The Holocene

Late Glacial and Early Holocene development of an oxbow lake in Central Europe (Poland) based on plant macrofossil and geochemical data

Journal:	*The Holocene*
Manuscript ID	HOL-19-0092.R1
Manuscript Type:	Paper
Date Submitted by the Author:	n/a
Complete List of Authors:	Gałka, Mariusz; University of Lodz, Department of Geobotany and Plant Ecology Lewandowska, Agnieszka; Adam Mickiewicz University Niedzielski, Przemysław ; Adam Mickiewicz University Sim, Thomas; University of Leeds Faculty of Environment, School of Geography Swindles, Graeme; University of Leeds, School of Geography Szczurek, Grzegorz; Adam Mickiewicz University, Institute of Archaeology
Keywords:	plant succession, climate change, Prosna river, peatland, plant macrofossils, Sphagnum
Abstract:	Sediments from an oxbow lake located in the Prosna River valley (Poland) were analysed to investigate the developmental history of the wetland ecosystem and any response to abrupt climatic changes. High resolution plant macrofossil analysis and radiocarbon dating were undertaken on two cores, with lower resolution geochemical analysis conducted on one of these cores. We provide evidence of a palaeolake with a Late Glacial origin (older than 12,500 years). Abundant fossil presence of macrophytes (e.g. multiple Potamogeton species) in the studied palaeomeander may indicate that the north-south orientation of the Prosna valley made it an important route for the spreading of aquatic plants during the Late Glacial. Chara sp., Batrachium sp. and Potamogeton spp. were the pioneer plants that colonized cold water with a high Ca2+ content. Early Holocene warming trigged a decrease in water level at oxbow lake and facilitated the expansion of thermophilous water plants e.g. Ceratophyllum demersum, Typha sp. and Lemna trisulca, which usually occur in shallow water. A decreasing water level resulted in the gradual isolation of the study site from the influence of groundwater, leading to acidification of the habitat and the development of a Sphagnum population, with S. contortum and S. teres as dominant species. The presence of S. contortum (the oldest occurrence in the European lowlands) and S. teres during the early Holocene may indicate that river valleys and the peatlands that developed in that region, acted as an important habitats (and possibly refugia) for some minerotrophic Sphagnum species.

Late Glacial and Early Holocene development of an oxbow lake in Central Europe (Poland) based on plant macrofossil and geochemical data

Mariusz Gałka[1]*, Agnieszka Lewandowska[2], Przemysław Niedzielski[3], Thomas Sim[4], Graeme Swindles[4,5], Grzegorz Szczurek[6],

[1]Department of Geobotany and Plant Ecology, University of Lodz, Poland: mariusz.galka@biol.uni.lodz.pl; ORCID: 0000-0001-8906-944X

[2]Department of Biogeography and Palaeoecology, Adam Mickiewicz University in Poznan, Poland: lewandowska.a@onet.com.pl

[3]Department of Analytical Chemistry, Adam Mickiewicz University in Poznan, Poland; pnied@amu.edu.pl

[4]School of Geography, University of Leeds, UK; gy12tgs@leeds.ac.uk

[5]Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, K1S 5B6, Canada; G.T.Swindles@leeds.ac.uk

[6]Institute of Archaeology, Adam Mickiewicz University in Poznan, Poland; grzegorzszczurek711@gmail.com

*Corresponding author: mariusz.galka@biol.uni.lodz.pl

Abstract

Sediments from an oxbow lake located in the Prosna River valley (Poland) were analysed to investigate the developmental history of the wetland ecosystem and any response to abrupt climatic changes. High resolution plant macrofossil analysis and radiocarbon dating were undertaken on two cores, with lower resolution geochemical analysis conducted on one of these cores. We provide evidence of a palaeolake with a Late Glacial origin (older than

12,500 years). Abundant fossil presence of macrophytes (e.g. multiple *Potamogeton* species) in the studied palaeomeander may indicate that the north-south orientation of the Prosna valley made it an important route for the spreading of aquatic plants during the Late Glacial. *Chara* sp., *Batrachium* sp. and *Potamogeton* spp. were the pioneer plants that colonized cold water with a high Ca^{2+} content. Early Holocene warming trigged a decrease in water level at oxbow lake and facilitated the expansion of thermophilous water plants e.g. *Ceratophyllum demersum, Typha* sp. and *Lemna trisulca*, which usually occur in shallow water. A decreasing water level resulted in the gradual isolation of the study site from the influence of groundwater, leading to acidification of the habitat and the development of a *Sphagnum* population, with *S. contortum* and *S. teres* as dominant species. The presence of *S. contortum* (the oldest occurrence in the European lowlands) and *S. teres* during the early Holocene may indicate that river valleys and the peatlands that developed in that region, acted as an important habitats (and possibly refugia) for some minerotrophic *Sphagnum* species.

Keywords: plant succession, climate change, Prosna River, peatland, plant macrofossils

Introduction

Rapid climate warming during the transition from the last glacial period to the Holocene resulted in a shift in biogeographic zones and the creation of meridional migration gateways for plants. River valleys are important habitats for many wetland plant species and provide suitable pathways for their expansion (cf. Naiman and Décamps, 1997), particularly since the deglaciation of northern Europe (Szafer, 1946; Kolstrup, 2007; Kołaczek et al., 2016). The Late Glacial and early Holocene (ca. 15,000-8500 years ago) was characterised by major climate fluctuations and a transition from a cold to warm climate (Rasmussen et al., 2014). This climatic warming influenced the fluvial processes occurring in European lowland river valleys (Starkel et al., 2006). Climate fluctuations in the Late Glacial have been directly linked to a changes in river bed morphology in Polish lowlands and changes in flora associated with the formation of meanders, oxbow lakes and peatlands (Starkel et al., 2006; 1997; Pawłowski et al*.,* 2016; Słowik et al., in review). Sediments deposited in river valleys produced a stratigraphic record and are surrounded by former oxbow lakes and peatlands. Detailed palaeoecological studies of the deposits accumulated in river valleys provide useful information about past environmental changes (Magyari et al., 2010; Pawłowski et al., 2015, 2016a, b; Kołaczek et al., 2016; 2018). Moreover, reconstructing the response of riparian and wetland biota to previous rapid climate changes (e.g. Late Glacial and early Holocene transition) can inform the prediction of future vegetation shifts in response to changing temperature, precipitation and flood frequency (Garssen et al., 2014; Thodsen et al., 2016; Dwire et al., 2018).

Previous studies of river valleys in the central part of the Polish lowlands have focused mainly on their evolution, palaeohydrology and the geochemical composition of organic deposits (Dąbrowski et al*.,* 1963; Michno, 2004, 2005; Starkel et al., 2006; Słowik, 2011, 2013; Borówka et al., 2015; Kittel et al., 2016). Recent palaeoecological studies of Late Glacial and Holocene sediments using fossil biotic data to investigate the influence of climate change (e.g. temperature) have been carried out in the Ner river (Kittel et al., 2016; Płóciennik et al., 2016), Grabia river (Pawłowski et al., 2015, 2016a,b) and Bug river (Kołaczek et al., 2018). However, detailed knowledge regarding local plant succession, especially macrophytes, and ecosystem adaptation to abrupt climate changes in river ecosystems is lacking.

The Prosna Valley has primarily been studied in terms of its geology and geomorphology (Dąbrowski et al., 1963; 1991; Dyjor, 1985; Młynarczyk and Rotnicki, 1989), alongside archaeological research aimed at understanding the relationship between settlement distribution and landform development (Dąbrowski et al., 1963; Stupnicka et al., 2006).

Here we present the first detailed plant macrofossil and geochemical records dated by radiocarbon analysis in the Prosna River valley. The Prosna valley is ideal for palaeoecological reconstructions because of unique and well-preserved palaeomeanders filled with organic sediment. The extent and scale of the resulting landforms appears to be linked with the establishment of fortified settlements e.g. near the village of Grodzisko (Kaczmarek and Szczurek, 2015).

Focussing on the long-term dynamics of oxbow ecosystem, we aim to: i) date the beginning of organic sediment deposition; ii) reconstruct the initial stage of development of local vegetation in the oxbow lake; iii) determine the impact of climatic changes on local plant succession; iv) detect the presence of possible refugia for some minerotrophic *Sphagnum* species; v) assess the variability of physicochemical parameters in the oxbow lake and investigate any potential relationship with plant succession.

Study site

The study site is located in Central Poland, near the village of Grodzisko, ~750 meters south-west of the current Prosna River (Fig. 1). In the Prosna River valley on the outskirts of the village, there are remains of a settlement called "Szwedzkie szańce". The fortified settlement is located in a marshy area of a former river valley, which enhances its natural defensive position (Śmigielski and Szczurek, 2013). Establishment of the settlement is associated with the defensive construction movement at the beginnings of the Iron Age in Wielkopolska (Kaczmarek and Szczurek, 2015).

The first phase of development for the Prosna fossil valley took place towards the end of the Pliocene and has evolved during subsequent glacial and interglacial cycles through to the Pleistocene and Holocene, creating the present day sediment record (Piszczygłowa, 2014). The youngest sediments filling the valley are comprised of glacial clay, the sand-gravel series, and organic deposits including gyttja and peat (Młynarczyk and Rotnicki, 1989; Piszczygłowa, 2014). The climate is temperate and affected by both maritime and continental influences. The average annual temperature is around 8.5 °C, with a small number of frost days across the year. The winter period is the most variable in terms of temperature, ranging between -8.8 °C and 2.2 °C. The growing season lasts 210 days. The Prosna valley, especially in the southern and eastern parts, has one of the lowest annual rainfalls in Poland at 500-550 mm (Woś, 1999; Lorenc, 2005).

The natural vegetation of the Prosna valley has been strongly modified by humans, with the area of palaeomeander converted to an agricultural meadow. The main tree species in the valley are: *Alnus glutinosa, Salix* spp., while in the drier places *Pinus sylvestris* is the dominant species. Among vascular plants *Carex* spp., *Juncus* spp., and *Ranuculus* spp., are dominant species.

Materials and methods

Cores were taken using a Russian peat corer, 5 cm in diameter and 50 cm in length. The cores GRI (186 cm long) and GRII (240 cm) were placed in PVC tubes following extraction, individually wrapped and stored at 4 °C until subsampling. In the laboratory the sediment was unpacked, cleaned and sliced into 1-cm slices using a surgical scalpel.

To determine the start of organic sediment accumulation in the study area, macrofossils of terrestrial plants from four samples were selected for AMS radiocarbon dating. Radiocarbon dating was carried out in the Poznan Radiocarbon Laboratory. The resulting conventional radiocarbon dates were calibrated using OxCal 4.1 software (Bronk-Ramsey, 2009).

Plant macrofossils were analysed at 1 cm intervals contiguously in the two cores for the time period of interest (Late Glacial/Early Holocene). In the GRI Core, 100 samples were analysed for plant macrofossil remains from 85-186 cm and in the GRII 105 samples were analysed from interval 135-240 cm. The total volume of material analysed for plant macrofossils per sample was ca. 8 cm^3. The samples were rinsed under a warm-water spray over 0.20 mesh screens. The vascular plant composition was determined on the basis of carpological remains and vegetative fragments (leaves, rootlets, epidermis) using the available identification keys (Tobolski, 2000; Velichkevich and Zastawniak, 2006, 2008). Mosses were identified using the keys prepared by and Hölzer (2010). The reference collection of plant macrofossils and recent plant material gathered by Mariusz Gałka was also used. The macrofossils were identified using a Nikon SMA 800 stereoscopic microscope under 10-200A and an Olympus CX 41 biological light microscope. Fossil fruits and seeds are expressed in absolute numbers, and the contribution of mosses (e.g., *Sphagnum contortum*) and vascular plants rootlets are expressed in percentage values of the total volume of a sieved sediment sample. A total of 205 samples were analysed. The names of the plant species were adopted following Mirek et al. (2002).

In order to determine the concentration of 59 chemical elements, a 5110 ICP-OES (Agilent, USA) inductively coupled plasma with optical emission spectrometry was used. For multi-elemental determination, the common conditions were as follows: radio frequency (RF) power, 1.2 kW, nebulizer gas flow, 0.7 L min^{-1}, auxiliary gas flow, 1.0 L min^{-1}, plasma gas flow, 12.0 L min^{-1}, viewing height for radial plasma observation, 8 mm, detector CCD (charge coupled device) temperature, -40 °C, and signal acquisition time, 5 seconds for 3 replicates. The detection limits were 0.01 mg kg^{-1} dry weight for all elements (at 3-sigma criteria). The uncertainty for the total analytical procedure (including sample preparation) was 20%. The traceability was checked using reference materials: CRM S-1–loess soil; CRM NCSDC (73349)–bush branches and leaves; CRM 2709–soil; CRM 405-estuarine sediments; and CRM 667-estuarine sediments. The recovery (80-120%) was acceptable for most elements. For uncertified elements, recovery with the standard addition method was defined.

Plant macrofossils and geochemical data are presented in diagrams and were plotted using the C2 software (Juggins, 2007). Stratigraphic clustering and ordination analysis was conducted in R version 3.4.3 (R Core Team, 2018). Stratigraphic zones in the plant macrofossil and geochemical records were defined using constrained incremental sum of squares cluster analysis (CONISS; Grimm, 1987) with the Gower dissimilarity index to allow for zero values in the packages vegan (Oksanen et al., 2019) and rioja (Juggins, 2018). We conducted ordination analysis to explore the relationship between corresponding geochemical and plant macrofossil data in the GRI record. Plant macrofossil species with <5 occurrences in the record were removed from ordination analysis to reduce clustering. As a result of the mixture of plant macrofossil relative abundance and count data we used the "capscale" function in vegan (Oksanen et al., 2019), a variant of constrained ordination of principle coordinates (CAP; Anderson and Willis, 2003), with Gower (1971) dissimilarity (see Birks, 2014). Correlation analysis (Spearman's Rank) was conducted on geochemical variables to identify redundant variables, these were then removed from the CAP analysis to improve clarity of the bi-plot.

Due to a hiatus spanning the middle Holocene at the study site, we present only the lower part of the collected profiles. The lower profiles span the Younger Dryas and the early Holocene, while the upper profile representing the late Holocene has a broader archaeological context and will be presented in another paper.

Results

Lithostratigraphy and chronology

The details of the sediment lithostratigraphy are presented in Table 1. At both sampling sites detrituous-calcareous gyttja accumulated on top of a silt and sand layer. Terrestrial plant macrofossil material for radiocarbon dating was selected from 1-cm core slices. Four samples were taken in total, with two from each core respectively (Table 2). Two of the samples (GRI, 145.5 cm; GRII, 226.5 cm) were selected in order to date the beginning of organic sediments (gyttja) accumulation. However, due to lack of reliable plant macrofossils it was impossible to date the bottommost part of the sediments in both cores. Nevertheless, our interpretation is that organic sediments were deposited in final stage of Younger Dryas period and after several hundreds of years into the early Holocene peat started forming (GRI 144 cm; GRII 172 cm) on top of the detrituous gyttja layer.

Plant macrofossils

Core GRI

Five zones in the local vegetation development we identified for plant macrofossils in GRI, confirmed by CONISS (Gower; Fig. 2). The zone GRI-pm-1 (186-165 cm) is characterised by a dominance of *Chara* sp. alongside *Potamogeton perfoliatus, Potamogeton fresii, Potamogeton natans* and *Myriophyum* sp.. GRI-pm-2 (165-147 cm) sees a decline in *Chara* sp. and is the last zone where *Potamogeton* spp. is present, while the macrophytes *Sparganium minimum*, *Typha* sp. appear. *Pinus sylvestris* macrofossils were also observed for the first time in GRI-pm-2. GRI-pm-3 (147-120 cm) is characterised by Cyperaceace, herbs, *Carex* spp., *Menyanthes trifoliata* and tree macrofossils. In GRI-pm-4 (120-97 cm) *Sphagnum contortum* dominates alongside periods of *Meesia triquetra* and *Sphagnum teres*. In the zone GRI-pm-5 (97-85 cm) mosses disappear, while numerous *Menyanthes trifoliata* seeds were present and *Alisma plantago-aquatica* appeared for the first time.

Core GRII

Six zones in the local vegetation development, confirmed by CONISS (Gower), were determined for the core GRII (Fig. 3). GRII-pm-1 (240-217 cm) is composed of *Chara* sp., *Myriophyllum* sp., *P. natans* and *P. fresii*. In GRII-pm-2 (217-202 cm) *Chara* sp. are still present, alongside *Carex* sp. and *P. sylvestris*. During GRII-pm-3 (202-187 cm) *Ceratophyllum demersum*, *Nuphar* sp. and *Typha* sp. appear with *Carex* sp. and the tree macrofossils (*P. sylvestris* and *Betula* sp.) are present throughout. In zone GRII-pm-4 (187-171 cm) the presence of tree macrofossils continues, while *Batrachium* sp., *Sparganium minimum*, *Lycopus europaeus, Ranunculus sceleratus* and charcoal pieces are recorded for the first time. GRII-pm-5 (171-149 cm) is characterized by numerous *Menyanthes trifoliata* seeds, *Calliergon cordifolium/giganteum* leaves, herbs and the presence of *Messia triquetra*. In GRII-pm-6 (149-135 cm) Cyperaceae rootlets dominate the record, with limited *P. sylvestris* and *Betula* sp. remains.

Geochemical analysis

Geochemical analysis was performed on the GRI core. Four stratigraphic zones were identified using CONISS (Gower; Fig. 4). A substantial concentration of Ca^{2+} characterises zone GRI-ge-1 (186-174 cm). Zone GRI-ge-2 (174-143.5 cm) is characterized by a decrease in Ca and increase in the concentration of Al and correlating variables. In the zone GRI-ge-3 (143.5-100 cm) there is a large decrease in Al, Zn, K, Mg, Cr with a parallel increase in Si and correlating variables. During zone GRI-ge-4 (100-85 cm) an increase in Al, Zn, Cr, Fe, Cu and Pb took place.

Constrained ordination of principle coordinates (CAP)

Ordination analysis (CAP) of plant macrofossil and depth data explains a degree of variation on both axis 1 (CAP1; 10.7%) and axis 2 (CAP2; 4%) (Fig. 5). Correlation analysis (Spearman's Rank) found that Al significantly correlated with Cr ($p < 0.001$), Cu ($p < 0.001$), Fe ($p < 0.05$), K ($p < 0.001$), Mg ($p < 0.001$), Mn ($p < 0.001$), Nd ($p < 0.001$), P ($p <0.01$) Pb ($p < 0.001$), Ti ($p < 0.01$) and Zn ($p < 0.001$), while Si correlated with As ($p <0.01$) and Na ($p < 0.01$). Ca correlated with Mg ($p <0.01$), but to a lesser extent that Al and Mg ($p < 0.001$). Therefore, redundant correlating variables were removed and only Ca, Al and Si were retained as environmental variables in the CAP analysis. Higher Si concentrations show a clear association with Cyperaceae and a slight association with brown mosses and herbs and some sites in GRI-pm-3. *Chara* sp. and GRI-pm-1 are clearly associated with increased Ca concentrations. Al shows a very slight association with *Sphagnum teres* and GRI-pm-2.

Discussion

The first stage of oxbow lake development during cold climate conditions

The oxbow lake at our study site is a palaeomeander of the Prosna River and formed during the Late Glacial period. AMS dating indicates that the accumulation of the organic-rich deposits began sometime before 12,374-11,767 cal. yr BP, most likely during Younger Dryas, but potential earlier. Many palaeomeanders in this part of the Europe have a Late Glacial origin, associated with the transition of river valleys from braided channels to a main meandering channel (Kozarski and Rotnicki, 1977; Gonera and Kozarski, 1987; Młynarczyk and Rotnicki, 1989; Duda and Borówka 2007; Forysiak et al., 2010; Forysiak, 2012; Starkel et al., 2015; Pawłowski et al., 2015, 2016a; Płóciennik et al., 2016; Słowik et al., in review).

Pawłowski et al. (2016a) suggests the summer temperature during Younger Dryas in central Poland oscillated ca. 14 °C, which would likely have facilitated the growth of some macrophyte species in the palaeolake. *Chara* sp., *Batrachium* sp., and *Potamogeton* spp. were the pioneer plants colonizing the cold alkaline water, rich in Ca and Mg (Fig. 5 and 6), with the relationship between *Chara* sp. and increased Ca concentrations further supported by ordination analysis (Fig. 5).

The presence of these submerged plants during the Late Glacial in the first stage of macrophyte succession is in agreement with records from many other European lowland lakes (Amon et al., 2010; Mortensen et al., 2011; Fajer et al., 2012; Gałka and Sznel, 2013; Kołaczek et al., 2015). In particular, stoneworts oospores (e.g. *Chara* sp.) have been shown to be common in the first stage of macrophyte succession, emphasising their pioneering role in colonising new water basins, such as palaeolakes formed in river valleys (Pawłowski et al., 2016; Płóciennik et al., 2016; Kołaczek et al., 2018). During the period, when oxbow lake existed at sampling site the *Potamogeton* species of *P. fresii, P. praelongus* and *P. alpinus* appeared (GRI-pm-2; GRII-pm-2), suggesting quite shallow and eutrophic water conditions (Zalewska-Gałosz, 2008). Only a single endocarp of *P. praelongus* was identified in the GRI core, supporting previous observations from other lakes located in European lowland and mountain sites that this species does not have competitive abilities to disperse compared to other *Potamogeton* species (Gałka et al., 2017 and references quoted there). The meridional orientation of the valley and relatively rich fossil presence of macrophytes in the palaeo-record may indicate that the Prosna River was an important pathway for the spreading of aquatic plants during the Late Glacial.

Early Holocene plant succession during warm climate conditions

Early Holocene (ca. 11, 300 cal yr BP, Kołaczek et al., 2018) mean June temperatures ca. 18°C likely led to expansion of thermophilous macrophytes such as *Ceratophyllum demersum* and *Typha* sp. at both sampling sites Fig. 2., (GRI-pm-2 and 3; GRI-pm-3). These plants typically grow in shallow water (Podbielkowski and Tomaszewicz, 1996) and are often recorded in transitional zone between lakes and peatlands during the early Holocene (Hannon and Gaillard, 1997; Gałka and Sznel, 2013; Kołaczek et al., 2015, 2018).

The warmer temperature appears to have had a positive effect on forest development and its density in areas surrounding rivers valleys. Both *Pinus sylvestris* and *Betula pubescens* macrofossils were observed in early Holocene sediments from both GRI and GRII. Those trees likely occupying mineral soils in the river valley and along river banks. However, typical riparian trees such *Salix* and *Populus* were not detected in studied cores. Nevertheless, river valleys were important routes for deciduous trees spreading in the European lowlands (Kolstrup, 2007; Kołaczek et al., 2018) and vegetation cover was an important factor in controlling river system evolution (Turner et al., 2013). Higher temperatures and potentially lower precipitation contributed to increased fire events during the early Holocene in river valleys and their surrounding areas. This is evidenced by the presence of early Holocene charcoal pieces in both our cores (Fig. 2 and 3) as well as in other sites located in river valleys across the Polish lowlands, e.g. Grabia (Pawłowski et al., 2016a,b), Ner (Kittel et al., 2016) and San (Kołaczek et al., 2018).

At ca. 11,750-11,260 cal. yr BP in the GRI core (Fig. 2, GRI-ge-3) there is an abrupt decrease in concentrations of Al, K, Mg, Ti, Fe and Cr and an increase in Si concentrations. This geochemical shift is associated with a disappearance of aquatic species and development typical peatland plants population with the appearance of *Carex rostrata, Carex lasiocarpa*, *Menyantes trifoliata*, brown mosses, Cyperaceae and herbs (Fig. 2., GRI-pm-3). Ordination analysis further supports the relationship between increased Si concentrations and brown mosses, Cyperaceae and herbs (Fig. 5 and 6). Such a visible change of geochemical composition might indicate isolation of the study site from the influence of the Prosna River, as has been recorded in other early Holocene palaeomeanders located in central Poland (Pawłowski et al., 2016a,b; Płóciennik et al., 2016).

A decrease in water level during the early Holocene has been documented in several central European lowland sites (cf. Gałka et al., 2015a and references quoted there). A decreased water table may explain the development of a *Sphagnum* population dominated by *S. contortum* in zone GRI-pm-4, preceded by a short phase of *Meesia triquetra* (cf. Gałka et al., 2015b; 2017) and followed by short stage of *Sphagnum teres* (Fig. 3; Fig.6). The presence of *S. contorum* in our early Holocene dated deposits from the Prosna River valley is the oldest such example in the European lowlands, with *S. contortum* being among the rarest of *Sphagnum* mosses encountered in the fossil state. To date, its fossil presence has only been confirmed at a few sites in the northern hemisphere (Gałka and Lamentowicz, 2014). *S. contortum* macrofossils were recorded e.g. in Late Glacial deposits at Scragh Bog, Central Ireland (O'Connell, 1980). In addition, the early Holocene presence of *S. teres* in GRI is important from a biogeographic perspective as one of the earliest fossil examples in Central Europe. Previously *S. teres* had only been recorded in Late Glacial peat layers from SE Germany (Hölzer and Hölzer, 1994), NE Poland (Gałka and Sznel, 2013) and in early Holocene (ca. 10,000 years ago) lake and peat deposits from the Eastern Carpathians, N Romania (Gałka et al., 2017). *S. contortum* and *S. teres* are minerotrophic species that often grow together and can be found in rich fen habitats with a pH ca. 6 (Hájková and Hájek, 2004; Hölzer, 2010; Tahvanainen, 2013). Their macrofossils are usually found in the peat layer preceding the development of poor fen conditions (Gałka and Lamentowicz, 2014; Gałka et al., 2018). The presence of early Holocene *Sphagnum* in this river valley peatland suggests that river ecosystems have played an important role for the survival and spreading of some minerotrophic *Sphagnum* species, especially in areas with limited topographic depressions for peatlands to develop. The disappearance of mosses in the upper part of both peat profiles (Fig. 2 and 3, GRI-pm-5; GRII-pm-6) may be linked to a changing interaction with the Prosna River. Increased heavy metal concentrations in sediments, especially Cu, Cr, Mn (Fig. 6), might indicate an increased influence of the Prosna River water and gradual flooding of this peatland. River waters are usually rich in Mn^{2+} ions or they transport this chemical element in a form of suspension colloid (Kabata-Pendias and Pendias, 1979). However, the increase in Mn could also have been caused by chemical weathering, as a result of preferential leaching of Mn from the soil under slightly acidic conditions. An increase of the water level at sampling sites is also supported by the low value of the Fe/Mn ratio (cf. Boyle 2001; Pawłowski et al., 2015b). A large increase in water level would have been required to cause the decline in minetrophic mosses such as *Messia triquetra* and *Sphagnum* species that are tolerant to wet and periodically submerged conditions (Montagnes, 1990; Hölzer, 2010). However, this decline in mosses could also have been caused by erosion during flood events, which is quite a common phenomenon in river valleys (Starkel, 2002).

Summary

We present detailed plant macrofossil data from two sediment sequences from a palaeolake in the Prosna River valley with supporting geochemical analysis and radiocarbon dating. We draw the following conclusions from our analysis:

1. The studied palaeomeander was formed in the Late Glacial (most likely in Younger Dryas). This is in agreement with records from other Polish lowland river valleys that document the development of oxbow lakes during this period.

2. Rich fossil presence of macrophytes in the studied palaeomeander, along with the meridional orientation of the valley may indicate that the Prosna valley was an important route for the spreading of aquatic plants in the Late Glacial and an important habitat for rare mosses such as *Meesia triquetra*.

3. Early Holocene warming likely led to a decrease in water level, triggering the terrestrialization process of the oxbow lake – as has been observed across many Polish lowland sites.

4. Organic sediments deposited in river valleys are a valuable source of biogeographic knowledge regarding the past distribution of mosses. *Sphagnum contortum* and *Sphagnum teres* macrofossils were found in the early Holocene deposits of the Prosna River valley. These early Holocene *Sphagnum* findings suggest that river valleys - and the peatlands that developed there - were important habitats for the survival and spread of some minerotrophic *Sphagnum* species, potentially even functioning as refugia.

Acknowledgments

We would like to thank Jakub Sypniewski, Karol Jakubowski and Jędrzej Proch for their help during laboratory work.

Founding

Radiocarbon dating was supported by Fundacja Ochrony Zabytków.

References

Amon L, Heinsalu A and Veski S (2010) Late glacial multiproxy evidence of vegetation development and environmental change at Solova, southeastern Estonia. *Estonian Journal of Earth Sciences* 59: 151-163.

Anderson MJ and Willis TJ (2003) Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. *Ecology* 84: 511-525.

Boyle JF (2001) Inorganic geochemical methods in palaeolimnology. In: Last WM and Smol

JP (Eds.), Tracking Environmental Change Using Lake Sediments, Physical and Geochemical Methods, vol. 2. Kluwer Acad. Publishers, Dordrecht, pp. 83-141.

Borówka RK, Tomkowiak J, Okupny S et al. (2015) Skład chemiczny osadów bagiennych z Doliny Luciąży (Torfowisko Bęczkowice na równinie piotrkowskiej). *Folia Quaternaria* 83: 5-23.

Bronk-Ramsey C (2009) Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* 51: 1023-1045.

Bos JAA, Sjoerd JP, Bohncke JJP et al. (2006) Lake-level fluctuations and small-scale vegetation patterns during the late glacial in The Netherlands. *Journal of Paleolimnology* 35: 211-238.

Dąbrowski . (1991) Rozwój doliny Prosny w plejstocenie. Geneza, litologia i stratygrafia utworów czwartorzędowych, Wydawnictwo Naukowe UAM, Poznań. *Geografia* 50: 35-46.

Duda T and Borówka RK (2007) Zmiany w krajobrazie doliny dolnej Odry na te rozwoju paleogeograficznego regionu. *Prace Komisji Krajobrazu Kulturowego* 7: 210-218.

Dwire KA, Mellmann-Brown S and Gurrieri JT. (2018) Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. *Climate Services* 10: 44-52.

Dyjor S (1985) Systemy Kopalnych dolin Polski Zachodniej, Problemy młodszego neogenu i eoplejstocenu w Polsce, Wydawnictwo PAN, Warszawa.

Fajer M, Waga JM, Rzetala M et al. (2012) The Late Vistulian and Holocene evolution of Jezioro Lake: a record of environmental change in southern Poland found in deposits and landforms. *Journal of Paleolimnology* 48: 651-667.

Forysiak J, Obremska M, Pawłowski D et al. (2010) Late Vistulian and Holocene changes in the Ner river velley in light of geological and palaeoecological data from the Ner-Zawada peatland. *Geologija* 52: 25-33.

Forysiak J (2012) Record of changes in the natural environment of the Late Weichselian and Holocene preserwed in the sediments of peatlands of the Łódź Region. *Acta Geographica Lodziensia* 90: 1-116.

Gałka M and Lamentowicz M (2014) *Sphagnum* succession in a Baltic bog in Central-Eastern Europe over the last 6200 years and paleoecology of *Sphagnum contortum*. *The Bryologist* 117: 22-36.

Gałka M, Tobolski K, and Bubak I (2015a) Late Glacial and Early Holocene lake level fluctuations in NE Poland tracked by macro-fossil, pollen and diatom records. *Quaternary International* 388: 23-38.

Gałka M, Miotk-Szpiganowicz G, Marczewska M et al. (2015b) Palaeoenvironmental changes in Central Europe (NE Poland) during the last 6200 years reconstructed from a high resolution multi-proxy peat archive. *The Holocene* 25: 421-434.

Gałka M and Sznel M (2013) Late Glacial and Early Holocene development of lakes in northeastern Poland in view of plant macrofossil analyses. *Quaternary International* 292: 124-135.

Gałka M, Swindles GT, Szal M et al. (2018) Response of plant communities to climate change during the late Holocene: Palaeoecological insights from peatlands in the Alaskan Arctic. *Ecological Indicators* 85: 525-536.

Gałka M, Tanţău I and Feurdean A (2017a) Plant succession in a peatland in the Eastern Carpathian Mts. (CE Europe) during the last 10,200 years: implications for peatland development and palaeoclimatic research. *Review Palaeobotany and Palynology* 244: 203-216.

Gałka M, Tobolski K, Lamentowicz Ł et al. (2017) Unveiling exceptional Baltic bog ecohydrology, autogenic succession and climate change during the last 2000 years in CE Europe using replicate cores, multi-proxy data and functional traits of testate amoebae. *Quaternary Science Reviews* 156: 90-106.

Gałka M, Tobolski K, Zawisza E et al. (2014) Postglacial history of vegetation, human activity and lake-level changes at Jezioro Linówek in northeast Poland, based on multi-proxy data. *Vegetation History and Archaeobotany* 23: 123-152.

Garssen AG, Verhoeven JTA and Soons MB (2014) Effects of climate-induced increases in summer drought on riparian plant species: a meta-analysis. *Freshwater Biology* 59: 1052-1063.

Gonera P and Kozarski S (1987) River channel changes and rough paleodischarge estimates for the Warta river, west-central Poland. *Geografiska Annaler Series A Physical Geography* 69: 163-171.

Gower JC (1971) A general coefficient of similarity and some of its properties. *Biometrics* 28: 857-871.

Hadenäs L (2003) The European species of the *Calliergon–Scorpidium–Drepanocladus* complex, including some related or similar species. *Meylania* 28: 1-116.

Hájková P and Hájek M (2004) Bryophyte and vascular plant responses to base-richness and water level gradients in western Carpathian Sphagnum-rich mires. *Folia Geobotanica* 39: 335-351.

Hannon GE and Gaillard MJ (1997) The plant-macrofossil record of past lake-level changes. *Journal of Paleolimnology* 18: 15-28.

Hoek WZ and Bos JAA (2007) Early Holocene climate oscillations-causes and consequences. *Quaternary Science Reviews* 26: 1901-1906.

Hölzer A (2010) Die Torfmoose Südwestdeutschlands und der Nachbargebiete.

Weissdorn - Verlag, Jena.

Hölzer A and Hölzer A (1994) Studies on the vegetation history of the Lautermoor in the Upper Rhine valley (SW Germany) by means of pollen, macrofossils, and geochemistry. *Dissertationes Botanicae* 234: 309-336.

Juggins S (2007) C2 user guide. Software for ecological and paleoecological data analysis and Visualization. University of Newcastle. Newcastle upon Tyne.

Kabata-Pendias A and Pendias H (1979) Pierwiastki śladowe w środowisku biologicznym. Wydawnictwo Geologiczne, Warszawa.

Kaczmarek M and Szczurek G (2015) The Early Iron Age Fortified Settlements in Wielkopolska (western Poland) – the past and present perspective of archaeological research, *Praehistorische Zeitschrift* 90: 245-270.

Kittel P, Płóciennik M, Borówka RK et al. (2016) Early Holocene hydrology and environments of the Ner River (Poland). *Quaternary Research* 85: 187-203

Kłosowski S and Tomaszewicz H (1996) Zur ökologie des *Trapetum natantis* und des Nymphoidetum peltatae in Polen. *Tuexenia* 16: 105-116.

Kolstrup E (2007) Water-borne macroscopic plant particle transport through central and northern Europe during warming phases: a hypothetical spreading mechanism for climatic pioneers. *GFF* 129: 307-313.

Kołaczek P, Gałka M, Karpińska-Kołaczek M et al. (2015) Late Pleniglacial and Late Glacial lake-mire transformations in south-eastern Poland reflected in aquatic and wetland vegetation changes. *Quaternary International* 388: 39-50.

Kołaczek P, Margielewski W, Gałka M et al. (2017) Five centuries of the Early Holocene forest development and its interactions with paleo ecosystem of small landslide lake in the Beskid Makowski Mountains (Western Carpathians, Poland). High resolution multi-proxy study. *Review of Paleobotany and Palynology* 244: 113-127.

Kozarski S and Rotnicki K (1977) Valley floors and changes of river channel patterns in the North Polish Plain during the Late-Würm and Holocene. *Quaestiones Geographicae*, 4: 51-93.

Lorenc H (red.) 2005. Atlas klimatu Polski. Instytut Meteorologii i Gospodarki Wodnej, Warszawa.

Magyari EK, Jakab G, Sümegi P et al. (2008) Holocene vegetation dynamics in the Bereg Plain, NE Hungary - the Báb-tava pollen and plant macrofossil record. *Acta GGM Debrecina Geology, Geomorphology, Physical Geography* 3: 33-50.

Mirek Z, Piękoś-Mirkowa H, Zając A et al. (2002) Flowering Plants and Pteridophytes of Poland. A Checklist. W. Szafer Institute of Botany, Polish Academy of Sciences. Kraków.

Młynarczyk Z and Rotnicki K (1989) Późnovistuliańskie i holoceńskie formy i osady środkowej Prosny i ich paleohydrograficzna interpretacja, Wydawnictwo Naukowe UAM. Poznań.

Montagnes RJS (1990) The Habitat and Distribution of *Meesia triquetra* in North America and Greenland. *The Bryologist* 93: 349-352.

Mortensen MF, Birks HH, Christensen C et al. (1997) The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics* 28: 621-658.

Normand S, Ricklefs RE, Skov F et al. (2011) Postglacial migration supplements climate in determining plant species ranges in Europe. *Biological Science* 278: 3644-3653.

O'Connell M (1980) The developmental history of Scragh Bog, Co. Westmeath, and the vegetation of its hinterland. *New Phytologist* 83: 301-309.

Piszczygłowa P (2014) Geologia i ewolucja Doliny Prosny w rejonie Kalisza w świetle analizy litologiczno-strukturalnej osadów. *Archives of Institute of Civil Engineering* 17: 51-60.

Pawłowski D, Płóciennik M, Brooks SJ et al. (2015a) A multiproxy study of Younger Dryas and Early Holocene climatic conditions from the Grabia River paleo-oxbow lake (central Poland). *Palaeogeography, Palaeoclimatology, Palaeoecology* 438: 34-50.

Pawłowski D, Milecka K, Kittel P et al. 2015b. Palaeoecological record of natural changes and human impact in a small river valley in Central Poland. *Quaternary International* 370: 12-28.

Pawłowski D, Borówka RK, Kowalewski FK et al. (2016a) Late Weichselian and Holocene record of the paleoenvironmental changes in a small river valley in Central Poland. *Quaternary Science Reviews* 135: 24-40.

Pawłowski D, Borówka RK, Kowalewski G. et al. (2016b) The response of flood-plain ecosystems to the Late Glacial and Early Holocene hydrological changes: A case study from a small Central European river Valley. *Catena* 147: 411-428.

Piękoś-Mirkowa H and Mirek Z (2003) Atlas roślin chronionych. Multico Oficyna Wydawnicza. Warszawa.

Płóciennik M, Self A, Birks HJB et al. (2011) Chironomidae (Insecta: Diptera) succession in Żabieniec bog and its palaeo-lake (central Poland) through the Late Weichselian and Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 307: 150-167.

Podbielkowski Z and Tomaszewicz H (1996) Zarys Hydrobotaniki. Wydawnictwo Naukowe PWN. Warszawa.

Rasmussen SO, Bigler M, Blockley SPE et al. (2014) A framework for robust naming and correlation of past abrupt climatic changes during the recent glacial period based on three synchronised Greenland ice-cores. *Quaternary Science Review* 106: 14-28.

R Core Team (2018) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Słowik M (2011) Reconstructing migration phases of meandering channels by means of ground-penetrating radar (GPR): The case of the Obra River, Poland. *Journal of Soils and Sediments* 11: 1262.

Słowik M (2013) Transformation of a lowland river from a meandering and multi-channel pattern into an artificial canal: Retracing a path of river channel changes (the Middle Obra River, W Poland). *Regional Environmental Change* 13: 1287-1299.

Słowik M, Gałka M and Marciniak A, How far upstream can sea change the land? Findings from the evolution of an inland delta (central Europe). *Global Planetary Change* (in review).

Starkel L (2002) Change in the frequency of extreme events as the indicator of climatic change in the Holocene (in fluvial systems). *Quaternary International* 91: 25-32.

Starkel L, Soja R, Michczyńska DJ (2006) Past hydrological events reflected in Holocene history of Polish rivers. *Catena* 66: 24-33.

Starkel L, Michczyńska DJ, Gębica P et al. (2015) Climatic fluctuations reflected in the evolution of fluvial systems in Central-Eastern Europe (60-8 ka cal. BP). *Quaternary International* 388: 97-118.

Stupnicka E, Baranowski T and Bendet W (2006) Wpływ czynników klimatycznych na procesy osadnicze w dolinach rzek środkowej Polski w okresie rzymskim i we wczesnym średniowieczu. *Archeologia Polski* 1-2: 93-120.

Szafer W (1946) Zarys historii rozwoju flory Holarktydy. *Annales Societatis Geologorum Poloniae* 16: 179-241.

Śmigielski W and Szczurek G (2013) Wyniki badań wykopaliskowych przeprowadzonych w 1973 roku na grodzisku ludności kultury łużyckiej w Grodzisku. In: Szczurek G and Różański A (eds.) Grodzisko z wczesnej epoki żelaza i wczesnego średniowiecza w Grodzisku, gm. Pleszew, woj. Wielkopolskie. Poznań. pp. 11-47.

Tahvanainen T (2013) Eräiden lehtisammallajien suhde suoveden pHarvoon. In: Aapala K, Similä and Penttinen J (eds.) Ojitettujen soiden Ennallistamisopas, Metsähallitus, Vantaa, Helsinki, pp. 54-55

Thodsen H, Baattrup-Pedersen A, Andersen HE et al. (2016) Climate change effects on lowland stream flood regimes and riparian rich fen vegetation communities in Denmark. *Hydrological Sciences Journal* 61: 344-358.

Tobolski K (2000) Przewodnik do oznaczania torfów i osadów jeziornych. Państwowe Wydawnictwo Naukowe. Warszawa.

Turner F, Tolksdorf F, Viehberg F et al. (2013) Lateglacial/early Holocene fluvial reactions of the Jeetzel river (Elbe valley, northern Germany) to abrupt climatic and environmental changes. *Quaternary Science Reviews* 60: 91-109.

Velichkevich FYu and Zastawniak E (2006) Atlas of Pleistocene vascular plant macroremains of Central and Eastern Europe, Part I - Pteridophytes and monocotyledons. W. Szafer Institute of Botany. Polish Academy of Sciences. Kraków.

Velichkevich FYu and Zastawniak E (2008) Atlas of vascular plant macroremains from the Pleistocene of central and eastern Europe, Part II - Herbaceous dicotyledons. W. Szafer Institute of Botany. Polish Academy of Sciences. Kraków.

Woś A (1999) Klimat Polski. Wydawnictwo Naukowe PWN.

Zając A and Zając M (2001) Atlas rozmieszczenia roślin naczyniowych w Polsce. Instytut Botaniki UJ. Kraków.

Zalewska-Gałosz J (2008) Rodzaj *Potamogeton* L. w Polsce taksonomia i rozmieszczenie. Instytut Botaniki Uniwersytetu Jagiellońskiego, Kraków.

Figure captions

Fig. 1. Study site: A) Regional setting with view of the glaciers extended over much of Europe during the last ice age (source https://commons.wikimedia.org/wiki/File:Weichsel-

W%C3%BCrm-Glaciation.png); B) LIDAR digital elevation model showing the sampling site marked by grey stars in the vicinity of the stronghold Grodzisko.

Fig. 2. Plant macrofossil diagram: A) core GRI, Grodzisko. Taxa with (%) are given in estimated volume percentages, others are given in counted numbers (with X-axis scale labels; note scale differences).

Fig. 3. Plant macrofossil diagram: GRII, Grodzisko. Taxa with (%) are given in estimated volume percentages, others are given in counted numbers (with X-axis scale labels; note scale differences).

Fig. 4. Results of the geochemical analysis of core GRI (mg/kg^{-1}).

Fig. 5. Constrained ordination of principle coordinates (CAP) species-depth bi-plot of plant macrofossils, depth and select geochemical variables. Stratigraphic zones are grouped for CONISS analysis of plant macrofossils in GRI.

Fig. 6. Comparison of selected plant taxa and geochemical results, core GRI.

List of tables

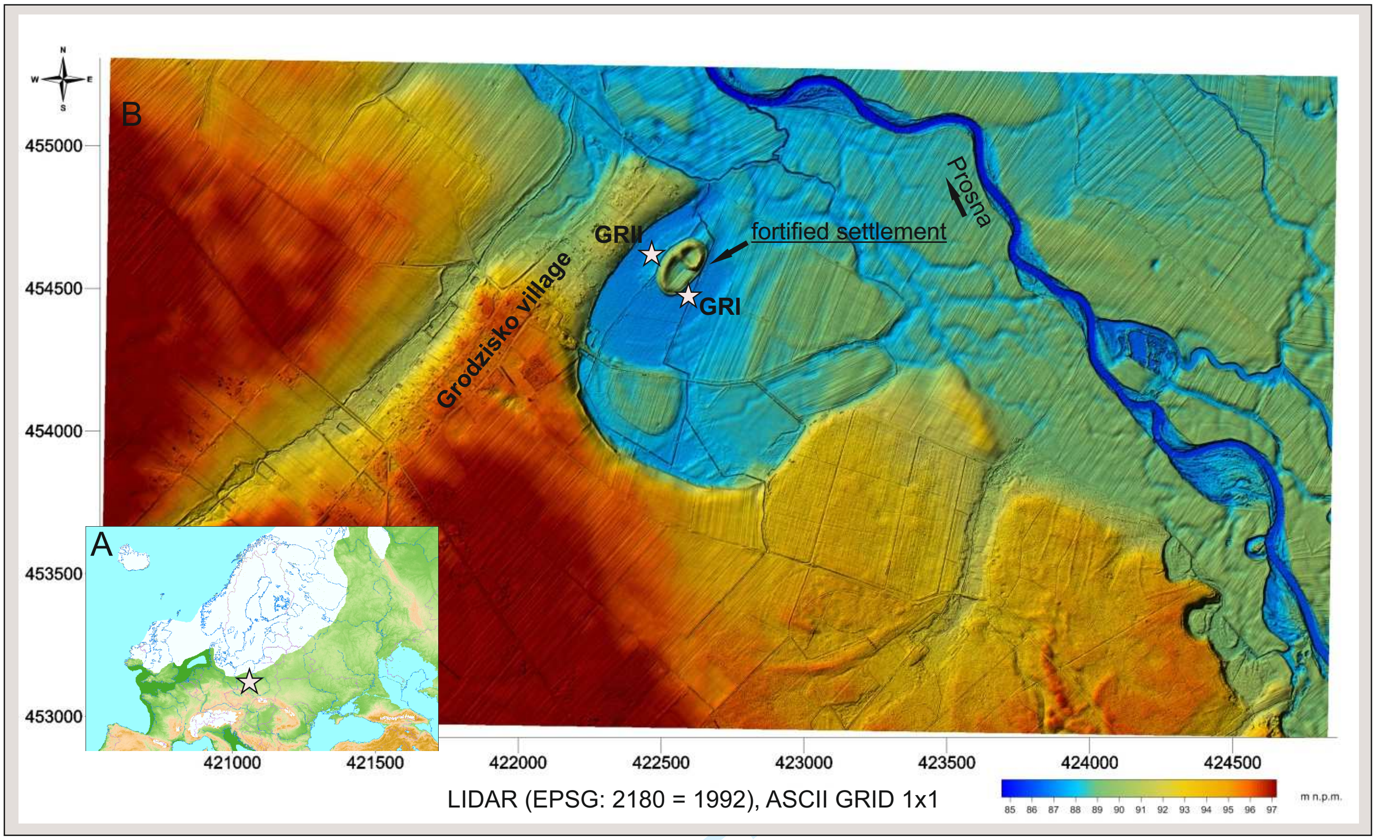
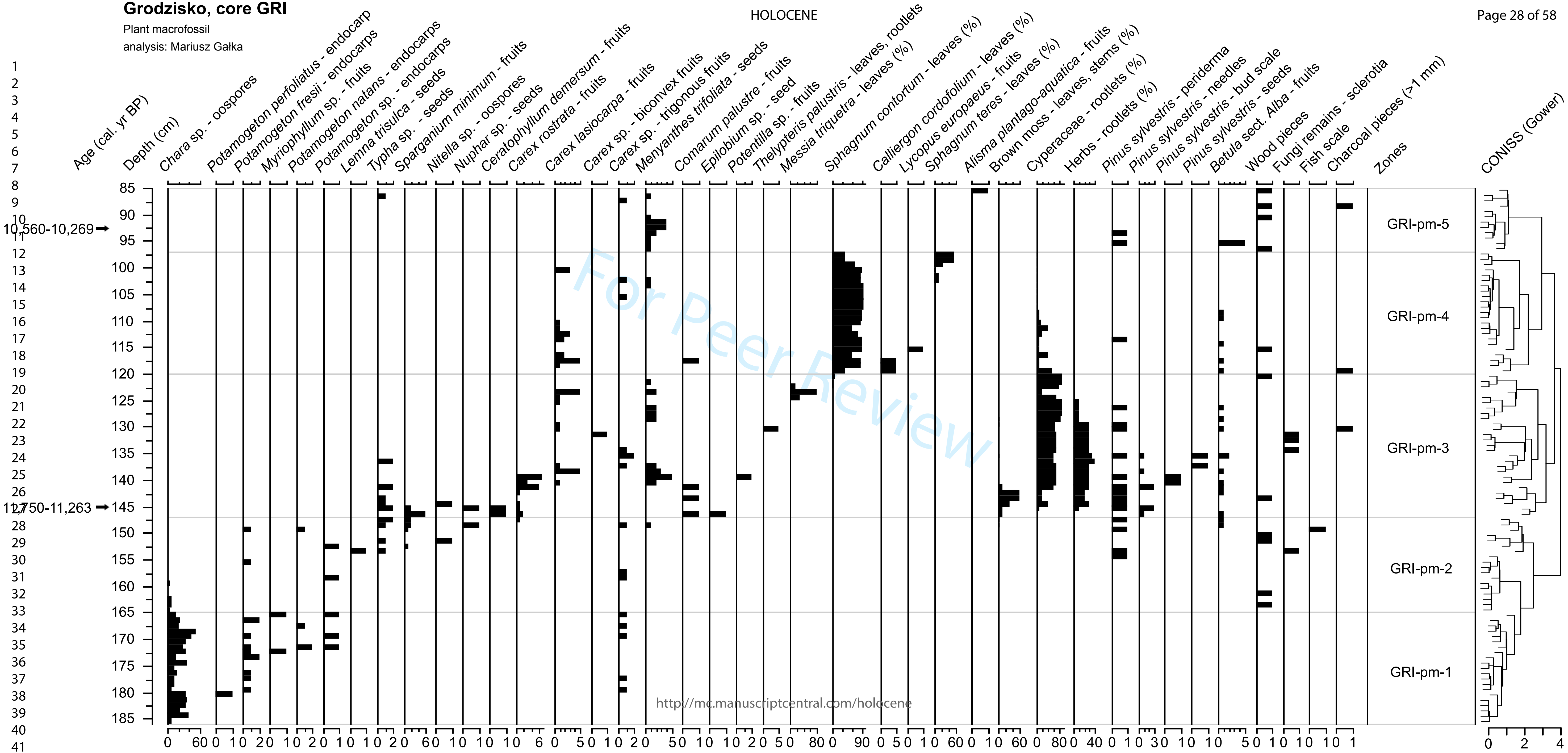


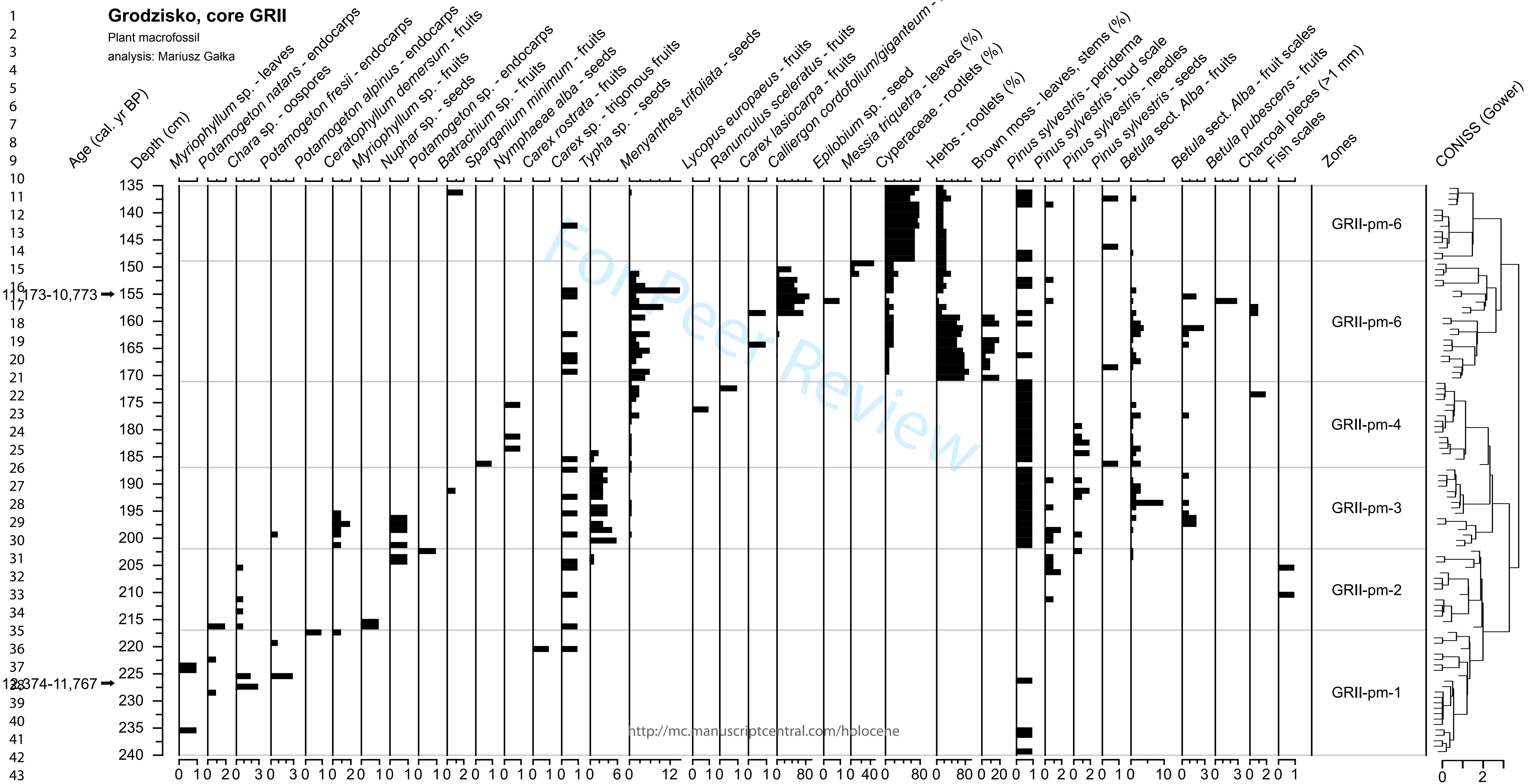
Fig. 1. Study site

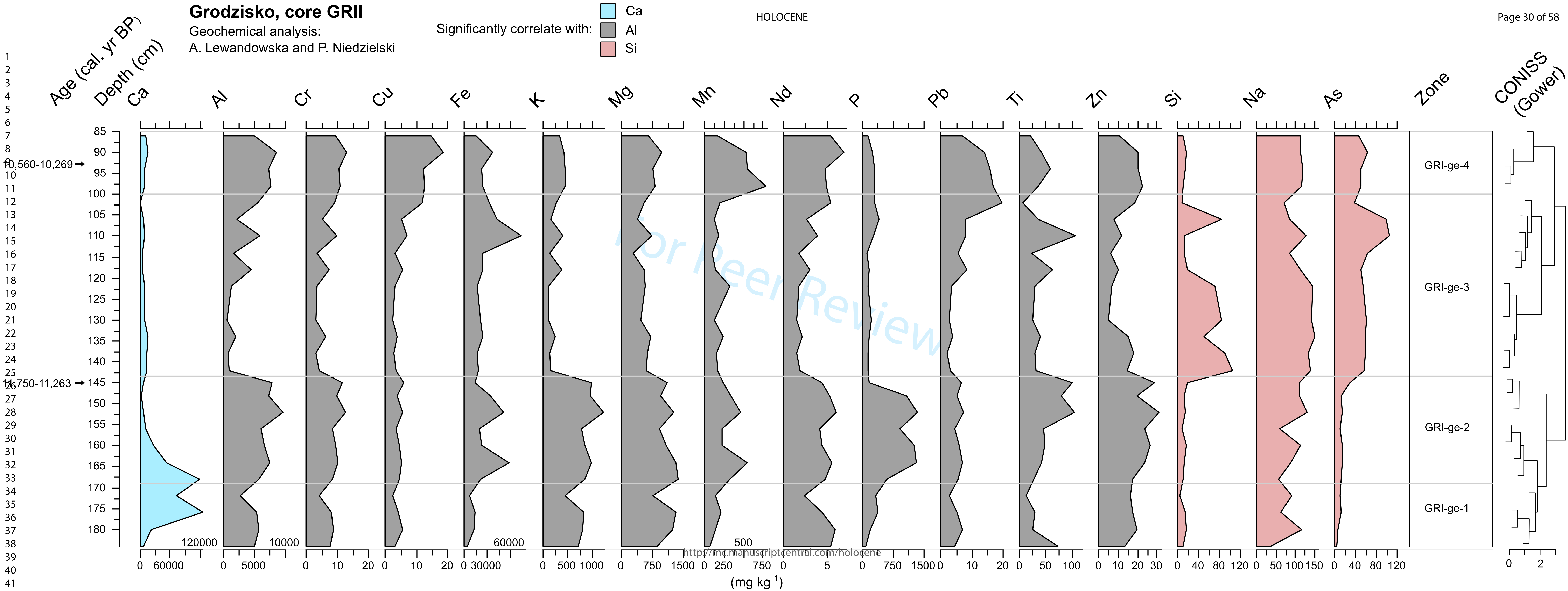
Grodzisko, core GRI

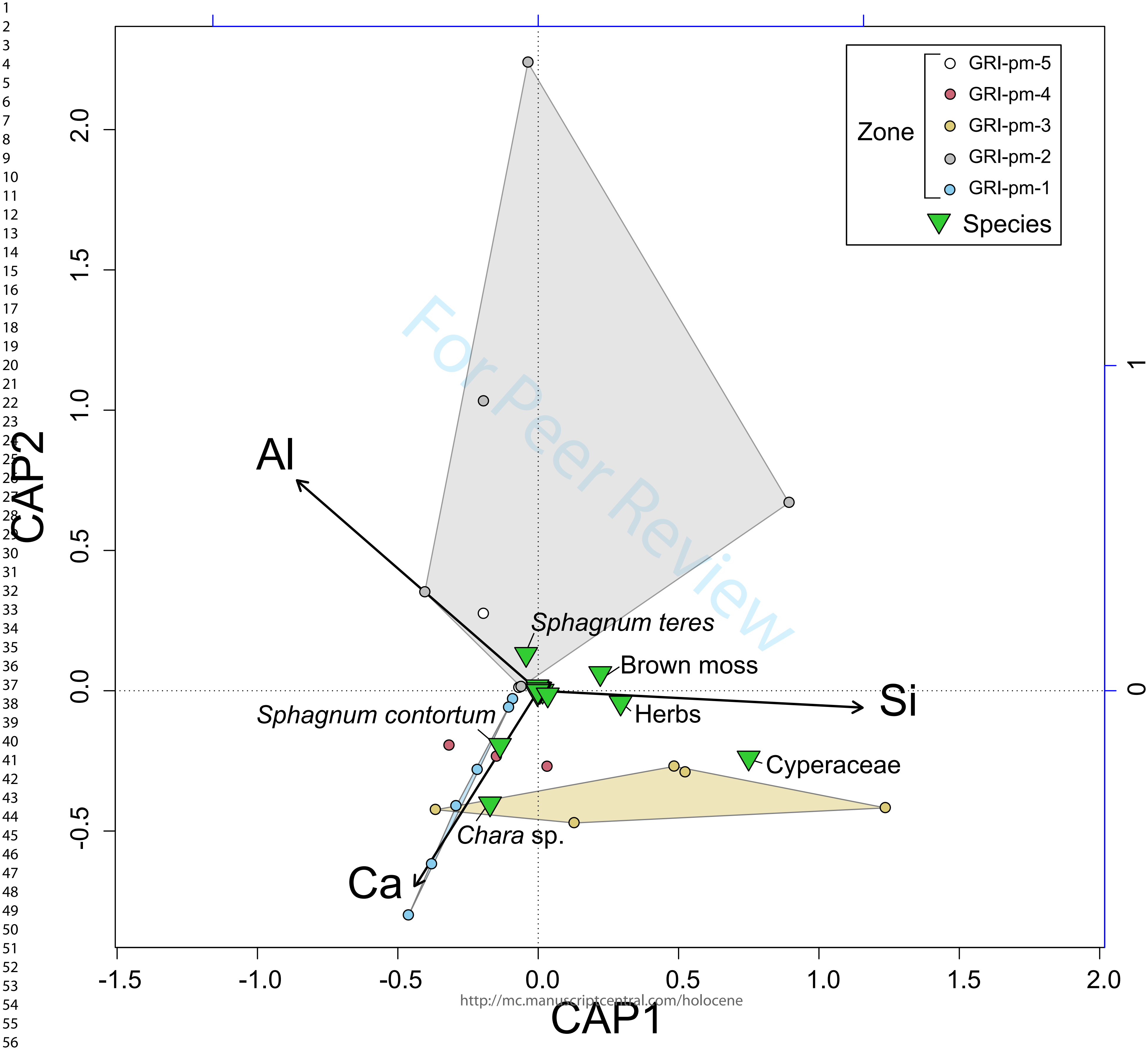
Plant macrofossil analysis: Mariusz Gałka

HOLOCENE




Grodzisko, core GRII
Plant macrofossil
analysis: Mariusz Gałka
Age (cal. yr BP)
Depth (cm)
Myriophyllum sp. - leaves
Potamogeton natans - endocarps
Chara sp. - oospores
Potamogeton fresii - endocarps
Potamogeton alpinus - endocarps
Ceratophyllum demersum - fruits
Myriophyllum sp. - fruits
Nuphar sp. - seeds
Potamogeton sp. - endocarps
Batrachium sp. - fruits
Sparganium minimum - fruits
Nymphaeae alba - seeds
Carex rostrata - fruits
Carex sp. - trigonous fruits
Typha sp. - seeds
Menyanthes trifoliata - seeds
Lycopus europaeus - fruits
Ranunculus sceleratus - fruits
Carex lasiocarpa - fruits
Calliergon cordofolium/giganteum - leaves (%)
Epilobium sp. - seed
Messia triquetra - leaves (%)
Cyperaceae - rootlets (%)
Herbs - rootlets (%)
Brown moss - leaves, stems (%)
Pinus sylvestris - periderma
Pinus sylvestris - bud scale
Pinus sylvestris - needles
Pinus sylvestris - seeds
Betula sect. Alba - fruits
Betula sect. Alba - fruit scales
Betula pubescens - fruits
Charcoal pieces (>1 mm)
Fish scales
Zones
CONISS (Gower)
11,173-10,773
12,374-11,767
GRII-pm-6
GRII-pm-6
GRII-pm-4
GRII-pm-3
GRII-pm-2
GRII-pm-1


Grodzisko, core GRII
Geochemical analysis:
A. Lewandowska and P. Niedzielski
Significantly correlate with:
Ca
Al
Si
Age (cal. yr BP)
Depth (cm)
Ca
Al
Cr
Cu
Fe
K
Mg
Mn
Nd
P
Pb
Ti
Zn
Si
Na
As
Zone
CONISS (Gower)
10,560-10,269
11,750-11,263
GRI-ge-4
GRI-ge-3
GRI-ge-2
GRI-ge-1
(mg kg^{-1})



Zone
GRI-pm-5
GRI-pm-4
GRI-pm-3
GRI-pm-2
GRI-pm-1
Species
Al
Si
Ca
Sphagnum teres
Brown moss
Herbs
Sphagnum contortum
Cyperaceae
Chara sp.
CAP1
CAP2
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
-0.5
0.0
0.5
1.0
1.5
2.0
0
1

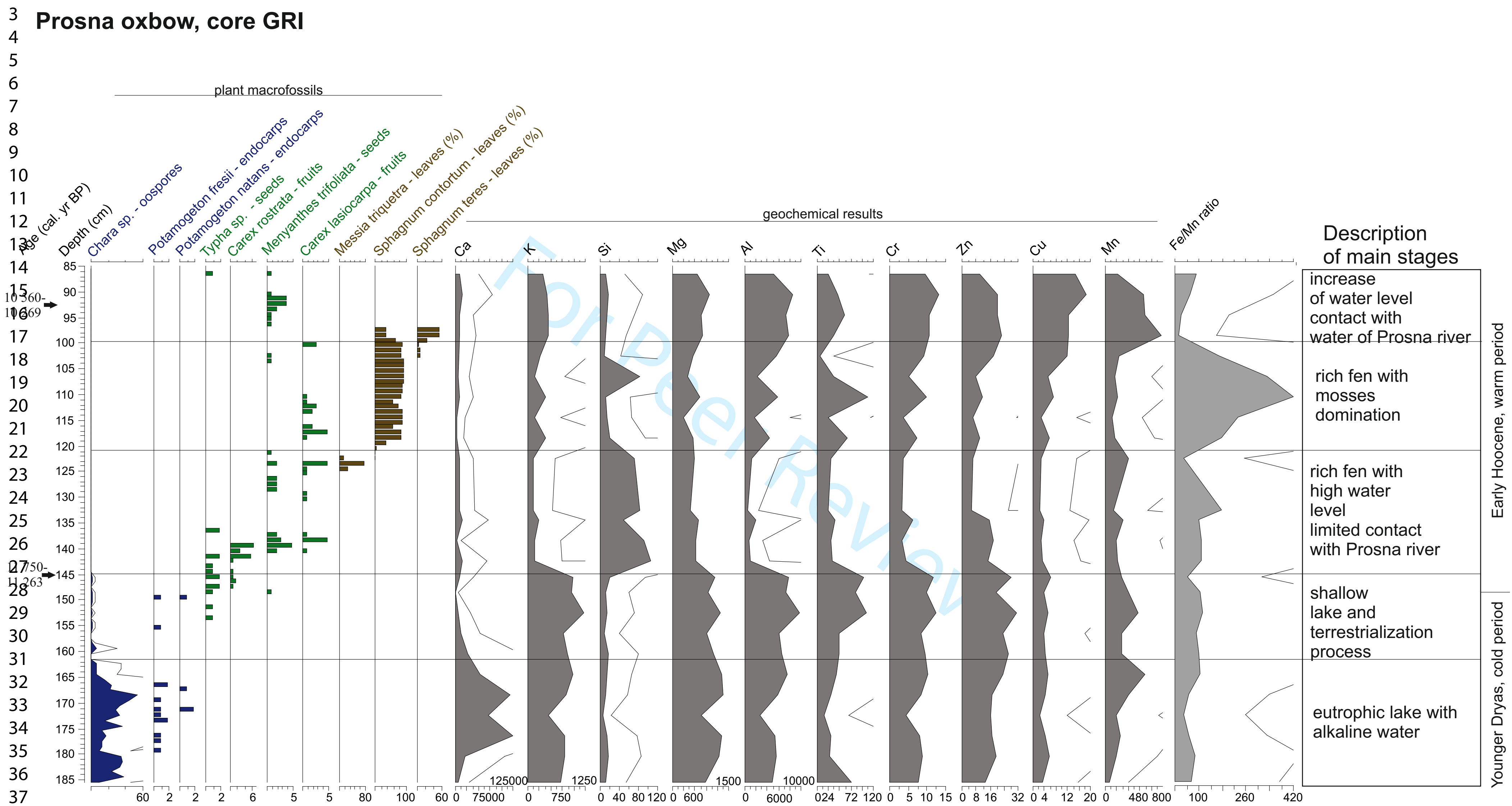

Prosna oxbow, core GRI
plant macrofossils
Age (cal. yr BP)
Depth (cm)
Chara sp. - oospores
Potamogeton fresii - endocarps
Potamogeton natans - endocarps
Typha sp. - seeds
Carex rostrata - fruits
Menyanthes trifoliata - seeds
Carex lasiocarpa - fruits
Messia triquetra - leaves (%)
Sphagnum contortum - leaves (%)
Sphagnum teres - leaves (%)
geochemical results
Ca
K
Si
Mg
Al
Ti
Cr
Zn
Cu
Mn
Fe/Mn ratio
10 360-10 269
11 750-11 263
Description of main stages
increase of water level contact with water of Prosna river
rich fen with mosses domination
rich fen with high water level limited contact with Prosna river
shallow lake and terrestrialization process
eutrophic lake with alkaline water
Early Hoocene, warm period
Younger Dryas, cold period

Table 1. Lithostratigraphic description of the sediment sequence.

Sampling site/Core	Description of sediments
GRI	186-178 cm silt with sand
	178-149 cm detritus-calcareous gyttja
	149-144 cm corase detritus gytjja
	144-125 cm herbaceous peat
	125-97 cm moos–herbaceous peat
	97-85 cm strongly decomposed herbaceous peat
GRII	240-235 cm silt with sand
	235-172 cm detritus-calcareous gyttja
	172-150 cm brown moos–herbaceous peat
	150-132 cm strongly decomposed herbaceous peat

Table 1. Radiocarbon dates from Grodzisko, core GRI and GRII

Depth (cm)	Material	Nr. Lab.	AMS date	Age (cal. yr BP)
GRI 92,5	*Menyanthes trifoliata* seeds, *Pinus sylvestris* seed	Poz-94372	9250 ± 50 BP	10 560-10 269
GRI 145,5	*Pinus sylvestris* needles and periderm	Poz-94373	10000 ± 60 BP	11 750-11 263
GRII 154,5	*Menyanthes trifoliata* seeds	Poz-94853	9620 ± 50 BP	11 173-10 773
GRII 226,5	Charred wood	Poz-94854	10260 ± 50 BP	12 374-11 767