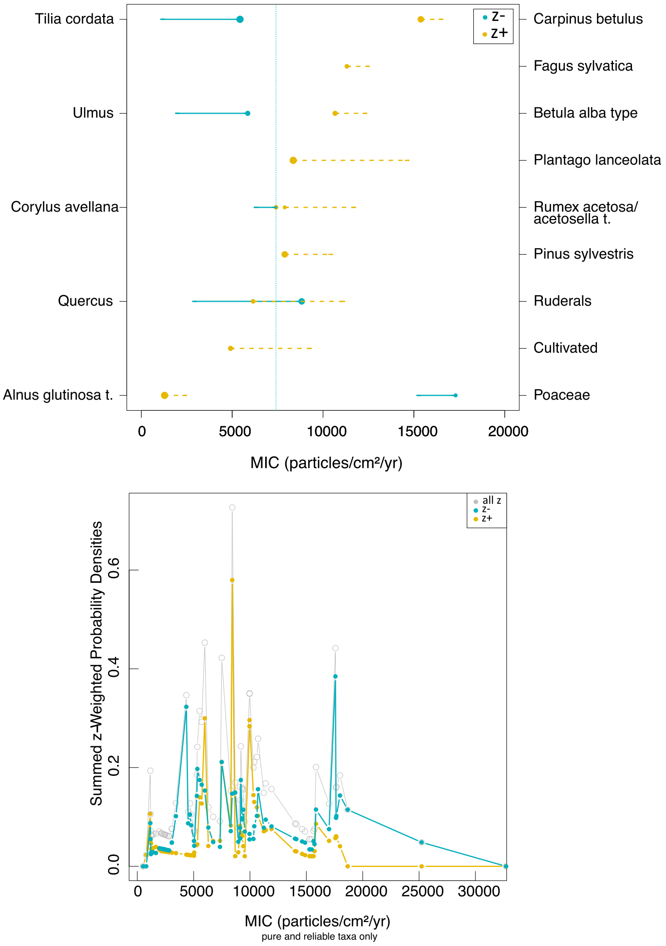

Figure 8

Fig. 8. Tipping point in vegetation community composition in relation to microcharcoal (MIC).(A) Plant taxa change points along the micro charcoal (MIC) gradient (purity >99%, $p < 0.05$ in >99% bootstraps) showing 5% and 95% bootstrap percentiles; dot colours show the taxa that either increase (z+) or decrease (z-) in abundance along the MIC gradient. Critical changing area reflects the 5%–95% bootstrap percentile range (in grey) of community change point (see subset c). (B) Plant community change point along the MIC gradient showing community threshold (dotted line) at max([sum(z_)]) and 5%–95% bootstrap percentile range. [sum(z_)] values represent the sum of responses for each possible change point along the gradient. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The fire threshold (ca. 7500 part./cm^2/yr) might be regarded as very local, however, it shows the boundary beyond which vegetation started to change in terms of human impact. It is difficult to tell however, how much climate change shaped this value. As the MIC data are related to regional fire activity, the threshold may be representative for the studied region. This kind of baseline might be significant as a reference for monitoring purposes and allow better understanding (in both space and time) of the spatial distribution of regions with the highest ignition potential. Palaeoecology-based identification of fire thresholds is especially important for the conservation strategies of the Arctic and permafrost (Mack et al., 2011; Turetsky et al., 2016) regions where fires have been appearing more frequently in recent years connected with recent climate change (Cockburn, 2019). Głęboczek mire is an example of an area which has been intensively burned at both the local and regional scale due to a high density of past human societies. Most probably, the threshold value will be different in areas with different human impact, however, we reveal the possible human-related fire tipping point which irreversibly changed the surrounding vegetation composition. The next attempt will be to make a synthesis using many sites possessing MIC data from N Poland, as previously made for water table depth (Lamentowicz et al., 2019).

The context of fire occurrence thresholds and past dynamics becomes more important when we consider recent global warming. Our new data show that the combination of highly flammable vegetation (woodlands in the mire were dominated by *P. sylvestris*) and past human disturbance is also relevant for ongoing and future changes of fire frequency in a changing climate (Słowiński et al., 2019).

Głęboczek mire went through various hydrological and trophic states from a vascular plant-dominated peatland to *a Sphagnum*-dominated peatland. It is always a difficult task to interpret to what extent human impact was responsible for these changes, however, we believe that the small Głęboczek basin was very sensitive to any land-use changes in the catchment. The mire was very unstable hydrologically which is expressed in wet eutrophic (telmatic) stages and *Sphagnum*-dominated acid phases. *Sphagnum* is present in the peat profile between ca. 6500-6000 (500 years), 4820-4350 cal. BP (530 years) and then continuously in more recent time since ca. 1500 cal. BP (1500 years). These shifts might be interpreted as transitions into ombrotrophy (bog stage) when local ground waters decreased - possibly also driven by lake water tables affecting the mire. The basin might have been connected to the nearby lake during very wet stages and disconnected during persistent droughts. The Głęboczek peatland became wetter since ca. 4300 cal. BP with an inundation trend between ca. 3200-1650 cal. BP (Fig. 9). The NPPs (indicated by the remains of *Pediastrum* and *Tetraedron minimum*) and plant macrofossil data suggest the presence of open water. This is confirmed by the testate amoebae data, which record very low concentrations during this time interval. We therefore interpret this as a stage of intermittent flooding alternating with drying events, with relatively long

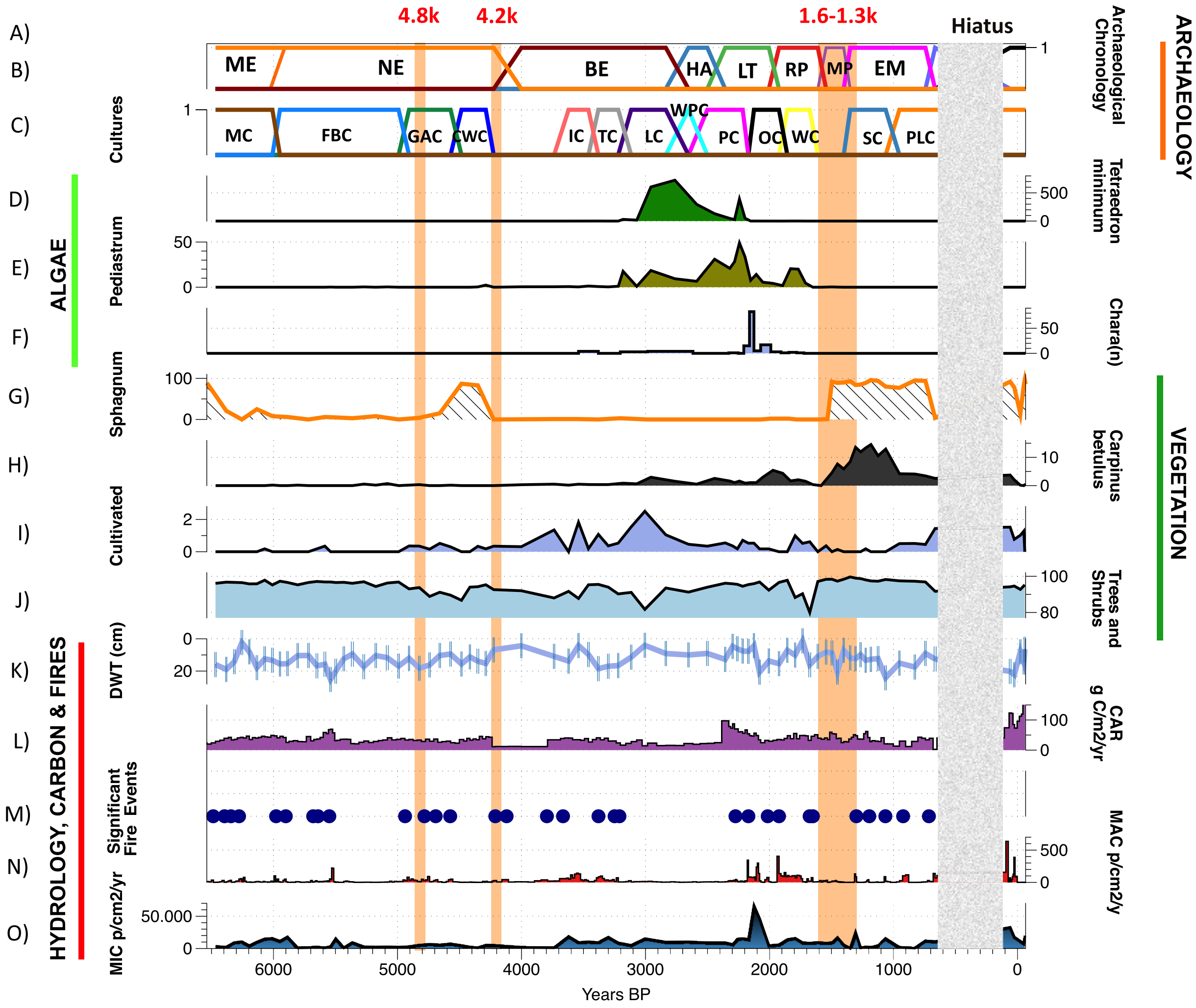

Fig. 9. Synthetic diagram of the Głęboczek multi-proxy data. A) More important climatic events connected to Bond cycles that possibly influenced the peatland development.. B) Archaeological chronology: ME - Mesolithic, NE - Neolithic, BE - Bronze Age, HA - Hallstatt Period, LT - La Tene (Pre-Roman) Period, RP - Roman Period, MP - Migration Period, EM - Early Middle Ages, LM - Late Middle Ages, MO - Modern Period.. C) Archaeological cultures: MC – Mesolithic C., FBC - Funnel Beaker C., GAC - Globular Amphora C., CWC - Corded Ware C., IC - Iwno C., TC - Trzciniec C., LC - Lusatian C., WP - Wielka Wieś Phase, PC - Pomeranian C., OC - Oksywie C., WC - Wielbark C., SC - Slavic C., PL - Polish C. D) *Tetraedron minimum* - indicating open water (%). E) *Pediastrum* - indicating eutrophication and open water (%). F) *Sphagnum* from the macrofossil record in indicating oligotrophic stages (%). G) *Chara* oospores - absolute values from the plant macrofossil record. H) *Carpinus betulus* percentage from the pollen record. I) Pollen indicators of cultivated fields (*Hordeum* t. cf., *Secale cereale*, *Cerealia* t. *Centaurea cyanus*, *Fagopyrum*) (%). J) Trees and shrubs from the pollen record (%). K) Testate amoebae-based reconstruction of the water table depth (cm). I) CAR - peat carbon accumulation rates $gC/cm^3/yr$. J) Statistically significant fire peaks/episodes calculated with the software CharAnalysis (Higuera et al., 2010). J) MAC - macroscopic charcoal influx (presented as sum of particles >500 µm and 100–500 µm) ($particles/cm^2/year$). K) MIC - microscopic charcoal influx.

periods of open water events. Just after the last telmatic stage the mire shifted abruptly into the bog stage with *Sphagnum* domination. Such frequent state shifts in mires have rarely been described in the literature, and most studies have focused upon the fen to bog transition as an effect of lake terrestrialisation and then acidification (Lamentowicz, 2005; Słowiński et al., 2016). Terrestrialisation is typical for peatlands situated in the recently glaciated areas of CE Europe (Kulczyński, 1949; Tobolski, 2003; Gąsiorowski et al., 2009). The lack of stability recorded in the Głęboczek profile is similar to other kettle hole peatlands in the Tuchola Pinewoods area (at a distance of 50 km from Głęboczek) (Lamentowicz et al., 2008b) - however this site experienced severe hydrological fluctuations which led to a 500-year hiatus recorded at the top of the profile.

The testate amoebae data (including periods of low abundance) suggests that the hydrology of the mire was highly unstable. Surprisingly, the telmatic stage between ca. 3300-1650 cal. BP is not as clearly visible in the NPP data. It is highly probable that the surface of the peatland was inundated seasonally (e.g. after snow melt or heavy rainfall) and remained for a part of the year under shallow water. This process was recorded for several peatlands in Poland such as Linje (Marcisz et al., 2015), Żabieniec (Lamentowicz et al., 2009a) and Tuchola (Lamentowicz et al., 2008b). Another example is the Mukrza mire which is also located in the Tuchola Pinewoods. This site was permanently inundated as result of damming of the Wda river which caused a local increase of the ground water which percolated through the sandy deposits of the outwash plain (Lamentowicz and Obremska, 2010). For the Głęboczek profile, *Centropyxis aculeata* peaks might be considered as a signal of wetter conditions and higher trophy (Lamentowicz and Mitchell, 2005). Very low concentrations of TA during the telmatic stage may also suggest that TA species typical for peatlands did not have good conditions for their development or they could have been washed into the lake basin during temporal flooding of the peatland. The lack of clear lake indicators like *Difflugia* spp. suggest that the mire remained terrestrial for at least part of the year. In the case of the Tuchola mire, *Diffugia urceollata* was an indicator of inundation which would suggest that this peatland possessed long-term high water table with additional nutrient inputs (Lamentowicz et al., 2008b). The contrast between NPPs and TA is highly intriguing, but it also suggests that small kettle hole peatlands with small catchment areas respond sharply to snowmelt and higher precipitation which result in flooding. They are also closely related to changes in the catchment conditions; therefore, land use features may modify the hydrological signal. In this sense they are closer to lakes in their signal than to large raised bogs which are expected to store the regional climatic signal (Charman, 2002). The development of raised bogs is more related to autogenic changes connected to the movement of microforms (Kettridge et al., 2012). In the case of small basins (several hectares in size), autogenic changes might play a less important role, providing a sharper allogenic signal (Warner et al., 1989; Lamentowicz et al., 2008b; Marcisz et al., 2015). Finally, we can state that small peatlands are less resilient than extensive sites which makes the more useful to identify subtle local changes. However, this question needs more studies in the future to quantify basin vs tipping point relationships.

The CAR was generally stable during the Mesolithic-Neolithic, lower during the Bronze Age, increased at 2330 cal. BP and then decreased during the Early Medieval period (Fig. 9). CAR fluctuations are not directly correlated to the plant macrofossil composition as we would expect to see higher values during periods of *Sphagnum* dominance. However, the CAR curve closely resembles the MIC and MAC curves which could suggest that fire occurrence in the catchment altered the hydrology of the site (increases in water table) which in turn affected long-term carbon accumulation.

The peat profile was very heterogenous therefore the plant composition was most possibly responsible for the CAR changes. In the top part (25 cm = 100 cal. BP) CAR reached 74−550 g C/m^2/yr (aver. = 185 g C/m^2/yr) - however, it is connected with the presence of the non-compacted acrotelm. These high CAR values are comparable with other peatlands from Poland (Bagno Mikołeska recorded CAR values between 140 and 142 g C/m^2/yr (Fiałkiewicz-Kozieł et al., 2014), Rzecin peatland recorded CAR values between 170 and 190 g C/m^2/yr (Milecka et al., 2017) and Teici bog (Latvia) recorded CAR values of 169 g C/m^2/yr (1.69 t C/ha/yr) during the last 180 years (Stivrins et al., 2018).

Considering the peat profile below 25 cm depth (in the catotelm) CAR was 37 g C/m^2/yr and varied from 2 to 97 g C/m^2/yr. Such values are unexceptional and are comparable with other peatlands from Europe or N and S America, where long and compacted profiles were analysed (Loisel and Garneau, 2010; Loisel and Yu, 2013; Loisel et al., 2014; Gallego-Sala et al., 2018).

5.2. Hornbeam (Carpinus betulus) history and increasing human pressure

Carpinus betulus is the important tree species that became more abundant since ca 3000 cal. BP along with increased fire activity. This covers the period from the Late Bronze Age to Early Middle Ages. The distinct increase in *C. betulus* around ca. 1600 cal. BP is associated with a decline of human impact in CE Europe (Ralska-Jasiewiczowa et al., 2003, 2004). Today pristine *C. betulus* woodlands are only found in Białowieża Forest (Latałowa et al., 2015). At the Głęboczek site *C. betulus* occurred in low abundance during the Neolithic and the Bronze Age, then started to expand and its fluctuations are associated with regeneration related to changing human impacts (Fig. 9). Increased forest openness around Głęboczek was recorded during the Iron Age when *C. betulus* abundance decreased. The pattern of the spread of *C. betulus* and fire activities, might suggest that humans may have been responsible for the changing abundance of *C. betulus* as through the exploitation. Forest cutting and fires introduced space for this species. Such patterns were noted for the hornbeam forests of Greater Poland (*Polish*: Wielkopolska), which experienced increased abundance of *C. betulus* along with intensifying human impact since the Bronze Age (Makohonienko, 2000). Moreover, the timing of the expansion of *C. betulus* and its fluctuations correlate well with the profile from the Tuchola kettle hole mire (Lamentowicz et al., 2008b) as well as other sites in the area (Hjelmroos, 1981; Berglund and Miotk-Szpiganowicz, 1992). The peak in abundance of this species is also well marked in both sites and can be related to the Migration Period (Zolitschka et al., 2003; Kaplan et al., 2009; Buntgen et al., 2011; Kołaczek et al., 2018). At the Głęboczek site *C. betulus* decreased around ca 1000 cal. BP as a result of the development of the Early Medieval economy, however, no clear response of other tree taxa was recorded, for example *Betula* increases in abundance (Fig. 3). This pattern suggests the importance of this species as it was especially selected and used mostly as firewood during the Middle Ages (Cywa, 2018). It is confirmed by the simultaneous increase of the macro charcoal with the *Carpinus betulus* decrease. A similar process of *C. betulus* disappearance in the Middle Ages was described by Makohonienko (2000) for Greater Poland. The horizon at ca. 1000 cal. BP is another important threshold meaning the loss of the virgin forest along with the development of the Polish state (Makohonienko, 2000). The history of this species which is connected with Medieval loss of forest naturalness is interesting and needs more attention in future studies. There is also an intriguing correlation between the spread of *C. betulus* during the Migration Period and the abrupt increase of *Sphagnum* in the profile. This suggests oligotrophication and decreasing water table depths in the peatland may have had a climatic origin. This pattern is so striking that it deserves our attention in the future.

5.3. Signal of the past societies

Although the development histories of many sites appear to be well documented, large gaps remain in our understanding of peatland ecosystem dynamics in relation to various stressors. The amount and types of disturbance in prehistoric central Europe landscapes since the retreat of the Vistulian ice sheet are still not well understood. Traces of past human activities are recorded in the Głęboczek profile. The peatland ecosystem was affected by various drivers connected with climate change and human activities. Changes to the vegetation of the mire and its surroundings were driven by extrinsic processes such as climatic fluctuations and those connected with gradually emerging human communities during the last 6500 years. The data show that even small changes in terms of forest cutting or burning may have had a distinct signal. The Głęboczek profile recorded intense anthropogenic fire activity in the surroundings, which suggests the importance of the area for the societies who were actively changing the landscape. Local fires represented by the MAC record indicate climate and human impact. MAC and cultivated area pollen indicators suggest that local human communities started changing the Głęboczek mire landscape as early as the Neolithic (ca. 5500 and 5000-4500 cal. BP) and later in the Bronze Age (ca. 3700-3200 cal. BP). Lower local fire activity was recorded during the late Bronze Age and the Hallstatt Period which may suggest a reduced importance of the area for people during this time interval, when the climate may have been wetter (as recorded by the micro-algal record). Increased precipitation may have supressed fire activity. We also recorded a hiatus in the top peat layers, possibly as a result of peatland burning. Other fire records from Poland do not show such distinct charcoal layers in the peat (Marcisz et al., 2015, 2017, 2019). Based on the MIC and pollen records, we determined a community threshold value of 7500 charcoal part./cm^2/yr at which vegetation changes have been observed. Anthropogenic indicators (such as *Plantago lanceolata* and *Rumex acetosa/acetosella* t.) as well as *Pinus sylvestris* responded positively to fires (Fig. 8). This threshold determines the critical consistent transition that related fires to human impact on the vegetation that took place ca. 3700 years BP when the level of 7500 charcoal part./cm^2/yr was consistently crossed until today. It was also intermittently crossed ca. 6000 and 5500 years BP, when it was natural or possibly connected to the activity of the Meso- and Neolithic societies.

We compared existing archaeological data and our multi-proxy palaeoecological indicators of human impact. In total, 19 sites situated within a radius of approx. 7 km from Głęboczek were identified based upon archival research, as well as the available literature (all mentioned archaeological sites are presented in Fig. 1 and Supplementary Table 1). Archaeological reconnaissance field surveys undertaken during the last years at nearby Lake Czechowskie (Fig. 1) served to document the presence of a few sites situated in the Iwiczno village.

5.3.1. *Beginnings — Mesolithic*

The oldest known archaeological artefacts in the Głęboczek vicinity are Mesolithic flint artefacts found in Młyńsko village (Łęga, 1946). The Głęboczek archive registered signal of early communities (Mesolithic (?) and Neolithic) impacts upon the environment, but past societies were also considerably affected by climatic changes. A decline of *Sphagnum* and a transition of the mire into an eutrophic stage can be related to the 6000 cal. BP event marking a climate induced change triggering the transition to the Neolithic (Warden et al., 2017). This climate warming after ca. 6000 cal. BP is thought to have supported the Mesolithic-Neolithic transition in N Europe (Warden et al., 2017).

Only a few traces of single short-lived Mesolithic camp sites were discovered in the Tuchola Pinewoods (Grabarczyk, 1992; Kabaciński, 2016). Importantly, in the Klonowice site, situated only about 10 km W of Głęboczek, a complex of camp sites was discovered with finds from the Mesolithic and Neolithic as well as the early Bronze Age (Domańska, 1995; Górska-Grabarczyk, 1996). Numerous Mesolithic sites were documented ca 35 km from Głęboczek to the WSW, in the Brda and Zbrzyca river valleys (Bagniewski, 1986, 1987). Some of them received very late radiocarbon dates (5000-4000 BP) (Bagniewski, 1987) and they may be evidence for significant activity of the hunter-gatherer communities.

5.3.2. *Neolithic*

A number of artefacts connected with the Neolithic have been discovered in the villages of Czarne and Iwiczno (Bericht, 1888). The Neolithisation of Eastern Pomerania began 7250/7150 cal. BP (Czerniak et al., 2016). It resulted from the spread of the Linear Pottery Culture (LPC) farmers, who came into contact with hunter-gatherer communities (Felczak, 2009; Czekaj-Zastawny et al., 2013). Several LPC sites are known for the area adjacent to the Vistula River valley, situated ca 30—35 km SE and ESE of Głęboczek (Felczak, 1987, 1998, 2009, 2009; Jarzęcka and Kochanowski, 2005; Kochanowski, 2005; Felczak, 2009; Czekaj-Zastawny et al., 2013; Kurzyk and Ostasz, 2015; Szmyt, 2017; Czerniak, 2018; Czerniak, 2018, 2018; Sikora et al., 2018).

From an archaeological point of view, the data obtained in the area of the Tuchola Pinewoods do not confirm an intense colonisation during the Neolithic (Grzelakowska, 1989a; Grabarczyk, 1992). The dominant ones are loose finds - mostly potsherds and stone axes (Rajewski, 1932; Łuka, 1974; Grabarczyk, 1992). Occasionally, elements of the LPC were discovered and the Globular Amphora Culture (GAC), as well as the Corded Ware Culture (CWC) (Jankowska, 1983), came to the conclusion that the Tuchola Pinewoods area was penetrated by small groups of people involved in forest cattle grazing during the Neolithic which may account for the weak evidence for human impact recorded in the Głęboczek profile. Jankowska (1983) and Grzelakowska (1989b) also emphasised the role of stock breeding in the economy of the FBC people in Pomerania, however cultivation on a small scale is not excluded. We recorded the first pollen indicators of agriculture at ca. 6100 cal. BP, but continuous signals of agrarian societies in the Głęboczek profile started at ca. 5000 cal. BP which suggests a smooth transition from hunter-gatherer into farming societies. This horizon can be regarded as the transition to the farming lifestyle of the Neolithic Revolution in the study area. The charcoal and pollen signals at ca. 5600 cal. BP possibly resulted from the activities of the FBC people.

5.3.3. *Bronze Age*

The cultural pattern of the area is not clear at the transition from the Neolithic to the Bronze Age, which in this part of Pomerania should be associated with the settlement of the Iwno Culture (IC) people (Włodarczak, 2017). Traces of IC settlement were discovered in the vicinity of the Vistula River Valley (Kurzyk and Ostasz, 2015), at a site situated more than 40 km NE of Głęboczek. In the Tuchola Pinewoods, only a few sites are dated to the early Bronze Age and connected with the activity of IC as well as the Trzciniec Culture (TC) people (Grzelakowska, 1989a) — all are situated between 15 and 45 km to the W of Głęboczek. Analysis of the distribution of sites dated to the older Bronze Age also indicates a very low number - in a radius of ca. 15—20 km from Głęboczek, there were sites in: Grabowo, Leśna Jania and Łąg (Dąbrowski, 2004). The increase in human impact on the vegetation was noted in pollen profiles from the Tuchola Pinewoods at the turn of the Neolithic and the Bronze Age. This could be associated with the development of forest cattle grazing and cereal cultivation (wheat, barley, and perhaps rye) (Hjelmroos, 1981; Berglund and Miotk-Szpiganowicz, 1992; Miotk-Szpiganowicz, 1992).

In this context, the Głęboczek data support the increased human impact during the Neolithic and Bronze Age. In the Głęboczek record we have found a strong Bronze Age anthropogenic signal since 4000 cal. BP marked by the cultivated land indicators, local deforestation and fires expressed by the peaks of the macro charcoal at ca. 3540 (IC) and 3380 cal. BP (TC). This clear signal suggests that the area was possibly densely populated during this time. However, there is no clear evidence from archaeological sources as no archaeological investigations have been undertaken nearby.

5.3.4. *Late Bronze Age and early Iron Age*

Significant cultural changes in Eastern Pomerania began during the middle Bronze Age. During this period (ca. 3250 cal. BP), new trends in funeral rites appeared — i.e. cremation. The settlement and occupation of the microregion by Lusatian Culture (LC) people was studied in Leśno (Walenta, 2008), situated ca 35 km NW of Głęboczek. However, the LC settlement during the younger Bronze Age was scattered in the Tuchola Pinewoods area and the sites are not numerous (Łuka, 1983; Górska-Grabarczyk, 1998). The situation changes markedly in the Early Iron Age (Dzięgielewski, 2017a, 2017b). At this time, the Pomeranian Culture (PC) developed in Eastern Pomerania. In the surroundings of the study site there are burial grounds with stone box graves and other finds from this period. A large number of cemeteries with stone box graves dated to the Early Iron Age were recorded throughout the whole area of Eastern Pomerania (Łuka, 1983), as confirmed by the results from the Starogard Lakeland (Fudziński, 2011) and Tuchola Pinewoods (Grabarczyk, 1992). Remnants of a PC settlement are known from Odry (Łuka, 1966; Grzelakowska, 1990), Leśno and Zalesie (Walenta, 2008).

Stone grinders discovered in the Lusatian Culture (LC) settlements in Leśno (Grzelakowska and Balwierz, 1985; Grzelakowska, 1989a; Walenta, 1992a), and Raciąż (Kmieciński, 1990; Grabarczyk, 1992) as well as re-used for the box graves' constructions (Ossowski, 1879). Cereal crops carried out by the PC people are confirmed by grain prints on pots and charred grains found in plant macro remains (Klichowska, 1979; Podgórski, 1979). Archaeologists however believe that stock breeding played a more important role than crop cultivation in the PC community economy (Łuka, 1974; Grzelakowska, 1989b; Grabarczyk, 1992). The results of former palynological research indicate that intense development of pastures and arable fields with cultivation of cereals, as well as distinct deforestation in the Tuchola Pinewoods date from the younger Bronze Age till the mid Pre-Roman Period (Berglund and Miotk-Szpiganowicz, 1992; Miotk-Szpiganowicz, 1992). In this context, the wet stage in Głęboczek dated to 3200-2400 cal. BP is marked by an increase of cultivated land indicators and Tetraedron minimum algae. This could confirm strong human impact during this time and increased openness in the landscape around the mire. This algae maximum appeared later than the cultivated land pollen indicators which suggests a time lag after the forest clearances. Independently, such a correlation suggests a strong dependence upon the basin hydrology and the surrounding vegetation. Simultaneously there were few local fires (indicated by the macroscopic charcoal), therefore we could assume that the wetter climatic phase overlapped with Bronze Age and the Early Iron Age human activities (Ossowski, 1879; Łuka, 1974; Grzelakowska and Balwierz, 1985; Grzelakowska, 1989a, 1989b; Kmieciński, 1990; Grabarczyk, 1992; Grabarczyk, 1992, 1992; Walenta, 1992a).

In Eastern Pomerania, a high level of depopulation has been proposed during the Pre-Roman Period (Łuka, 1983; Strobin, 2017). The number of known sites from this period decreased significantly, which should be combined with significant cultural and settlement changes (Strobin, 2017). Based on the archaeological data, the Tuchola Pinewoods area was uninhabited between the ca. 2200 cal. BP and until the ca. 1900–1875 cal. BP (Walenta, 1980; Kokowski, 1988; Strobin, 2011). However, a continuous settlement by PC communities to the Roman Period in separate microregions of the Tuchola Pinewoods area has also been considered (Berglund and Miotk-Szpiganowicz, 1992; Walenta, 1992b), and also from Czechowskie Lake (Obremska et al., 2017). Cemeteries of the Oksywie Culture (OC) people from the Younger Pre-Roman Period (ca. 2200-2100 cal. BP) are more frequent in the Vistula River valley, but they also occur in the Pomeranian Lakeland – e.g. in Chwarzno ca 12 km N of Głęboczek (Strobin, 2011).

5.3.5. *Roman Period to the Middle Ages*

The Głęboczek area is almost completely devoid of documented remnants from the Roman Period. However, a cemetery of the Wielbark Culture (WC) people dated to the Early Roman Period are known from Osowo Leśne (Szymańska, 1974) ca. 7 km E (Szymańska, 1974) Czarna Woda and Złe Mięso (Grabarczyk, 1997) ca. 7 km SW, and Struga (Słowik, 1997) ca. 10 SW of Głęboczek. The large necropolis with barrows and stone constructions from this period were excavated in Odry (Grabarczyk, 1997) ca. 15 km W and in Leśno (Walenta, 1980, 1999) and 35 km NW (Słowik, 1997) of the site area.

The most intense occupation of the WC societies was from ca 1870 to ca 1680 cal. BP (Grabarczyk, 1985, 1997; Walenta, 2009). The WC people settlement in Ostrowite was dated however from ca 1900 cal. BP to ca 1550–1600 cal. BP (Sikora et al., 2018). The evidence for intense economic activity, including agriculture, during this period was documented in archaeological materials (see Grabarczyk 1992, 1997; Walenta, 2009). In Odry, a quern-stone was excavated (Grabarczyk 1992), as well as traces of ploughing (Kmieciński, 1968), which could be connected to the Roman Period (Kittel, 2005).

Palaeoecological signal from the Głęboczek site are contrasting to the lack of archaeological sites from the study area. The human impact signal decreased in the Głęboczek profile after ca. 3380 cal. BP and increased again later during the Pre-Roman (La Tène) Period, and the Roman Period with the strongest signal between ca. 1800 and 1600 cal. BP (marked by high fire activity and deforestation). It was connected with the WC societies which expanded during this time in Pomerania and reviewed in archaeological and palaeoecological sources (Grabarczyk, 1985, 1997). In the neighbouring Lake Czechowskie the record of human impacts related to the WC covers nearly 400 years (between ca. 1900 and 1400 cal. BP) (Obremska et al., 2017). During this time a deforestation signal (including *C. betulus*) was inferred together with higher local fire activity. A subsequent reduction in burning, reforestation (expansion of *C. betulus*) and oligotrophication of the site was an effect of the settlement hiatus during the Migration Period.

Traces of human activity in Eastern Pomerania are also very rare for the period from the end of the ca. 1650–1300 cal. BP. The Migration Period is represented by only a very few sites in the Eastern Pomeranian territories (Mączyńska, 2007; Kokowski, 2016). In the early Middle Ages, ring-forts became settlement centres. The nearest to Głęboczek are the strongholds in Grabów, 25 km to ESE and in Raciąż, Ostrowite and Obrowo (Zoll-Adamikowa, 1969; Sikora et al., 2017) located 40–45 km to the SW of Głęboczek.

5.4. *Possible climatic drivers*

Our multi-proxy study provided not only information about the impacts of past human societies on the local environment, but it also allowed us to investigate the potential climatic drivers which affected the mire. We identified distinct shifts in the palaeohydrological and trophic nature of the site recorded by the testate amoebae, plant macrofossil and peat carbon accumulation rate data (Fig. 9).

The cold event at ca. 4200 cal. BP might be connected with the end of the second *Sphagnum* increase and decrease in the Głęboczek carbon accumulation rates. This episode has been globally recognised (Cullen et al., 2000; Bond et al., 2001; Marchant and Hooghiemstra, 2004), however *Sphagnum* encroachment fits better to the cold event determined ca. 4800 cal. BP by Wanner et al. (2011). Contrasting responses have been identified in different parts of the world - causing droughts at lower latitudes as well as cooler and wetter conditions at higher latitudes (Booth et al., 2005). In the case of the Głęboczek site, *Sphagnum* encroachment overlaps with reduced human impact and the global cold period (Wanner et al., 2011), this might suggest less favourable climatic conditions for the local communities. Fluctuations of the water table in the peatland and the surrounding hydrological system could be an effect of climate cooling (Wanner et al., 2011). Stążki raised bog (located near Kartuzy) experienced a similar phase ca. 4200 cal. BP (Gałka et al., 2013) as well as Tuchola mire which includes a hiatus and records lower peat accumulation rates (Lamentowicz et al., 2008b). These are different peatland types and the responses reflect different patterns, but in the end they experienced lowered water tables at ca. 4.2 k. cal. BP. However, the robustness of the age-depth models in these studies is distinctly lower; hence, these chronological inferences considering the '4.2 k. BP event' are more tentative. We should stress that also local catchment and autogenic processes can be responsible for the hydrological/trophic changes in Głęboczek, however, we cannot exclude the climate as the driver of change in the mire ecosystem.

At ca. 3500 cal. BP a prolonged wet shift occurred and lasted for ca. 1600 years. The increase of the water table might be partly connected with climatic changes. The telmatic stage probably resulted in the intermittent inundation of the surface. This is the time of the development of the Bronze Age and Early Iron Age societies in the area. The weakening human impact signal during the higher water table phase between ca. 2800-2600 cal. BP possibly reflects higher effective precipitation which affected the Lusatian Culture at the Biskupin settlement (Dzięgielewski, 2017b). Baltic bogs (Bagno Kusowo, Stążki and Gązwa) in N Poland responded as well with higher accumulation rates and synchronous change in the plant composition towards the *Sphagnum fuscum/rubellum* dominated communities (Gałka et al., 2013, 2015). This wet shift has also been observed in other European wetlands (Martin-Puertas et al., 2012) and has been interpreted as the effect of the grand solar minimum at ca. 2800 cal. BP by some authors (van Geel et al., 1996). We expected to see the clear ca. 2600 cal. BP wet climatic shift but the peatland remained hydrologically unstable during this period. However, at ca. 2400 cal. BP carbon accumulation rates increased sharply along with a higher number of *Chara* oospores. This can indicate higher accumulation rates of organic matter under the moister climate conditions. However, this period is also connected with a higher human impact and local fires which potentially led to deforestation and increases of the water level in the mire as well as in Lake Głęboczek, which is an alternative explanation (non-climatic) for this wet shift.

The Głęboczek profile recorded a pronounced climatic and societal shift during the Dark Ages Cold Period (DACP) (Williams, 2000; Helama et al., 2017), which is indicated by the decrease in pollen indicators of human impact. This climatic deterioration affected past societies and triggered the Migration Period (ca. 1600-1300 cal. BP) (Buntgen et al., 2011; Moschen et al., 2011). The signal of the cooler and possibly wetter conditions is expressed by the decrease of macro charcoal as well as a sharp transition to the *Sphagnum*-dominated ecosystem. At this point in time Głęboczek crossed the next ecological tipping point.

6. Conclusions

We provided a new proxy-based reconstruction of the past environmental change and human impact in N Poland based on the densely-dated peat profile. The archaeological data confirm a human presence in the Głęboczek area as early as the Neolithic. This peatland connected with the wetland system of the nearby lakes experienced several critical transitions and bog-fen-bog shifts which imply connection and disconnection from the local ground water tables. Using the charcoal and pollen data we determined that the local pollen-based community threshold for fire intensity (measured as micro charcoal influx) is ca 7500 particles/cm^2/year. We discovered that it was also important tipping point for the divergence between plants related positively (e.g. human indicators, *Carpinus betulus*) or negatively (e.g. *Quercus*) to the fires. The first pollen grains connected with human activities were found at ca. 6100 cal. BP, however there is evidence for constant human impacts since ca. 5000 cal. BP.

Past societies actively affected the mire's environment. The strongest signal comes from the Neolithic (Funnel Beaker Culture, Globular Amphora Culture and Corded Ware Culture), Bronze Age (Iwno Culture, Trzciniec Culture and Lusatian Culture) and then Pre-Roman and Roman Periods (Pomeranian Culture and/or Oksywie Culture and Wielbark Culture). These past societies exploited the natural resources and actively used fire.

Our data correspond well with the recent global assessment of land use in the Holocene that shows the Earth largely transformed by hunter-gatherers, farmers, and pastoralists by 3000 years ago (Stephens et al., 2019). We also agree with Stephens et al. (2019) that large-scale anthropogenic global environmental change is not a recent phenomenon that confronts with the emerging Anthropocene definition.

The Głęboczek profile is the first densely ^{14}C dated multi-proxy peat profile which has been investigated in an archaeologically unexplored area. We show that probably there are still many undiscovered archaeological sites in the area which might lead to new interesting findings to better understand cultural development of local societies from the Pomerania and their relations with the natural landscape and resources.

The context of fire occurrence thresholds and past dynamics becomes more important when we consider recent global warming. Our new data show that the combination of highly flammable vegetation (woodlands in the mire were dominated by *P. sylvestris*) and past human disturbance is also relevant for ongoing and future changes of fire frequency in a changing climate.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.105954.

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