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Palaeoenvironmental conditions and human activity in the vicinity of the Grodzisko fortified settlement (central Europe, Poland) from the late-Neolithic to the Roman period

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Abstract (max 200 words)

We present results from palaeoecological analysis conducted on deposits accumulated in an oxbow lake of the Prosna River (Poland), next to Grodzisko fortified settlement. Palaeobotanical and geochemical analysis - supported by radiocarbon dating - were undertaken to: i) reconstruct palaeoenvironmental conditions of the oxbow lake and its surrounding area; ii) determine the beginning of the human activity in the fortified settlement vicinity and; iii) assess the impact of human pressure on the environment. Grodzisko fortified settlement was originally located on a river inland island, encircled by a wetland - improving its defensive value. Increases in the water level (1800-1300 BC and 700-200 BC) created a small lake/moat around the fortified settlement. Indicators for human activity from pollen records suggest the presense of human populations from the late Neolithic, ca. 2800 BC, with a clear intensification ca. 1700 BC. From ca. 1600 BC a decrease in some decidous trees suggests forest clearence. Low levels of human activity indicator pollen ca. 2000 BC suggest a reduction of human pressure (possible depopulation). Regular presence of macrocharcoal pieces and an increase in human activity indictor pollen from ca. 1300 to 200 BC provides evidence for permanent human habitation around the sampling site.

Key words: Plant Macrofossils, Stronghold, Plant Succession, Climate Change, Geochemics

INTRODUCTION

Rivers have played a very important role in the development of various civilizations around the world. They have been communication routes and a place to obtain food and fresh water, hence many cities and settlements were located on their banks. Before river systems and the surrounding landscapes began to be modified extensively by humans they tended to flow in multiple channels, between which there were mineral islands and numerous wetlands. These islands and peninsulas were surrounded by water or swamps and often provided a strong defensive position. Hence, many fortified settlements were located in such landscapes (Jankuhn, 2004).

The landscape of the Central European Lowlands was shaped by the presence of the Scandinavian ice sheet and meltwater, including the presence of many rivers flowing mostly from the south to the north. Numerous oxbow lakes have been filled by mineral and organic sediments in these river valleys over thousand years (Starkel et al., 2006; Pawłowski et al., 2015; Słowik et al., 2019, 2021). The presence of organic sediments deposited near archaeological localities creates an opportunity for palaeoecological analyses, allowing for multi-proxy reconstructions of past environmental conditions in terms of palaeohydrology and land cover, e.g. types of cultivated cereals (Gałka et al., 2014; Mercuri et al., 2015; Van der Veen, 2018). Moreover, integration of archaeological and palaeoenvironmental evidence improves understanding of phases of human activity and population dynamics (cf. Kittel et al., 2018; Kneisel et al., 2019). The Prosna valley is ideal for palaeoecological reconstructions because of unique and well-preserved palaeomeanders filled with organic sediment that has accumulated during the Holocene (Młynarczyk and Rotnicki, 1989; Piszczygłowa, 2014; Gałka et al., 2020). Moreover, many fortified settlements were located in the Prosna River valley and its vincity from the Late Bronze Age to Middle Ages (Śmigielski, 1993; Janiak, 2003; Teske, 1999, 2000; Szczurek, 2017). Such a high concentration of human settlements over the centuries resulted from a strategic location on trade routes. The Prosna River valley, together with the Barycz River valley, was one of the most important north-south arteries of intercultural communication since the late Bronze Age (Horst, 1990; Fogel, 1993; Lasak, 2004; Kaczmarek, 2012).

Although this area is important in scope for the reconstruction of migration routes, knowledge about past landscape and environmental conditions remains poor. In this paper, we present the results from palaeoecological analyses (palaeobotanical and geochemical) on organic sediments accumulated in a former oxbow lake within the Prosna valley, supported by radiocarbon dating. The aims of this study are: i) reconstruct palaeoenvironmental conditions in the oxbow and its surroundings from ca. 3800 BC to 200 AD; ii) determine the beginning of human activity in the vicinity of the fortified settlement and iii) the quantify the impact on vegetation at a regional and local scale. Because of a hiatus spanning the middle Holocene at the study site, we present here only the upper part of the collected profiles that have broader archaeological context, spanning the period between ca. 4000 BC and 200 AD. The results of palaeoecological analyses from the lower profiles are presented elsewhere (see Gałka et al., 2020) and span the Younger Dryas and early Holocene (up to ca. 10,000 cal. yr BP) with a focus on the development of the oxbow lake and local vegetation.

Settlement transformations in the Grodzisko area revealed by archaeological research

The first methodical archaeological research took place in 1973 within the framework of the verification programme of Lusatian fortified settlements in Wielkopolska (Greater Poland). The works uncovered the remains of defensive, residential and economic buildings. The rampart was a wooden-earth construction and its outer wall consisted of a number of large, thick, pointed oak posts of a preserved length of 80-90 cm, driven into the ground. The main central part of the rampart's construction consisted of 3-6 layers of tree trunks of deciduous species. The width of the base of the dike was 10.1 m in the surveyed section (12 m for the prewall structures) and was likely covered by a massive earthen embankment over 5 m high (Śmigielski, 1993; Śmigielski and Szczurek, 2013). Owing to the lack of independent indicators of chronology (dendrochronology, ^{14}C) it is difficult to establish the date when the fortified settlement was erected and occupied. The archaeological material recorded during the research, mainly ceramic, allows to date the defensive structures to the Early Iron Age. The analysis of construction methods shows that the defensive perimeter was a wooden-earth rampart with a grid core construction, known from other Wielkopolska settlements of the Early Iron Age (Śmigielski, 1993; Szamałek 2009; Kaczmarek and Szczurek, 2015).

The next research was carried out in 1991 within a framework of studies on early medieval mounds of the Kalisz region and its aim was, above all, to clarify the chronology of the early medieval phase of the site. During these studies wooden constructions thought to be of an earlier identified rampart and relics of fortifications from the period of the formation of the Polish state (10th century) were discovered. The lack of elaboration of the results of these studies seriously hampers our knowledge about the discussed object. The result of the radiocarbon analysis of the wood sample from the shaft construction (section 2), indicating 1217-835 cal. BC (Teske, unpublished data), should be considered as an important, although individual, date. It is impossible to draw far-reaching conclusions based on a single date obtained by the radiocarbon dating; however, an older metric for part of the construction of this multiphase and multicultural site should also be considered. Based on materials from earlier excavations, the settlement is dated to the Early Iron Age ca. 800-650 BC.

Between 2004 and 2005 small-scale excavations were carried out at the junction of the two parts of the settlement, which made it possible to record, among other things, a defensive perimeter dating to the early Middle Ages (Teske et al., 2013).

The latest stage of fieldwork comprises a broad geophysical survey of the entire mound and the adjacent area of 4.5 ha in total, as well as a detailed inventory of the site together with a discussion and summary of the research results to date. The registered geophysical anomalies and distinct damp marks correlated with the results of earlier excavations provided a basis for the formulation of working hypotheses regarding the parameters of the fortified settlement in subsequent settlement phases, type of development within its interior and the communication system (Szczurek and Różański, 2013).

Important discoveries concerning the Grodzisko settlement were made in 2016-2017. In the Grodzisko Forest, located near the fortified settlement (3 km to the south-west), field vetting combined with detailed LiDAR data analysis and comprehensive geophysical reconnaissance led to the preliminary identification of 14 objects of which their terrain suggests are the reminants of a barrow cemetery. It is difficult to date the graves on the basis of their characterisitcs and form, but the barrows identified non-invasively in Grodzisko show an obvious similarity to the known burial mounds from, among others, the Krotoszyn Forest, about 40 km away, which were surveyed by Czebreszuk et al. (2013).

From this point of view, the area of the left bank of the lower Prosna River should be considered part of a micro-region of settlements during the period prior to the construction of a defensive settlement in the early Iron Age. The use of this site by human populations in the Middle Bronze Age appears to be a fundamental issue. A marked increase in the number of settlements in the valleys of large rivers, such as the Prosna, was most likely related to the formation of important communication arteries, which were part of a network of long-distance exchange routes between the Baltic coast and southern Europe (Kaczmarek, 2012). One of the important settlement centres on the map of cultural and trade connections may have been the area of Grodzisko. In summary, despite great interest in the archaeological community in the Grodzisko site, knowledge of its history is highly incomplete. Above all, the chronology of the various phases of settlement use needs to be better established using robust geochronological methods, which will reveal a new chapter in understanding the role of this site in the settlement structures of various cultural systems.

2. STUDY SITE

The study site is located in Central Poland, near the village of Grodzisko, ~750 m southwest of the current Prosna River (Figure 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 (Lorenc, 2005; Woś, 1999). 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* and *Salix* spp., while in the drier places, *Pinus sylvestris* is the dominant species. Among vascular plants, *Carex* spp., *Juncus* spp. and *Ranunculus* spp. are the dominant species.

3. MATERIAL AND METHODS

3.1. Sampling and chronology

Cores were taken using a Russian peat corer, 5 cm in diameter and 50 cm in length. The cores GRI (186 cm) 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. The upper most part of the organic sediments (above 26 cm in core GRI and above 28 cm in core GRII) were highly decomposed and were therefore excluded from detailed analysis due to the risk of contamination, because this area has recently been used by humans for agriculture.

To determine the chronology of deposits in the study area, seven ^{14}C AMS dates from terrestrial plant macrofossils were carried out in the Poznan Radiocarbon Laboratory (Table 1). These dates were used to construct Bayesian age-depth models (*P_Sequence* function, $k_0=1$, $\log_{10}(k/k_0)=1$, interpolation=1 cm) calculated with OxCal 4.3 software (Bronk Ramsey, 2006, 2008; Bronk Ramsey and Lee, 2013). The IntCal20 atmospheric curve (Reimer et al., 2020) was used as the calibration set. For better readability, in the following sections of this article, μ (mean) values from the age-depth model are rounded to tens and expressed as 'cal. AD' or 'cal. BC'.

3.2. Palaeobotanical analysis

Plant macrofossils were analysed at 1-cm intervals contiguously in the two cores for the time period of interest (late Holocene). In the GRI Core, 60 samples were analysed for plant macrofossil remains from 28 to 88 cm, and in the GRII, 93 samples were analysed from interval

27 to 120 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). 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 10–200 magnification and an Olympus CX 41 biological light microscope. Fossil fruits and seeds are expressed in absolute numbers. A total of 205 samples were analysed. The names of the plant species were adopted following Mirek et al. (2002).

A total of 23 samples (15 from GR1 and 8 from GRII) were prepared for palynological analyses, using the standard laboratory procedures (Berglund and Ralska-Jasiewiczowa, 1986). To remove carbonates samples were treated with 10% hydrochloric acid. This step was followed by digestion in hot 10% potassium hydroxide (to remove humic compounds) and soaking in 40% hydrofluoric acid for 24 h (to remove the mineral fraction). Next, acetolysis was performed. One *Lycopodium* tablet (Batch 3862 containing 9666 spores per tablet; produced by the Lund University) was added to each sample during the laboratory procedures for the calculation of microfossil concentration (Stockmarr, 1971). Pollen, spores, and selected non-pollen palynomorphs (NPPs) were counted under an upright microscope until the number of total pollen sum (TPS) grains in each sample reached at least 500. Sporomorphs 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 arboreal pollen (AP) and non-arboreal pollen (NAP), after pollen of aquatic and wetland plants but including Cyperaceae, cryptogams, spores and NPPs were excluded from TPS.

3. 3. Geochemical analysis

In order to determine the concentration of 59 chemical elements in 14 samples, 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 s for three replicates. The detection limits were 0.01 mg kg^{-1} dry weight for all elements (at three-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. We publish only selected elements that are important for palaeoenvironmental reconstruction.

3.4. Statistical analysis and data presentation

Stratigraphic clustering and ordination analysis were conducted in R version 3.6.3 (R Core Team, 2020). For the plant macrofossil, pollen and geochemical data, stratigraphic zones were informed by constrained incremental sum of squares cluster analysis (CONISS; Grimm, 1987) conducted in the packages *rioja* (Juggins, 2020) and *vegan* (Oksanen et al., 2020), using Gower (1971) dissimilarity to facilitate zero values. Plant macrofossils, pollen and geochemical data are presented in diagrams and were plotted using the C2 software (Juggins, 2007).

Ordination analysis was conducted to explore the relationship between plant macrofossil and pollen data with corresponding geochemical concentrations in the GRI core. Pollen taxa with abundance values < 5% and redundant correlating geochemical variables were removed from the analysis to reduced clustering. The “capscale” function in *vegan* (Oksanen et al., 2020) was used for the ordination analysis, which is a variant of canonical analysis of principle coordinates (CAP; Anderson and Willis, 2003). CAP with Gower (1971) dissimilarity enabled analysis of mixed stratigraphic plant macrofossil data including both count and presence/absence data (see Birks, 2014).

4. RESULTS

4.1. Lithostratigraphy and chronology

At both sampling sites, detritus-calcareous gyttja accumulated on top of a silt and sand layer (cf. Gałka et al., 2020). Above the detritus-calcareous gyttja, herbaceous peat and coarse detritus gyttja were deposited. The most upper part of sediments excluded from detailed studies contain highly decomposed peat. Series of ^{14}C dates and further age-depth models (App. 1) revealed no rapid declines of sediment accumulation rates suggesting lack of long-term hiatuses or contamination of sediments caused by the erosive activity of the river. The GRI core spans the period from ca. 3800 BC to ca. 150 BC and in core GRII covers the period from ca. 7000 BC to ca. 450 AD.

4.2. Palaeobotanical analysis

Plant macrofossils

Core GRI. We identified four zones in the local vegetation development for plant macrofossils in GRI. Zone GRI-pm-1 (ca. 3800-2000 BC) is dominated by *Alisma plantago-aquatica* and *Typha* sp., with *Lemna trisulca* and *Menyanthes trifoliata* also present in this zone. Zone GRI-pm-2 (ca. 2000-1450 BC) is characterised by a decrease in numer of macrofossils of *Alisma plantago-aquatica* and *Typha* sp. And the appearance of *Nuphar* sp. and *Peucedanum palustre*. Zone GRI-pm-3 (ca. 1450-800 BC) is dominated by *Alisma plantago-aquatica* and *Typha* sp. Macrocharcol pieces are abundant in this zone. During zone GRI-pm-4 (ca. 800-150 BC) there is a decrease in *Alisma plantago-aquatica* and *Typha* sp., with *Nitella* sp., *Chara* sp., and *Juncus* cf. *effusus* dominating the plant community. *Sambucus nigra* seeds, and macrocharcoal pieces are also common.

Core GRII. We identified three zones in the local vegetation development for plant macrofossils in GRII. In the first phase GRII-pm-1 (ca. 7000-4000 BC) *Alisma plantago-aquatica, Carex* sp. and *Pinus sylvestris* are the dominate species. Single *Lemna* seeds are also present. Zone GRII-pm-2 (ca. 4000-1000 BC) is characterised by appearance of *Typha* sp., *Lemna trisulca*, and macrocharcol pieces (ca. 2000 BC). During the third phase GRII-pm-3 (ca. 1000 BC-450 AD) there is an increase in *Typha* sp. and the appearance of aquatic plants such as *Stratiotes aloides* and *Potamogeton crispus.* In the upper part of this zone an increase in numer of macrofossils of *Schoenoplectus lacustris* took place, *Sambucus nigra* is present and macrocharcoal pieces are recorded.

Pollen

Core GRI. We identified three zones in the regional and local vegetation development for pollen in GRI. In the zone GRI-po-1 (ca. 3800-1700 BC) *Pinus sylvestris* type*, Alnus glutinosa* type*, Corylus avellana* and *Quercus* are dominant species among trees, alongside the consistent presence of *Urtica* and Apiaceae undiff., and a peak ca. 3400 BC in *Alisma* type and *Myriophyllum vercicillatum*. Zone GRI-po-2 (ca. 1700-900 BC) is characterised by a decrease in pollen percentages of deciduous trees such as *Corylus avellana, Tilia cordata, Fraxinus excelsior*. There is a continuous presence of Cerealia type and an increase of ruderals species such as *Artemisia*, *Rumex acetosa/acetosella* type, and *Plantago lanceolata.* In the most upper part of this zone *Secale cereale* appears. Additionally in GRI-po-2, Cyperaceae, *Sparganium* type, and *Potamogeton* s. *Eupotamogeton* reach their highest values. In the zone GRI-po-3 (ca. 900-350 BC) there are further decreases in deciduous trees such as *Corylus avellana, Tilia cordata, Fraxinus excelsion,* and *Ulmus*. Cerealia and ruderals plants (*Rumex acetosa/acetosella* type and *Plantago lanceolata*) reach their highest values. In addition, a drop in wetland plants (*Typha latifolia* and *Alisma* type) is recorded.

Core GRII. We identified two zones in the regional and local vegetation development for pollen in GRII. Zone GRII-po-1 is characterised by the highest value of *Pinus sylvestris* type (ca. 1800 BC), *Alnus glutinosa* type (ca. 900 BC), and *Corylus avellana* (ca. 1300 BC). Additionally in the bottom part of this zone, higher values of cultivated and ruderal plants are documented. Pollen of wetland plants such as Cyperaceae and *Sparganium* type remain at a consistently low value (ca. 1 %). During zone GRII-po-2 a decrease in some deciduous trees (*Tilia cordata, Ulmus, Corylus avellana*) also is observed. In addition, increases or new appearances of openland herbs as well as increase in wetland plants (Cyperaceae, *Sparganium* type, *Typha latifolia*) and algal NPPs (HdV-128A and HdV-128B) are recorded in GRII-po-2.

4.3. Geochemical analysis

We identified four zones in the geochemical results for GRI. In the zone GRI-ge-1 (ca. 3350-2200 BC) high values are reached for Al, Mg, and Pb. In contrast Ni, Cu, Zn remain at low levels. During zone GRI-ge-2 (ca. 2200-1550 BC) peaks in Ti, Ca, Ni, Cu, Si, P, and Na are observed. Zone GRI-ge-3 (ca. 1550-700 BC) is characterised by drop in almost all elements. Only Zn increases during this zone. Zone GRI-ge-4 (ca. 700-300 BC) is distinguished by peaks of Fe, Pb, and Mn.

4.4. Constrained analysis of principle coordinates (CAP)

Canonical analysis of principal coordinates (CAP) of plant macrofossil and sample depth data (Fig. 5A) explains a degree of variation for axis 1 (CAP1; 15.85%) and axis 2 (CAP2; 2.68%), while pollen and sample depth data (Fig. 5B) explain a greater amount of variation for axis 1 (CAP1; 36.65%) and axis 2 (CAP2; 8.96%) respectively. Redundant correlating geochemical variables were removed from CAP analysis, with Al, Ca, Mn and Zn retained. Correlation analysis showed that Al correlated positively with Cr ($p < 0.001$), Fe ($p < 0.01$), K ($p < 0.001$), Mg ($p < 0.001$), P ($p < 0.1$), Pb ($p < 0.05$) and Si ($p < 0.1$). Ca correlated positively with As ($p < 0.001$), Cu ($p <0.1$), Ni ($p < 0.05$) and Ti ($p < 0.001$), while Mn correlated positively with Na ($p < 0.1$). Zn correlated with As ($p < 0.01$), P ($p < 0.01$) and Ti ($p <0.05$); however, these were negative correlations therefore Zn was retained in the analysis.

In the plant macrofossil ordination analysis (Fig. 5A) increased Zn concentrations are linked with increased abundance of *Typha* sp. and there is a slight association between *Alisma plantago-aquatica* and Mn levels. In the pollen ordination analysis (Fig. 5B) *Salix* sp. and Apiaceae are linked with higher Zn concentrations, Poaceae sp. and *Alnus glutinosa* type are associated with increased Mn levels, and higher CA concentrations show an association with *Pinus sylvestris* type and a slight association with *Corylus avellana*.

5. DISCUSSION

5.1. Palaeoenvironmental conditions of the oxbow lake and surrounded area from ca. 3800 BC to 200 AD

Published lithological data (Gałka et al., 2020) and futher geological drills (Szczurek and Gałka, unpublic. data) document that the mineral hill, presently occupied by Grodzisko fortified settlement, is encircled by a depression filled with organic deposits. Based on the LIDAR data (Fig. 1), it might be speculated that that mineral hill existed as a separated mineral island or peninnsula from the Late Glacial period. According to our previous palaeoecological data we documented the presence of the wetland ecosystem (originally as oxbow lake) at our sampling sites from ca. 12,000 years (Gałka et al., 2020). Palaeobotanical data from GRII evidences the presence of a wetland ecosystems covered by typical peatland plants such as *Carex pseucocyperus, Alisma plantago-aquatica,* and cf. *Oeanthe aquatica* (Fig. 2) between ca. 7000 to ca. 4000 BC. Presence of these plants indicates that the water level was high, perhaps even above the peatland surface (Ellenberg et al., 1991; Zarzycki et al., 2002). Additionally, in the surroundings of the sampling site grew trees such as *Pinus sylvestris, Alnus glutinosa,* and *Betula*. Pollen data from GRI documents that the forest is dominated by *P. sylvestris* and some decidious trees such as *Quercus, Tilia,* and *Ulmus*. The moist soils in depressions or along river/lake banks were occupied by trees such as *Alnus glutinosa, Salix* and *Fraxinus excelsior*. From ca. 2000 BC, following climatic changes (cooler and wetter conditions), soil transformation and an increase of human pressure, *Carpinus betulus* and *Fagus sylvatica* expanded across the European Lowlands (Ralska-Jasiewiczowa et al., 2003). *C. betulus* and *F. sylvatica* may have been an additional component of the forest ecosystem in the surrounding area, however; in contrast to other European areas (cf. Ralska-Jasiewiczowa et al., 2003), their low pollen values at both sampling sites suggests that *C. betula* (< 4%) and *F. sylvatica* (< 1%) did not play a dominant role in the forest around the Grodzisko stronghold until ca. 200 AD. Therefore these species most likely were not used alongside oak for the construction of fortifications. Although oak trunks were most often used in the construction of wood and earth fortifications founded in the Early Iron Age in Wielkopolska, there is some evidence for the use of pine, birch and ash, e.g. Koziegłowy, near Konin (Szamałek, 2009).

Our palaeoecological data at both sampling sites indicate that a wetland ecosystem has been consistently present until 200 AD. Almost constant presence of plant communities dominated by *Alisma plantago-aquatica, Typha*, *Lemna* (plant macrofossils and pollen), and *Hottonia* *palustris* (pollen) suggests that there were no extended periods with a low water level (Fig. 6). Furthermore, periods of prolonged water table draw down would be evidenced by high levels of peat decomposition or hiatuses in accumulation of deposits – for which there is no evidence. Moreover, the presence of plant macrofossils and pollen of aquatic plants between 1800 and 1300 BC and between 700 and 200 BC indicates there was an increase in the water level around fortified settlement, ultimately leading to the development of a small lake/pond that was colonized by submerged aquatic plants such as *Chara, Potamogeton,* and *Myriophyllum*. An increased water level is also evidenced by lower Fe/Mn ratio at that time (cf. Boyle, 2001; Pawłowski et al., 2015; Fig. 4). Double peaks of Si ca. 1800 and 800 BC (Figs. 4 and 6) may be connected with diatom productivity in the shallow lake (cf. Peinerud, 2000), further supported by increases in Si being coincident with the presence of aquatic plants such as *Nuphar*, *Myriophyllum* and *Hottonia*. Moreover, these latter two Si peaks are not reflected in Ti and Al, and thus, flood activity as a source of Si peaks should be excluded. Based on the LIDAR data (Fig. 1) it can be assumed that in the past there were many beds in the Prosna river valley (anabranching-multi channel systems), which was typical for European Lowlands rivers (cf. Kaiser et al., 2012; Słowik et al., 2020 and references quoted there). Until ca. 1600 BC high concentrations of Ca, Ti and As may indicate the presence of flowing waters at GRI. Quite a sharp increase in Zn (indicated as a pollution related element) from ca. 1600 BC may represent the isolation from the influence of Prosna River waters of the GRI sampling site. The increase in peatland plants (plant macrofossils and pollen) at GRI (and partly at GRII) supports this reconstruction regarding a lower water level at that time and suggests a change in habitat from flowing to stagnant water. The channel was gradually overgrown with typical peatland plants such as *Typha* sp. and *Alisma plantago-aquatica*, the former of which is associated with higher Zn concentration (Fig. 5).

5.2. Human presence and location of the Grodzisko fortified settlement

The appearance of the human activity indicator pollen (e.g. Cerealia type, *Plantago lanceola, Rumext acetosa/acetosella* type) ca. 2800 BC suggests the presence of the late Neolithic human populations with an intensification in human activity ca. 1700 BC. From ca. 1600 BC there is a constistant decrease in some decidous taxa (*Corylus avellana, Tilia cordata, Fraxinus excelsior*), likely representing the clearence of forest ecosystems. The presence of open areas surrounding the Grodzisko stronghold is suggested by the occurrence of a number of open habitat herbs such as *Artemisia* (up to 1,6%), Chenopodicace (0.7%), and Apiaceae (up to 18.1 %).

About 2000 BC we record the lowest value of human activity indicator sum and observe the presence of macrocharcoal pieces at both sampling sites (Fig. 6). This most likely indicates a regress of human pressure (possible depopulations) in this area. Simultaneous presence of the charcoal pieces in both cores might indicate a fire event ignited by human population. Moreover, this fire event may be connected with the destruction of local human populations living in the fortified settlement or its surroundings. The presence of macrocharcoal pieces ca. 2000 BC coincides with a decrease of some elements (Al, As, Cr, Fe, Pb), perhaps indicating some disturbance of river activity e.g. changes of steam bed and quite abrupt water level changes. Until ca. 1300 BC we do not record any macrocharcoal presence at both sites. During this time the wetland and local forest ecosystem may have experienced less human pressure.

Regular presence of macrocharcoal pieces (Fig. 6) and high values of pollen human activity indicator from ca. 1300 BC at both sites indicates the permanent presence of a human population around sampling site and suggests either new construction or reoccupation of the fortified settlement. Presence of fields with cultivated cereals (most likely *Triticum* type and *Secale cereale* among it) ca. 1300 BC and 800 BC in the vicinity of Grodzisko stronghold is indirectly documented by *Agrostemna githago* pollen in core GRI (Fig. 3). *A. githago* is a weed that grows in the crop and its presence in palaeobotanical records is considered as a plant originating alongside cultivated cereals (Behre, 1981; Marinova and Atanassova, 2006). In addition, local trees pollen abundance at this time reaches a low value (ca. 25 %) at core GRI, which may be associated with deforestation, in which *Alnus, Salix* or *Populus* - that grew in close vicinity of the stronghold - suffered the most. Re-adaptation of this site or original construction ca. 1300 BC is in line with the radiocarbon date (ca. 1217-835 BC) obtained from the bottom of the earthwork construction (Teske, unpublished data). Colonization of old abandoned settlements or destroyed strongholds is quite a frequent phenomenon due to the advantageous location providing more effective defense or shelter. Such a process has been documented for many archaeological sites in later times, when defensive settlements from the early Iron Age were reused in the Middle Ages e.g. Komorowo, district Szamotuły (Malinowski, 2006) and Biskupin, district Żnin (Rajewski, 1938). As we indicate above, the mineral hill on which Grodzisko stronghold is built has been continually surrounded by wetland, enhancing the defensive value of the location. Thus, such sites were likely to be re-inhabited by various populations over hundreds of years.

Our palaeoecological data indicated an increased water level ca. 800 BC that links with an abrupt climatic shift towards cooler and wetter conditions associated with decreased solar activity (cf. van Geel et al., 1998). However, we do not notice any negative impact of that event on the local populations at that time. In our pollen records we do not record decrease in human activity indicator sum. To the contrary, pollen sum of human activity indicator tends to increase, accompanied by further decreases in pollen percentages some tree species such as *T. cordata, C. avellana,* and *Ulmus* - suggesting deforestation. Hence, our data from Grodzisko are in agreement with studies conducted by Armit et al. (2014) that suggest that this climatic downturn did not initiate population collapse at the end of the European Bronze Age (cf. Dzięgielewski, 2012).

Pollen data evidences permanent human presence in the surroundings of the Grodzisko fortified settlement until 200 AD (Fig. 3). Although Cerealia type pollen were regularly noted since ca. 1800 BC at both sites, *Secale cereale* (rye) pollen was found from ca. 600 BC at GRI and GRII. Cultivation of rye in this region since ca. 600 BC agrees with other data, which documented that rye cultivation begun during the Early Iron Age and Roman period, becoming an important food, mainly in the northern regions with poor soils and an unfavourable climate (Behre, 1992). Although rye is commonly recorded in pollen studies in Central Europe from the late Bronze Age (Behre, 1992; Okuniewska-Nowaczyk et al., 2004), originally it was a weed among *Triticum* (wheat) and *Hordeum* (barley) cultivation. Gradually, most likely since the Iron Age, rye was cultivated as a separate cereal (Behre, 1992; Lityńska-Zając and Wasylikowa, 2005), especially where soil fertility was lower such as the sandy soils in our study area. Nonetheless, high amounts of charred rye grains have been found in Poland from the Roman Period (Okuniewska-Nowaczyk et al., 2004 and papers quoted there). Therefore, despite the fact we did not record wheat and barley pollen in our two cores, the finding of rye pollen evidences the presence of fields in the Grodzisko area since at least ca. 600 BC.

6. CONCLUSION

We draw the following conclusions from our multi-proxy palaeoecological analysis from two profiles near Grodzisko fortified settlement located in Prosna River valley, central Poland:

1. Grodzisko fortified settlement was located on a former river island and was surrounded by a wetland with a high water level, allowing the development of rush plant communities such as *Typha latifolia, Sparganium, Lemna* or *Alisma plantago-aquatica.* Between 1800 and 1300 BC and between 700 and 200 BC increases in the water level around the fortified settlement took place - leading to the development of a small lake/pond subsequently colonized by submerged aquatic plants such as *Chara, Potamogeton,* and *Myriophyllum.*

2. Levels of the human activity indicator pollen suggests the presence of late Neolithic period human populations since at least ca. 2800 BC, with a clear intensification in human activity ca. 1700 BC. From ca. 1600 BC there is a constant decline in some deciduous tree species (*Corylus avellana, Tilia cordata,* and *Fraxinus excelsior*) with a parallel increase in of human activity indicators, suggesting clearance of forest ecosystems by local human populations.

3. Ca. 2000 BC we record a minimum value of human activity indicator pollen, which most likely indicates a reduction of human pressure (and possible depopulation) in this area. However, the cause of this phenomenon remains unknown.

4. Constant presence of the macrocharcoal pieces from ca. 1300 BC at the sampling site may indicate permanent residence of the human population and could be linked to the new construction or renewal of the fortified settlement.

5. Cultivation of rye in this region since ca. 600 BC agrees with other documented data, suggesting that rye cultivation begun during the Early Iron Age and Roman period in Central Europe.

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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) bird's eye view of the settlement (photo: M. Mackiewicz); C) 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. B) core GR II. Taxa with (%) are given in estimated volume percentages, others are given in counted numbers (with X-axis scale labels; note scale differences).

Fig. 3. Selected taxa of pollen, spores and palynomorphs representing regional and local plant succession in wetland around Grodzisko stronghold. 5% times exaggeration.

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 (A) and pollen (B), depth and select geochemical variables.

Fig. 6. Comparison of selected plant taxa and geochemical results, core GRI. Local trees included taxa commonly occur in river valley: *Alnus glutinosa, Fraxinus excelsior*, *Salix* sp., and *Populus*.

List of tables

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