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Tracing the environmental footprint of a Lusatian Urnfield culture stronghold in northern Poland

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ABSTRACT

During the Late Bronze Age and Early Iron Age (ca. 1100–380 BCE), the lands of central-eastern Europe were inhabited by the people of Lusatian Urnfield culture (LUc). They started functioning in the 14th century BCE and erected special types of strongholds (defensive settlements). In this article, we aimed to examine if a relatively short-term process of building a stronghold might have been recorded in the palaeoenvironmental archive of the Linje mire situated near Gzin – a case study stronghold in central-north Poland. It is a pronounced structure in the landscape, but its chronology is estimated only on ceramics. Our multi-proxy palaeoecological research, confronted with the archaeological data, revealed that LUc people were present in the Gzin area at least from ca. 1040 cal. BCE. We estimated that a minimum of 20–35 ha of oak-dominated woodland should have been felled for timber consumed only for the stronghold rampart. Indeed, erecting of the stronghold was marked by a synchronous decline in *Quercus, Corylus avellana* and *Carpinus betulus* pollen values at ca. 870 cal. BCE, and coincident with increased climate instability of the 2.8 ka event. Our study suggests that humans were a significant factor enhancing the impact of the 2.8 ka event on the woodland ecosystem, as societal reaction required increased consumption of timber. Moreover, strongholds in prehistory, no matter time and location, might have significantly influenced woodland ecosystems, leaving the footprint even in remote palaeoecological archives.

1. Introduction

Areas surrounding lakes or wetlands, close to watercourses, naturally encouraged human settlement in prehistory (Kneisel, 2011; Sobkowiak-Tabaka et al., 2021; Gałka et al., 2021). By enriching local ecosystems, they provided food, water and other vital resources like iron through the bog ores (Larsson, 1999). In addition, they ensured a natural obstacle to impede mobility, while at the same time acted as a safeguard against attacks (Kołodziejski, 1993; Jaeger, 2015). Several different cultures in Europe relied on wetlands when choosing settlement locations, e.g., the circum-Alpine Neolithic – Late Bronze Age pile dwelling settlements (Menotti, 2004); Bronze Age wetland settlements in England (Knight et al., 2019; Cromarty et al., 2006) or those along the northern coast of the Mediterranean Sea (Ballmer et al., 2025). One of the archaeological cultures with a particular preference for erecting its settlements near lakes and peatlands is the Lusatian Urnfields culture (LUc) (Chochorowski et al., 2000; van Beek and Louwen, 2013; Dzięgielewski, 2017b; Gałka et al., 2021; Żurek et al., 2022; Gackowski et al., 2024a), characteristic of the Bronze Age and Early Iron Age (EIA) in Central Europe and dated to 1300–500 cal. BCE (Kaczmarek, 2012). From the perspective of world heritage, this culture is known, i.a., by sites such as Sumpringwall Biehla, Sentfengerg or Marburg (Herman, 1970;

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Kobyliński and Nebelsick, 2008; Nakoinz et al., 2017). However, the recent palaeoecological studies on LUc are mainly limited to Poland and Germany (e.g., Gałka et al., 2021; Niebieszczański et al., 2023; Kneisel et al., 2019). In Poland, LUc is recognisable mainly through the fortified settlement at Biskupin (Tobiasz et al., 2022), located on a lake's peninsula and functioning between 750 and 700 cal. BCE (Ważny, 2009; Dzięgielewski, 2017a). Numerous other sites of LUc, similar to Biskupin, were constructed between the Vistula and Oder Rivers at approximately the same time, ca. 1000–500 cal. BCE and disappeared around 500 cal. BCE. Hundreds of strongholds indicate their relevance for the people of LUc (Kołodziejski, 1993; Malinowski, 2006; Harding and Rączkowski, 2010). However, the impact of LUc on local forests connected to wood cutting for stronghold construction remains unknown. The reasons for their construction are also not accurately explained. They could relate to the development of contemporary socioeconomic conditions, which caused a need for protecting collected goods (Dzięgielewski, 2017a; Malinowski, 2006) and/or religious practices (Chudziakowa, 1978). These structures were built as a result of the community's effort and labour, but also the sourcing of great masses of timber that inflicted changes in local vegetation. In general, the Bronze Age is a time of increased wood utilisation and widespread human-made deforestation (Strandberg et al., 2023). These clearances affected, e.g., the north-western Mediterranean around 3000 BCE (Hazell et al., 2022), Germany for various times throughout the Bronze Age (Kneisel et al., 2019) or the Iberian Peninsula since at least 2000 BCE (Tereso et al., 2016) and many other areas.

Another problem stems from the fact that the strongholds were erected during the global cold period of 1350–550 cal. BCE (3300–2500 cal. BP; *sensu* Wanner et al., 2011) that overlapped with the period of the increased amount of drift ice in the northern Atlantic at ca. 2800 cal. BP (850 cal. BCE; 2.8 ka BP; Bond et al., 2001) and Homeric solar minimum at ca. 2750–2550 BP (800–600 cal. BCE). This period was characterised by cooling, increased wind strength and climate humidity in western Europe (Martin-Puertas et al., 2012), but palaeoclimatic reconstructions from central Europe revealed instabilities rather than common patterns of cooling and humidity changes. About 2.8 ka BP, a short-term decrease in mean July temperatures, was identified by Pleskot et al. (2022a) in north-western Poland. Simultaneously, higher fluvial activity occurred, as reconstructed for Poland (Starkel et al., 2013), and increased water levels in mid-European lakes (Magny, 2004). As people of LUc preferred to settle near lakes and/or peatlands, any dramatic hydrological changes might have affected their functioning.

Generally, most of the LUc strongholds is not fully recognised in terms of their impact on the local environment and the accurate timing of their functioning. Only a few of them were subjected to multi-proxy palaeoecological studies (Kaczmarek and Szczurek, 2015), or existing data provides limited insight into the past environments (Milecka, 2013; Niewiarowski et al., 1992). Although many strongholds were excavated during the last century, only some were fully investigated by archaeological methods (Kaczmarek and Szczurek, 2015). There is also a problem with defining the time of settlement's raising and thus the first significant logging, as well as the final abandonment of the stronghold. Hence, using peat deposits that are important palaeoecological archives might be helpful to answer the existing questions about the LUc settlements. Such deposits, if not reworked, can harbour information about human impact and past ecosystem functioning through the accumulation of numerous micro- and macrofossils on the millennial scale (Birks and Birks, 1980; Charman, 2002; Mercuri et al., 2015). Among them are, e.g. indicators of different human activities, such as plant cultivation or animal breeding (Behre, 1981; Poska et al., 2004; Shumilovskikh and van Geel, 2020).

The stronghold in Gzin (northern Poland), which has been known since 1901 CE (Chudziakowa, 1978), is one of such not fully investigated sites. It is situated directly at the edge of the Vistula River valley and about 3 km from the Linje peatland that has been subjected to various high-resolution multi-proxy palaeoecological studies (Marcisz et al., 2015; Noryśkiewicz, 2005). Even though this peatland possesses a 12.5 m thick stratigraphically undisturbed peat deposit covering the entire Holocene period (12 k years) (Fiutek et al., 2022; Noryśkiewicz, 2005), the times of LUc people remain incompletely recognised. Previous studies on this peatland either investigated only the last 2000 years history of the site (Marcisz et al., 2015) or were characterised by low resolution of ^{14}C dates carried out on bulk peat and relatively low resolution of sampling for analyses (Noryśkiewicz, 2005). These approaches were insufficient to reconstruct in detail the timing of interactions between the local LUc society and the environment.

In this article, we use the archaeological data from a LUc fortified settlement in Gzin compared with the multi-proxy palaeoecological record from the Linje peatland to discuss the local environmental history. The analyses were supported by high-resolution AMS ^{14}C dating. The main aims were to (i) reconstruct the timing of the main stages of human impact on the landscape between 13th century BCE and 4th century CE, (ii) estimate the amount of wood that was needed to construct the fortified settlement in Gzin, and (iii) describe changes in woodland composition due to the construction of fortifications and natural climate changes such as 2.8 ka event. Our additional aim was (iv) to compare the reconstructed timing of the fortifications' establishment with the emergence and functioning of other known LUc fortified settlements in central Europe.

2. Site setting

2.1. Geographical location

The LUc settlement in Gzin is located on a sandur plain above the Vistula River valley (N 53° 12′ 25.65″, E 18° 18′ 2.001″ Fig. 1). It was erected on the elevated edge of the valley, ca. 5.5 km straight south of the Vistula River. From north, east and south, the stronghold is enclosed by deeply cut ravines, which increased its defensive potential. The area around the stronghold consists of luvisols on glacial tills, gley soils in valleys, and podzolic soils on sandy terraces (Markiewicz, 2008). Modern soil patterns suggest that the potential vegetation of this area should consist of continental mixed pine-oak woodlands (*Querco-Pinetum*), subcontinental lowland lime-oak-hornbeam woodlands, and lowland ash-elm floodplain woodlands (Matuszkiewicz and Wolski, 2023). Mixed forests dominate the present vegetation surrounding the Gzin site. The most common species are *Pinus sylvestris* and *Alnus glutinosa* (mostly around local wetlands), whereas *Quercus* and *Betula* are also present in the forests.

The Linje peatland is located ca. 3 km south of Gzin site (53°11,015″N,18°18,034′E), situated at the border between a moraine hill and a sandur with a system of dunes (Słowińska et al., 2010). The mean annual temperature in this area is currently 7.5–8.0 °C, the coldest month is January with a mean of ca. −2 °C, whereas the warmest one is July with a mean of 18 °C. The annual precipitation is about 530 mm a year (Buttler et al., 2023; Słowińska et al., 2022). The peatland is a poor fen with a central ombrotrophic part and biogenic deposits reaching 12.3 m of thickness (Marcisz et al., 2015; Fiutek et al., 2022). It is surrounded by a mixed forest dominated by *P. sylvestris*, *Betula pendula* and *Quercus robur*, and covers 6 ha. Its area is now overgrown mainly by plant communities from classes: *Ledo-Sphagnetum magellanici*, *Eriophoro vaginatum-Sphagnum fallax*, *Phragmitetea australis*, *Scheuchzerio-Caricetea nigrae* and *Sphagno squarrosi-Alnetum* (Kucharski and Kloss, 2005). Due to climate change and more frequent heat waves, water level has dropped in recent years, and *Pinus sylvestris* is spreading on the surface of the peatland. In the 19th century CE, the mire was drained, but in 1901 it became a Nature Reserve due to the presence of a glacial relict *Betula nana*, and from 2008, Linje has been listed as an EU Natura 2000 protected area (PLH040020).

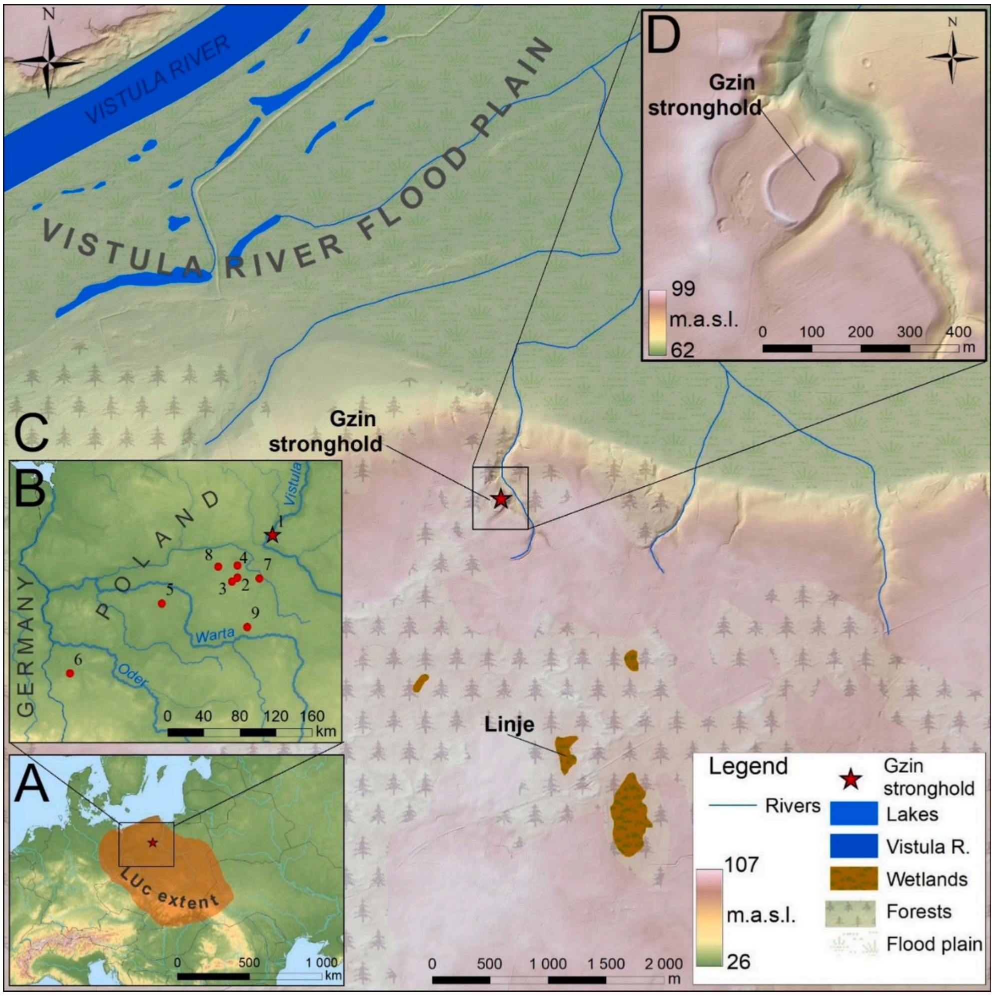

Fig. 1. Location of the Gzin stronghold and Linje mire on: A. Area of western, central and eastern Europe with the distribution of LUc culture; B. Area of western Poland with location of other LUc culture strongholds: 1 – Gzin (Chudziakowa, 1992); 2 – Biskupin (Ważny, 2009); 3 – Sobiejuchy (Harding et al., 2009); 4 – Izdebno (Chudziak et al., 2011; Kaczmarek and Szczurek, 2015); 5 – Komorowo; 6 – Wicina (Jaszewska, 2013); 7 – Jankowo (Ostoja-Zagórski, 1978); 8 – Smuszewo (Durczewski, 1985); 9 – Słupca (Malinowski, 1958); C. Hypsometric map of the LUc stronghold location with relation to the Linje peatland and Vistula River; D. Hypsometric plan of the Gzin stronghold. Figure produced in ESRI ArcMap 10.1.

2.2. *Archaeological background*

2.2.1. *Fortified settlement*

Excavations at the Gzin stronghold were carried out by J. Chudziakowa in 1968–1976 CE. An area of 800 m^2 within the *maydan* and a fragment of the rampart were examined. The fortified settlement was built on a quadrilateral plan measuring ca. 180x112 m with rounded corners. The pattern of the rampart course is strictly connected to the morphology of elevation upon which the stronghold was erected. Several graves and numerous pits containing fragments of ceramic vessels, post-consumption remains (like animal bones), and human bones were recorded. Some of the discovered human bones bear traces of consumption, which might indicate cases of cannibalism (Chudziakowa, 1978). The buildings within the central area of the stronghold were most likely distributed just on the inner side of the rampart. The central part of the settlement was free of any buildings but abundant in waste pits (86 features) with a depth reaching four meters. The remains of the rampart, which have been preserved to this day, contain remnants of timber and soil structures. The fortification was constructed within two phases separated by a fire event. The only ^{14}C date was carried out on antler cheekpieces found in the context of cremation burial and dates to ca. 550–475 BCE (Gackowski et al., 2024b). However, this chronology doesn't provide any information about the time of erecting embankments and further development of the stronghold. According to recorded archaeological material, the site existed between Hallstatt D (HaD) and Laten A (LtA) (620–300 cal. BCE) (Chudziakowa, 1992).

Based on findings, most likely related to rituals, and the lack of a compact interior part of the stronghold, such as in the case of Biskupin (Terlikowski et al., 2018), the Gzin stronghold has been defined in the literature as a cult site for the LUc population (Chudziakowa, 1978). However, limited data from excavations does not allow an unequivocal interpretation of its function in the local settlement network of that time.

3. Materials and methods

3.1. *Archaeological data*

3.1.1. *Spatial integration of archaeological data*

To draw a view of the LUc settlement network around the Gzin stronghold, we have used the Polish Archaeological Record (in Polish: Archeologiczne Zdjęcie Polski – AZP) data (Konopka, 1984). In the case of Gzin, six sheets of AZP areas were analysed, which provided a total of 100 LUc-related sites. The area covered by the analysis is delimited by a buffer with a diameter of 5 km, whose central point is the stronghold in Gzin. The defined research zone was set according to the standards of site catchment analysis (Jankuhn, 2004) and reveals a range of an hour's walk, namely the area of the nearest exploitation by the stronghold's inhabitants.

The chronology of the findings is not detailed enough to select sites that can be contemporaneous with the stronghold. Spatial and archaeological data obtained from AZP were visualised and processed using QGIS version 3.34.2 and ESRI ArcGIS software (Hodgkinson and Robinson, 2011). The Kernel Density algorithm was used to analyse settlement patterns in the research area (Baxter, 2003). The population field was added to the script to represent different categories of sites: 1 – settlement trace, cemetery, 2 – settlement point, 3 – settlement, stronghold. The results were expressed by the occurrence of sites per 1 ha and 25 × 25 m raster cell resolution.

3.1.2. Potential wood consumption for the stronghold building

The volume of utilised wood was assumed to estimate the impact of stronghold construction on the forest vegetation. Considering the archive excavations' results (Chudziakowa, 1992) and comparing with similar fortifications from well-investigated Biskupin site (Balcer, 1963; Dzięgielewski, 2017; Terlikowski et al., 2018), six physical quantities and assumptions were made: (i) log's diameter; (ii) size of construction boxes; (iii) number of boxes in 1 m wide cross-section of a rampart; (iv) width of the rampart; (v) height of the rampart (5 m and 1 m); (vi) circuit of the rampart (480 m in total: 212 m of 1 m height and 268 m of 5 m height). Due to differences in height of the rampart (assumption v), which is much lower in the S-E part of the site, we estimated minimum and maximum capacities. The former calculation relates to actual dimensions, whereas the latter to full-height embankment around the entire perimeter. The formulas applied are presented in Fig. 2.

Next, the volume of wood was extrapolated to the potential area of woodland felled to deliver it. Unfortunately, there is no detailed study on the taxonomical content of timber used for this rampart; hence, we assumed oak (*Quercus*) as the most probable, based on more invasive archaeological studies on LUc strongholds such as Biskupin (Kaczmarek and Szczurek, 2015; Dzięgielewski, 2017a). Finally, a calculation incorporating the age of trees, soil, and climatic conditions was carried out using the website https://foresteurope.org. To calculate the total surface of woodland cut for the embankment building, we applied a conversion factor in which 1 ha of oak-dominated forest delivers 200–350 m^3 of timber (Matthews et al., 2016; Böl̈oni et al., 2021).

3.2. Core retrieval and sampling

The core (Linje_2019), 1230 cm-long, was retrieved from the central section of the mire characterised by the maximum peat thickness (Fig. 1), using the Russian-type sampler (10 × 100 cm) in May 2019.

Preliminary ^{14}C AMS dating, carried out in 1-metre resolution, enabled selecting a section representing the period outlined by this study, i.e. from 350 to 200 cm. The selected part was cut into 2.5 cm thick slices, and subsamples of 1 cm volume for the palynological analysis were collected from the centre of each slice. The residues have been subjected to the selection of plant macrofossils for ^{14}C AMS dating and analyses of plant macrofossil and macroscopic charcoal (fraction size >100 μm). The subsampled material was stored in a cold room at a temperature of 4 °C.

3.3. Absolute chronology and peat accumulation rates

The Bayesian age-depth model was constructed to determine the absolute chronology and was based on 13 out of 14 ^{14}C AMS dates (Table 1). The age-depth model was constructed using the OxCal 4.4.4 software (Bronk Ramsey, 1995, 2006), by applying the *P_Sequence*

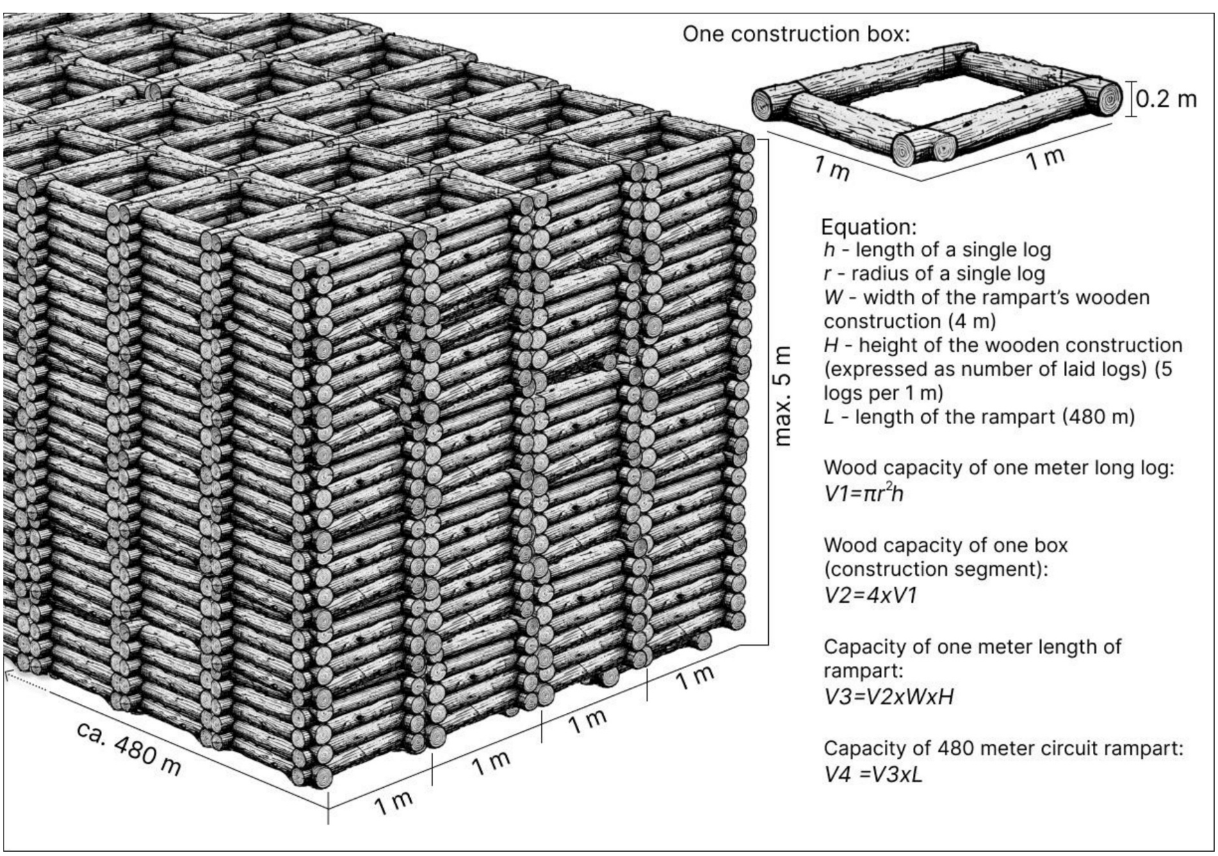

Fig. 2. Schematic and simplified cross-section of the inner wooden structure of the embankment and formulas for the calculation of timber consumption. The figure was produced in Figma Free Online Web Design. The graphic of wooden construction was created by ChatGPT 4o.

Table 1
Radiocarbon dates of the Linje_2019 profile – peat section 200–351 cm.

Laboratory code- number	Depth [cm b.g.l.]	^{14}C date [^{14}C BP]	Calibrated date (95.4 % probability) [cal. BCE/CE]	Material dated; remarks
Poz-158585	202.5–205	1680 ± 30	255 CE–286 CE (13.8 %) 326 CE–433 CE (81.7 %)	*Sphagnum* stems
Poz-158587	212.5–215	1880 ± 30	81 CE–99 CE (5.1 %) 110 CE–236 CE (90.3 %)	*Sphagnum* stems
Poz-158588	222.5–225	2160 ± 30	356 BCE–279 BCE (36.4 %) 257 BCE–248 BCE (1.0 %) 233 BCE–97 BCE (56.1 %) 72 BCE–57 BCE (2.0 %)	*Sphagnum* stems
Poz-158589	232.5–235	2240 ± 35	392 BCE–342 BCE (26.5 %) 323 BCE–200 BCE (69.0 %)	*Sphagnum* stems
Poz-157839	242.5–245	2480 ± 35	773 BCE–468 BCE (94.0 %) 435 BCE–423 BCE (1.5 %)	*Sphagnum* stems
Poz-127851	250–251	2395 ± 30	726 BCE–700 BCE (4.3 %) 664 BCE–650 BCE (2.5 %) 546 BCE–396 BCE (88.7 %)	*Sphagnum* stems
Poz-157881	252.5–255	2385 ± 30	719 BCE–708 BCE (1.8 %) 662 BCE–653 BCE (1.4 %) 544 BCE–393 BCE (92.2 %)	*Sphagnum* stems
Poz-158591	262.5–265	3300 ± 35	1678 BCE–1654 BCE (2.4 %) 1641 BCE–1498 BCE (93.0 %)	*Sphagnum* stems; outlier
Poz-158592	272.5–275	2440 ± 30	751 BCE–684 BCE (22.3 %) 668 BCE–634 BCE (9.8 %) 622 BCE–613 BCE (1.1 %) 591 BCE–408 BCE (62.3 %)	*Sphagnum* stems
Poz-157840	282.5–285	2490 ± 35	777 BCE–477 BCE (95.4 %)	*Sphagnum* stems
Poz-157841	297.5–300	2580 ± 35	812 BCE–748 BCE (74.4 %) 687 BCE–666 BCE (6.2 %) 641 BCE–568 BCE (14.9 %)	*Sphagnum* stems
Poz-157842	307.5–310	2685 ± 35	905 BCE–799 BCE (95.4 %)	*Sphagnum* stems
Poz-158598	317.5–320	2665 ± 30	900 BCE–857 BCE (21.6 %) 849 BCE–792 BCE (73.8 %)	*Sphagnum* stems
Poz-127853	350–351	3045 ± 30	1400 BCE–1220 BCE (95.4 %)	*Sphagnum* stems

function with the following parameters: $k_0 = 0.5$, $log_{10}(k/k_0) = 1$ and *interpolation* = 0.5 cm (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). The IntCal20 (Reimer et al., 2020) ^{14}C atmospheric curve was used as the calibration set. Date Poz-158591 was excluded from the modelling as it was distinctly older than neighbouring dates. The sections of the profile in which peat properties point to potential changes in the peat accumulation rate (AR_{peat}) were introduced to the model as boundaries (*Boundary* command). The boundaries were placed based on visual inspection of lithology and changes in total pollen concentration (e.g. Kołaczek et al., 2016). These were placed at depths: (i) 350 cm—the bottom of the model, (ii) 317.5 cm—a decline in pollen concentration, (iii) 270 cm—a decline in pollen concentration, the bottom of the layer with the lowest pollen concentration, (iv) 230 cm—an increase in pollen concentration, a top of the layer with the lowest pollen concentration in the profile, (v) 200 cm—a top of the analysed section.

In the following sections of this article, μ (mean) values retrieved from the age-depth model rounded to tens were applied. The age was expressed as BCE/CE (Before Common Era/Common Era). The AR_{peat} was calculated by the OxCal 4.4.4 software and presented in the unit: cm yr^{-1}.

To validate absolute chronology, the profile was examined in terms of the presence of cryptotephra/tephra layers. The initial screening for cryptotephra/tephra shards was performed on the peat material from the Linje core divided into 120, 10 cm-thick monoliths. The peat was incinerated at 500 °C for 5 h and sieved through the 50 and 25 µm sieves. The density separation was performed on the remaining fraction with the use of Sodium Polytungstate in search for cryptotephra/tephra particles according to protocol by Blockley et al. (2005), modified by Lane et al. (2014). The separated material was then analysed under the optical microscope with 40× magnification.

3.4. Plant macrofossils

Plant macrofossil analysis was carried out to recognise the quantitative content of plant remains to validate and interpret changes in the peat accumulation rate. Twenty-two samples of volume ca. 11–27 cm^3 were analysed for main peat components according to the Quadrat protocol (Barber et al., 1994; Väliranta et al., 2007; Mauquoy et al., 2010) without chemical pre-treatment of the samples. Identification of the botanical remains followed relevant literature (e.g., Grosse-Brauckmann, 1972; Katz et al., 1977; Mauquoy and van Geel, 2007) and a reference collection. Percentages of unidentified organic matter and macrocharcoal (≥1 mm) were also estimated as peat components in addition to botanical remains.

3.5. Pollen, non-pollen palynomorphs and charcoal

Sixty samples were prepared for palynological analyses, using the standard laboratory procedures (Berglund and Ralska-Jasiewiczowa, 1986). As peat was devoid of calcium carbonates and distinct mineral particles, only pretreatment by digestion in hot 10 % potassium hydroxide to remove humic compounds was applied. Next, acetolysis was performed. One *Lycopodium* tablet (Batch 050220211, containing 18,407 spores per tablet; produced by Lund University) was added to each sample during the laboratory procedures for later calculations of microfossil concentration (Stockmarr, 1971). Pollen, spores, and selected non-pollen palynomorphs (NPPs) were counted under an upright microscope until the total pollen sum (TPS) of grains in each sample reached at least 500 pollen grains. TPS is the sum of arboreal pollen (AP) and non-arboreal pollen (NAP), from which pollen of aquatic and wetland taxa, spores and NPPs are excluded. The exceptions were samples from the depths 246.25 and 243.75 cm, where pollen concentration was low and hence TPS < 500. Especially, the sample from a depth of 246.25 cm was almost devoid of pollen and thus excluded from the analysis. Sporomorphs were identified with the assistance of atlases and keys (Moore et al., 1991; Beug, 2004; van Geel and Aptroot, 2006). Microscopic charcoal particles (fraction size: 10–100 µm) were counted on the same slides as pollen and NPPs until the number of particles and *Lycopodium* spores reached, at least, 200 (Tinner and Hu, 2003; Finsinger and Tinner, 2005).

The results of the palynological analysis were expressed as percentages and accumulation rates (selected, most frequent taxa), whereas microscopic charcoal only as accumulation rates. Percentages of pollen grains, spores, and NPPs were calculated based on the ratio of an individual taxon to the TPS. Selected pollen taxa and microscopic charcoal accumulation rates (PAR_{taxon} and $CHAR_{micro,}$ respectively) were calculated based on the formula $C_t \times AR_{peat}$, in which C_t is the concentration of taxon or charcoal particles (unit: grains or particles cm^{-3}) and AR_{peat} (unit: cm yr^{-1}) is the accumulation rate of deposits retrieved from the age-depth model calculated by the OxCal 4.4.4 program.

For macroscopic charcoal (fraction size: >600 µm, representing local fire activity according to Adolf et al., 2018) analysis, 59 samples were prepared in total, according to the standard procedures (Whitlock and Larsen, 2001; Conedera et al., 2009). The sample from a depth of 337.5–335 cm (336.25 cm) was lost before laboratory preparation. Macroscopic charcoal particles were counted under a stereomicroscope with 40 × magnification. Macroscopic charcoal accumulation rate ($CHAR_{macro}$) was calculated according to the formula: $CHAR_{macro} = C_{macro} \times AR_{peat}$, in which C_{macro} is the concentration of macrocharcoal (unit: particles cm^{-3}).

3.6. Statistical analyses and data visualisation

The results of pollen, NPP, micro- and macrocharcoal analyses were drawn as diagrams using the TILIA Graph programme (Grimm, 1991). Diagrams were divided into phases based on the percentage values of arboreal pollen taxa, using a CONISS dendrogram applying square root transformation (Edwards and Cavalli-Sforza's chord distance; Grimm, 1987).

4. Results and interpretation

4.1. Archaeological data

4.1.1. Spatial integration of archaeological data

Two major concentrations of LUc settlement can be distinguished within the study area (Fig. 3). The first is located to the north, within the Vistula River flood plain and consists of 34 sites (15 settlement points, 16 settlement traces, 2 cemeteries located at the elevated dunes and 1 of unknown function). All of them are located on the western side of the valley, possibly due to the presence of peatlands in the east, which may have impeded settlement in the past.

The second concentration of 52 sites (1 stronghold, 28 settlements, 2 settlement points, and 21 settlement traces) occurs in the nearest vicinity of the stronghold. Sites are stretched along small valleys in the central and eastern part of the area. Considering the high number of settlements and proximity to the Gzin stronghold, this location might have witnessed the highest settlement intensity in the times of the LUc. The remaining number of sites was found in the southern part of the research area, deep in the morainic plateau, comprising loosely scattered 14 sites (4 settlements, 10 settlement traces), at least 1 km away

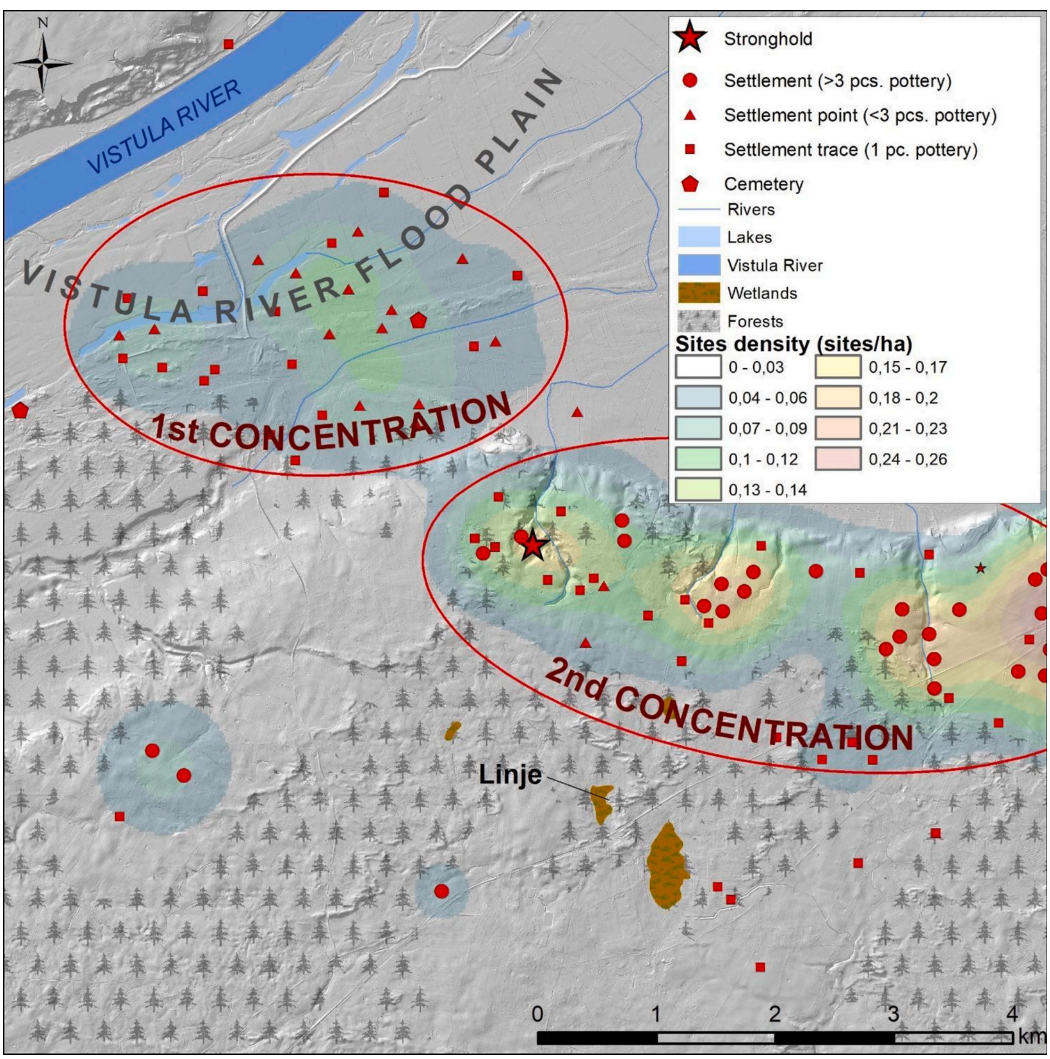

Fig. 3. LUc settlement network in the nearest vicinity of Gzin stronghold with the results of Kernel Density analysis. Background shaded relief model produced after geoportal.gov.pl. Figure produced in ESRI ArcMap 10.1.

from Linje. It may be assumed that these are traces of occasional penetration of this area by inhabitants, associated with the exploitation of local resources.

These records are also validated by the results of Kernel Density analysis (Fig. 3). The highest densities are in the areas around the small valleys, close to the edge of the morainic plateau near the stronghold and south-east of it. In the Vistula River valley, there is an agglomeration of less concentrated sites at an area of approximately 7 km^2.

These results should be treated cautiously as the local settlement network was acquired during the Polish Archaeological Record project (in Polish: Archeologiczne Zdjęcie Polski – AZP). Due to the lack of chronological differentiation of LUc materials, and limited availability of some areas (e.g., the forested ones), the presented picture does not provide full information about settlement structures of that time. In the case of areas near Linje peatland, modern woodland cover seems to distort proper reconstruction of LUc settlement density based on the AZP data (Fig. 3). The small number of sites around the Linje peatland might be underestimated as a result of a densely forested area, which obstructs field walking by archaeologists. This potential knowledge gap might be filled with the results of palaeoecological analyses.

4.1.2. Potential wood consumption for the stronghold building

Calculation of potential wood utilisation for the stronghold building revealed that 3898.08 m^3 of wood was required for the building of the actual size embankment, and if a full-height embankment of 5 m was assumed, then the construction would consume 6028.8 m^3 (Fig. 2). As there is no data about the taxonomic composition of wood utilised for the Gzin stronghold construction, we used analogies from other strongholds (Ważny, 1994; Kaczmarek and Szczurek, 2015). Moreover, some of the physical properties of oak timber, such as high density and durability (Sydor, 2011), suggest it as the main building material. This volume of wood required logging in the area from ca. 11.14–19.49 ha (minimum) to 24.12–30.14 ha (maximum) of mesic natural oak-dominated forest (cf. Matthews et al., 2016; Bölöni et al., 2021). However, this should be treated as a minimum, as not every oak was suitable to provide proper timber. According to archaeological data (Chudziakowa, 1992), younger trees were favoured over the old ones with wider trunks. Nevertheless, oak should have regularly occurred in that area because the potential woodlands are continental mixed pine-oak woodlands (*Querco-Pinetum*), subcontinental lowland lime-oak-hornbeam woodlands (*Tilio-Carpinetum*), and lowland ash-elm floodplain woodlands (*Ficario-Ulmetum*) (Matuszkiewicz et al., 1995; Supplementary Data 1). The richest in oaks are pine-oak woodlands, and these probably could have grown in the vicinity of Linje peatland (Supplementary Data 1). Pollen analysis confirms this assumption (see subchapter 4.3).

4.2. Absolute chronology, peat accumulation rates and plant macrofossil content

The age-depth model revealed the model agreement (A_{model}) = 53 %. Even though the recommended minimum is 60 % (Bronk Ramsey, 2008), the model was accepted due to the substantial prevalence of the dates that revealed an individual agreement index (A_{date}) higher than 60 %. Only two dates have A_{date} equal to 37 and 43 % (Fig. 2). Unfortunately, no volcanic shards were found in the profile to additionally validate the reliability of the accepted age-depth model. According to the age-depth model, the studied fragment of the profile reflects a period between ca. 1272 ± 57 BCE and 412 ± 76 CE. The 1σ error ranged between 15 (ca. 829–780 BCE) and 76 (ca. 410 CE) calibrated years. The highest peat accumulation rate (AR_{peat}) was identified in section 317.5–300 cm (ca. 860–790 BCE) and reached 0.22–0.23 cm yr^{-1}, whereas the lowest AR_{peat} in section 240–200 cm (ca. 430 BCE –440 BCE) with values 0.03–0.06 cm yr^{-1} (Fig. 2). The highest pollen concentrations correspond with the lowest AR_{peat} in the sections reflecting the periods of ca. 1290–860 cal. BCE (350–317.5 cm) and ca. 250 cal. BCE–440 CE (230–200 cm), whereas the lowest pollen concentrations coincided with high AR_{peat} at ca. 850–770 BCE (315–297.5 cm) and ca. 670–250 BCE (270–230 cm). Similar relationships between pollen concentration and AR_{peat} were described in other studies from peatlands (Marcisz et al., 2015; Lamentowicz et al., 2015).

The dominant peat-forming taxon was *Sphagnum* (20–86.9 %, Fig. 4). The lowest contribution of identifiable *Sphagnum* remains in peat (20–26.7 %) was linked with the high proportion of unidentified organic matter (10–13 %), Ericaceae rootlets (18.9–20 %), and undifferentiated monocot remains (19.6–29 %) in the layer spanning the period of ca. 180– 330 CE (Fig. 4). This time interval, being a part of the profile section reflecting the lowest AR_{peat} in the profile, suggests a predominance of dry conditions and/or water table fluctuations, supporting the spread of vascular plants, which contributed to stronger peat decomposition and, thus, the decline of AR_{peat}. Peat decomposition contributed to peat compaction, which caused an increase in pollen concentration. Moreover, previous high-resolution palaeoecological studies performed on the Linje peatland (Marcisz et al., 2015) allowed detailed dating of the local vegetation changes based on pollen analysis. One such distinct change was the regeneration of *Carpinus betulus* stands at ca. 100–1 BCE that is consistent with our study's results (see subchapter 4.3). This also confirms the reliability of the age-depth model calculated for this study (Fig. 4).

4.3. Pollen and charcoal: forest and grassland vegetation changes and human impact

Lin-tp-1 zone; 350–260 cm; ca. *1260–550 BCE*

During this period, crucial events like the beginning of colonisation, construction and growth of settlement structures connected with the LUc societies should have taken place. Also, as a result of the development of EIA societies, at around 680–-550 BCE, the stronghold should have been built as indicated by the dating of some of the EIA fortified settlements in Poland (Kaczmarek and Szczurek, 2015; Dzięgielewski, 2017b).

At that time the peatland vicinity was overgrown by Scots pine (*Pinus sylvestris* type: 23.5–64.6 %; 1400–18,870 grains $cm^{-2}yr^{-1}$), birch (*Betula alba* type: 8.8–30.5 %, 400–14,870 grains $cm^{-2}yr^{-1}$, Figs. 5 and 6) and in wetter outskirts of peatland by *Alnus glutinosa* (pollen type 6.8–19.7 %, 410–5840 grains $cm^{-2}yr^{-1}$). Such high values of PAR of *P. sylvestris* type and *B. alba* type suggest the presence of dense canopies in peatland surroundings, as well as mature trees on the peatland surface (Hicks and Sunnari, 2005). Important deciduous components of woodlands were oaks (*Quercus*: 3.1–13.2 %, 240–2600 grains $cm^{-2}yr^{-1}$), common hazel (*Corylus avellana*: 1.2–13.3 %, 180–1380 grains $cm^{-2}yr^{-1}$), common hornbeam (*Carpinus betulus*: 0.8–13 %, 160–3460 grains $cm^{-2}yr^{-1}$) and scattered European beech (*Fagus sylvatica*), elm (*Ulmus*) and common ash (*Fraxinus excelsior*). From ca. 870 to 770 BCE, *Quercus* pollen percentages and accumulation rates declined (from 12.9 to 3.1 %; 3420–310 grains $cm^{-2}yr^{-1}$), which might be related to increasing settlement pressure and/or the rising of the stronghold and its embankment in Gzin (see subchapter 5.1). This process required large amounts of oak wood (Ważny, 1994). Simultaneously, pollen of *C. betulus* and *C. avellana* decreased, which may suggest that these species were also utilised by settlers. The traces of agriculture were present as single grains of Cerealia type from ca. 910 BCE. As this pollen type may harbour some wild species of grasses (Beug, 2004), a firm indicator of crops is *Secale cereale* (Behre, 1981), identified in the layers at ca. 1040, 810 and 750 BCE. Open areas in the peatland vicinity were marked by the pollen of Poaceae (0.9–5.7 %), *Artemisia* (0.3–3.5 %), *Rumex acetosa/acetosella* type (0–2.5 %) and *Plantago lanceolata* (0–0.7 %). The lack of distinct changes in the abundance of coprophilous fungi fails to indicate any influence of pastoral activity.

Microcharcoal accumulation rates ($CHAR_{micro}$) revealed two periods with higher fire activity ca. 1050–860 (1250–5260 particles cm^{-2} yr^{-1}) and 700–500 BCE (1370–6590 particles cm^{-2} yr^{-1}). However, neither

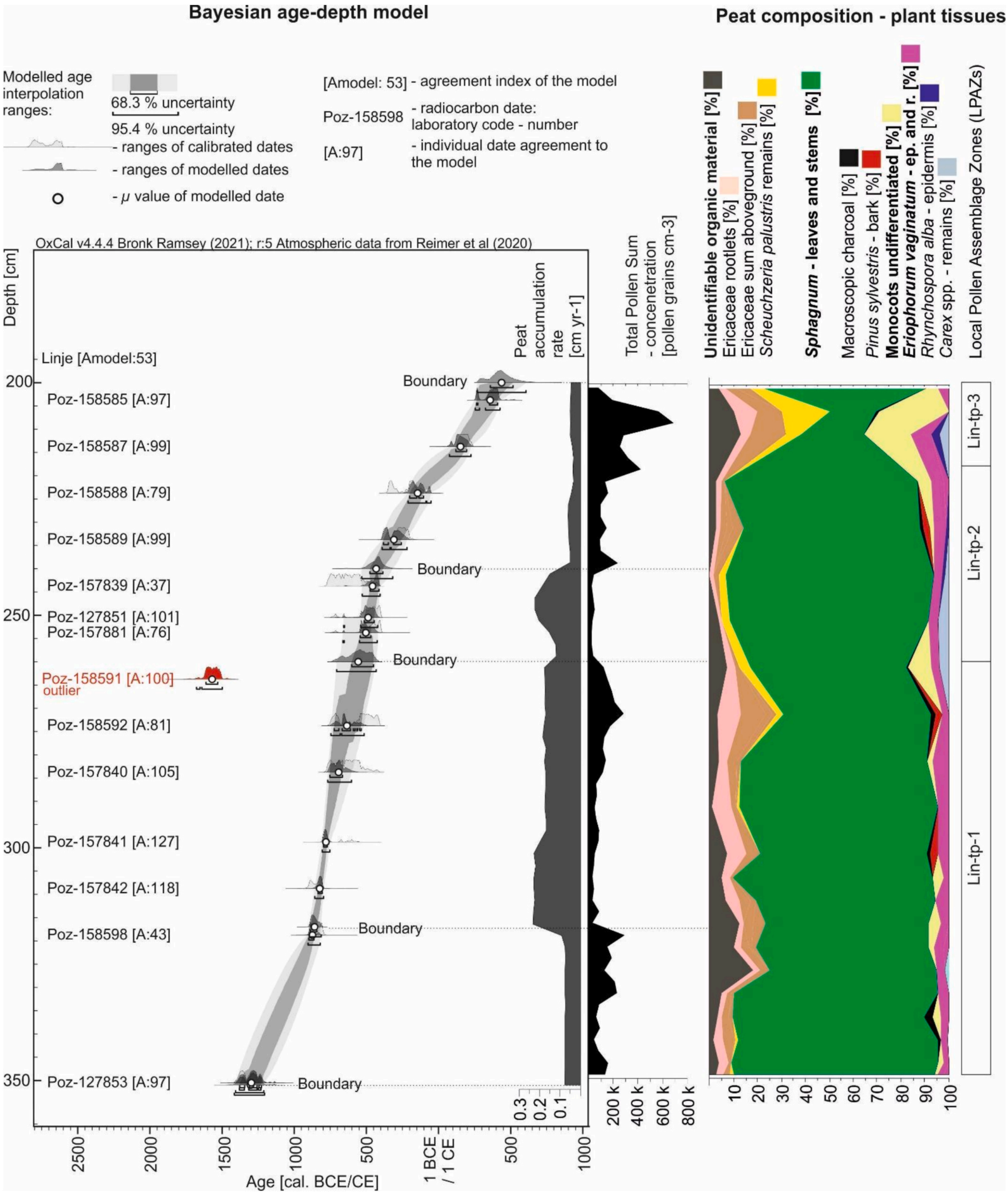

Fig. 4. Age-depth model and simplified botanical peat composition.

period overlapped with a decline of oak linked to the building time of the stronghold. About 1260–990 BCE, higher concentrations and accumulation rates of macroscopic charcoal ($CHAC_{macro}$ max. 33 particles cm^{-3}; $CHAR_{micro}$ up to 2.5 particles cm^{-2} yr^{-1}) may suggest slightly higher local fire activity. During plant macrofossil analysis, a sample at the depth of 336.25 cm (ca. 1110 BCE) was noticed due to a considerable amount of macrocharcoal (nearly 4 % of the peat components). However, these values are still relatively low and do not suggest local fire activity on the peatland and in its close vicinity.

Lin-tp-2 zone; 260–217.5 cm; ca. *550 BCE–40 CE*

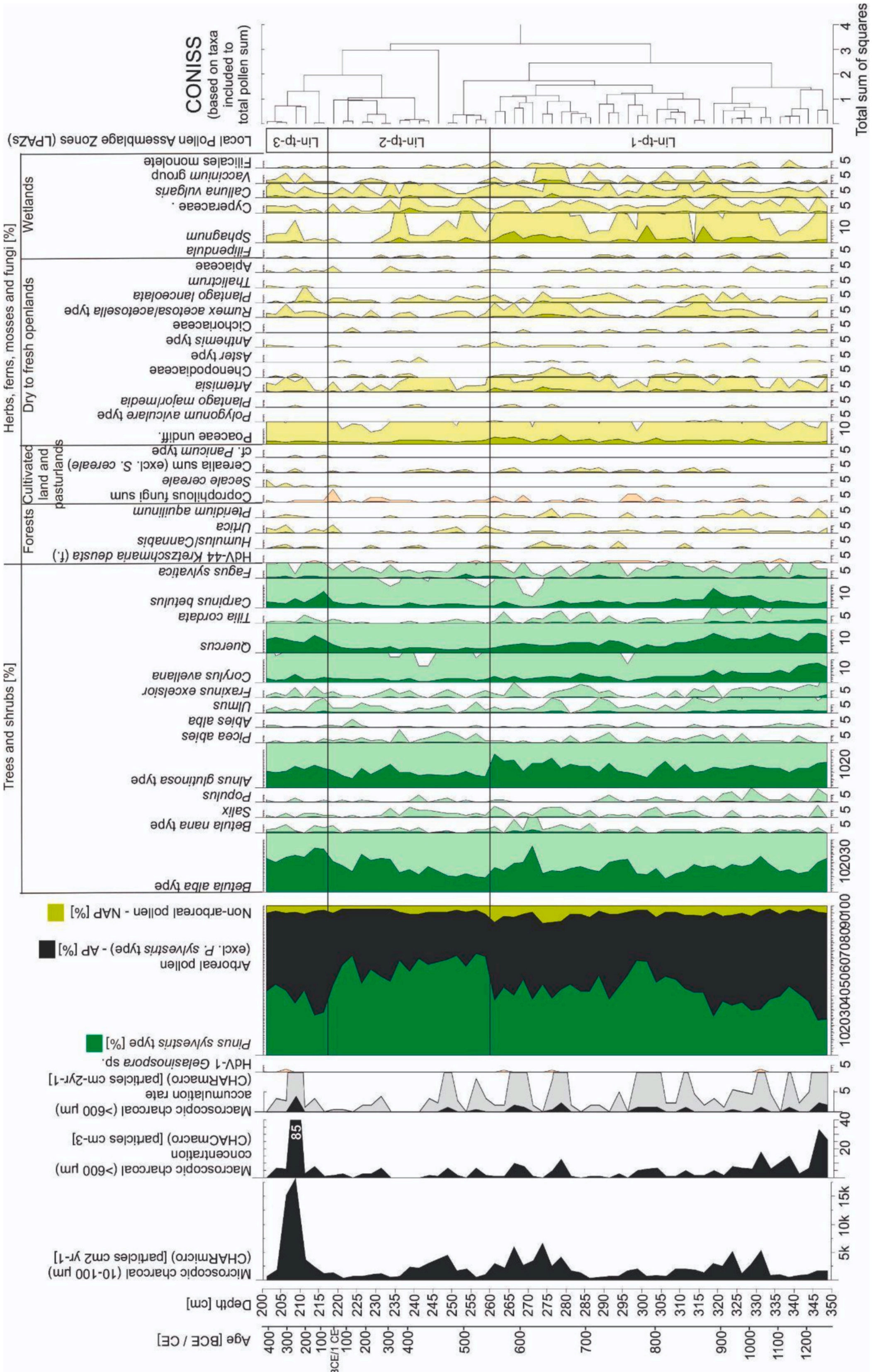

Fig. 5. Simplified diagram presenting pollen, non-pollen palynomorph and charcoal data. Lighter colours are used in individual curves to show values magnified by 10×. Abbreviations: f. – fungus, excl. – excluding, undiff. – undifferentiated.

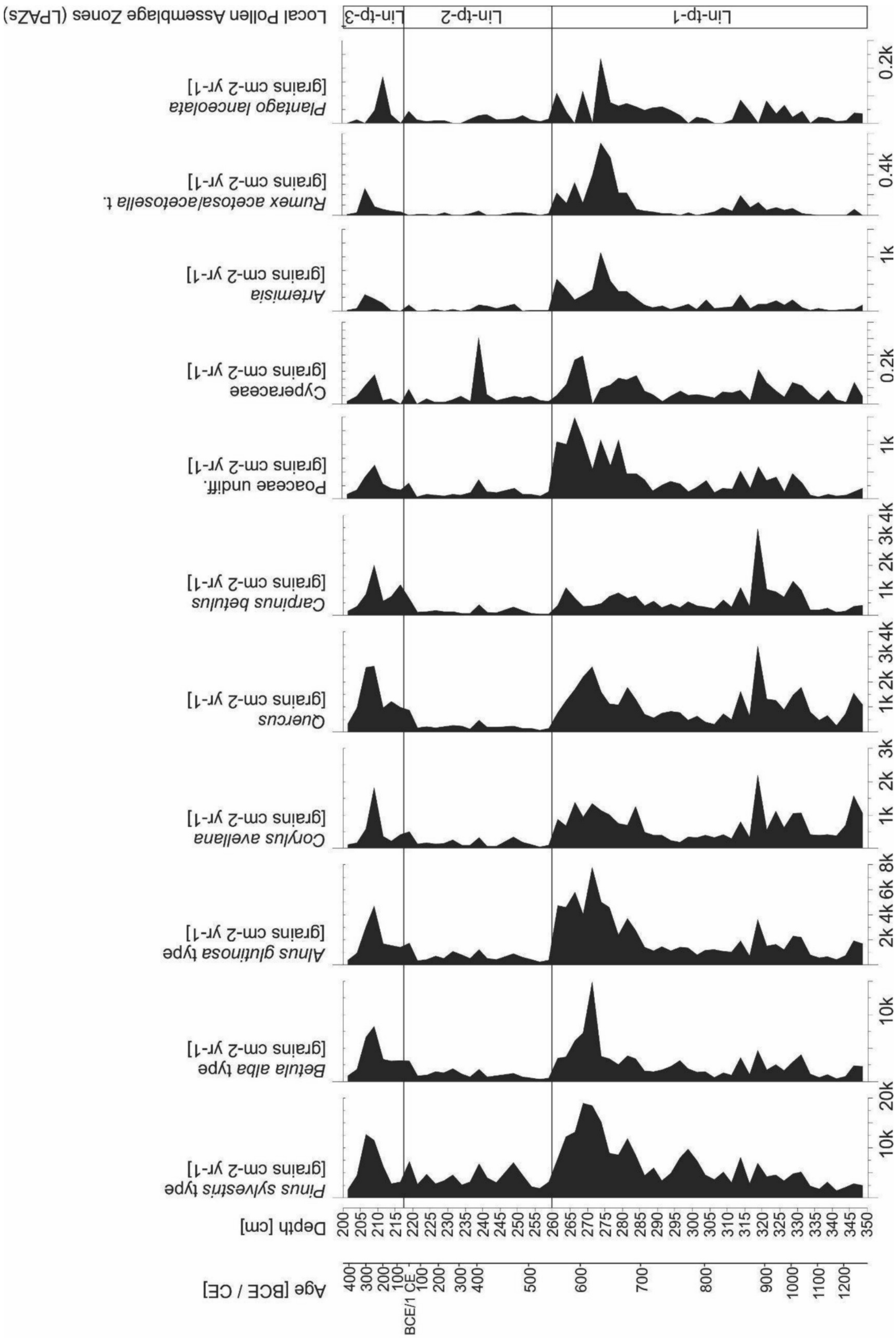

Fig. 6. Pollen accumulation rates (PARs) of selected taxa.

Archaeological data reflect the probable fall of the Gzin stronghold and further cultural changes when the LUc societies were displaced by the Pomeranian culture spreading from the North (Kaczmarek, 2012). In Linje, this period was characterised by a decline in pollen accumulation rate, which might have been an effect of climate cooling during vegetation season (cf. Barnekow et al., 2007; Huusko and Hicks, 2009; van der Knaap et al., 2010). Values of arboreal pollen (AP: 94.3–98.2 %) were higher in comparison to the Lin-tp-1 zone (94.3–98.1 %), so deforestation does not seem to be a good explanation. An increase in the percentages of *Pinus sylvestris* pollen (47.7–69.6 %) may have resulted from the spread of Scots pine in the peatland vicinity and on its surface (presence of stomata). Additionally, this species probably still occurred in dense forest stands as indicated by PAR values (1930–7250 particles cm^{-2} yr^{-1}, cf. Hicks and Sunnari, 2005). *Betula* sp. (*B. alba* type: 9.6–25.1 %, 280–3080 particles cm^{-2} yr^{-1}) was probably the main admixture in these woodlands. Both taxa revealed opposite trends in percentage values and a rising one characterised *B. alba* type. Percentages of *Alnus glutinosa* type (6.2–15.8 %) and *Quercus* (2.2–5.7 %) declined, which, at least partly, was a result of the increased input of Scots pine pollen produced by trees that probably entered the peatland. However, the rise of the stronghold and its embankment in Gzin or their renewal might also be an alternative explanation for such distinct declines in accumulation rates of trees (see subchapter 5.1). Single Cerealia type pollen grains have been identified in ca. 44 % of samples, but *Secale cereale* was detected in only one sample, ca. 10 cal. CE. About 270 cal. BCE, a grain resembling *Panicum* type was identified, which may suggest some changes in the cultivation structure.

The older half of the zone (510–380 BCE) was characterised by a slight increase in fire activity in the region ($CHAR_{micro}$: 1680–4470 particles cm^{-2} yr^{-1}).

Lin-tp-3; 217.5–200 cm; ca. *40–440 CE*

During this period, the area was inhabited by people of the Przeworsk culture, which is identified mainly through the presence of cemeteries. The end of this time frame also encompasses the beginning of the Migration Period, when a significant population decrease happened in north-central Europe.

Scots pine (*P. sylvestris* type: 29.1–48.1 %) retreated and it was probably substituted by birch (*B. alba* type: 19.6–29.5 %). *Quercus* (7.9–11.6 %) and *Carpinus betulus* (3–11.2 %) expanded in moderately wet and drier habitats. Proportions of AP were slightly lower (94.7–97.6 %), which indicates some deforestation in the vicinity of peatland. Agricultural activity increased, which is seen in the more frequent presence of *Secale cereale*, in comparison with the Lin-tp-2 zone, together with Cerealia type and cf. *Panicum* type.

This zone was characterised by the highest fire activity during the studied period. About 230–330 CE, a distinct rise in $CHAR_{micro}$ was identified (15,240–18,140 particles cm^{-2} yr^{-1}). A greater fire activity was also indicated by the highest $CHAC_{macro}$ (85 particles cm^{-3}) and $CHAR_{macro}$ (4.1 particles cm^{-2} yr^{-1}) ca. 230–280 cal. CE, which shows the impact of fire on the Linje peatland and/or its vicinity. However, $CHAR_{macro}$ might have been biased by the low peat accumulation rate values in this zone, and the scale of local fire impact on the forest and peatland ecosystem might have been underestimated.

5. Discussion

5.1. Toward deciphering the environmental footprint of the stronghold building

The estimated volume of wood used for erecting the Gzin stronghold embankment, at least ca. 3898.08 m^3, should have been collected from at least ca. 11 ha of natural oak-dominated forest (cf. Matthews et al., 2016; Bölöni et al., 2021). However, this timber was probably also utilised for the maintenance of settlements in the stronghold's vicinity, and oak was not a local forest dominant as revealed by our study (Fig. 5). Therefore, the exploited area must have been greater than this estimation (Supplementary Data 1). On the other hand, the extent of oak depletion in the woodlands might have been overestimated, as other taxa could have also been utilised for the stronghold construction. *Alnus glutinosa*, *Fraxinus excelsior*, *Betula* sp., *Picea abies* and *Corylus avellana* were used for some construction elements in the past, as revealed in Jankowo and Biskupin sites (Walenta, 2014; Kaczmarek and Szczurek, 2015). Therefore, it cannot be excluded that some of these taxa were also used in Gzin. Moreover, another local taxon, *Carpinus betulus,* might have been a probable source of timber due to its caloric and other physical features (Pinchevska et al., 2019).

The fortified settlements of the LUc were rather short-lived and were occupied for ca. 150 years (e.g., Biskupin: Dzięgielewski, 2017a; Sobiejuchy: Harding et al., 2009) (Fig. 7). However, occupation of LUc should have been recorded in the rapid changes in the pollen spectra (Kołaczek et al., 2025; Izdebski et al., 2025) as the settlement was considerably large, similar to Biskupin (>2 ha, Kaczmarek and Szczurek, 2015). In the analysed period, two distinct declines in the percentages and pollen accumulation rates (PAR) of *Quercus* occurred, but also in *Corylus avellana* and *Carpinus betulus*: (i) ca. 870–800 cal. BCE (*Quercus* decline from 12.9 to 4.2 %) and (ii) ca. 610–520 BCE (*Quercus* decline from 6.1 to 2.7 %). Yet both decreases had different characteristics. The first one represents a simultaneous fall in the percentages and PARs of *Quercus*, *C. avellana* and *C. betulus*, and had the biggest amplitude in the first 20 calibrated years. The second is characterised by rather asynchronous decreases in PARs of the main arboreal taxa (Fig. 6), but with a contemporaneous increase in *P. sylvestris* pollen percentages (despite its decline in pollen accumulation rate) and probable increase in the woodland cover (increase in AP values; Figs. 5 and 6). In both cases, the amplitudes of *Quercus* PAR decline are comparable; however, the second decline (ca. 610 BCE) was more time-transgressive. In our opinion, the decline at ca. 870 BCE seems to be a more probable record of the period of the Gzin stronghold construction. During the second oak decline at ca. 610 BCE, PARs of most of the arboreal taxa and Poaceae rapidly decreased (Fig. 6), but it might be explained not only by changes in the woodland structure, but also by changes in peat properties. It should be mentioned that PAR or pollen influx from peatland deposits is not always a firm indicator of woodland changes in the past. From our experience, changes in the peat composition or structure, e.g., the appearance of wood, subfossil clumps and mineral insertions, may substantially change the results of PAR (Kołaczek et al., 2016, 2020, 2021). Moreover, PAR values from peat deposits are rarely presented as a result of pollen analysis because they often show different trends than percentage data (Kamenik et al., 2009; Nosova et al., 2019; Hiebenga et al., 2024) and therefore are more complicated to interpret.

The second decline of oak (ca. 610 BCE) is connected with changes in the woodland composition toward the spread and domination of *P. sylvestris*. The expansion of Scots pine was identified ca. 850 BCE (around 2.8 ka event), and later, in western and northern Poland (Latałowa et al., 2004). For example, Pleskot et al. (2022b) revealed a rapid expansion of Scots pine at ca. 870 cal. BCE (around 2.8 ka event) in Lake Spore (north-western Poland), whereas in Lake Gościąż (northern Poland) this taxon became more frequent ca. 750 BCE (Ralska-Jasiewiczowa and van Geel, 1998). This expansion was linked with the settlement regression after a 2.8 ka climatic event and/or transition toward the more humid Subatlantic phase of the Holocene (Starkel et al., 2013). In Linje peatland, the expansion of *P. sylvestris* was identified ca. 240 calibrated years later, so it fails to be a universal benchmark of woodland development after the 2.8 ka event for the northern area of Poland. The explanation of these discrepancies might be a different potential of peatlands as a palaeoecological archive when compared to lakes. Periods of prolonged low water tables may stimulate spread of *P. sylvestris*, *Betula pendula* and *Betula pubescens* on the surface of peatlands (Margielewski et al., 2024; Kołaczek et al., 2018; Czerwiński et al., 2021; Krąpiec et al., 2016) and this may cause overrepresentation of their pollen grains in pollen spectra (Czerwiński et al., 2021; Kołaczek et al., 2018). In the case of Linje, higher humidity and location of the mire

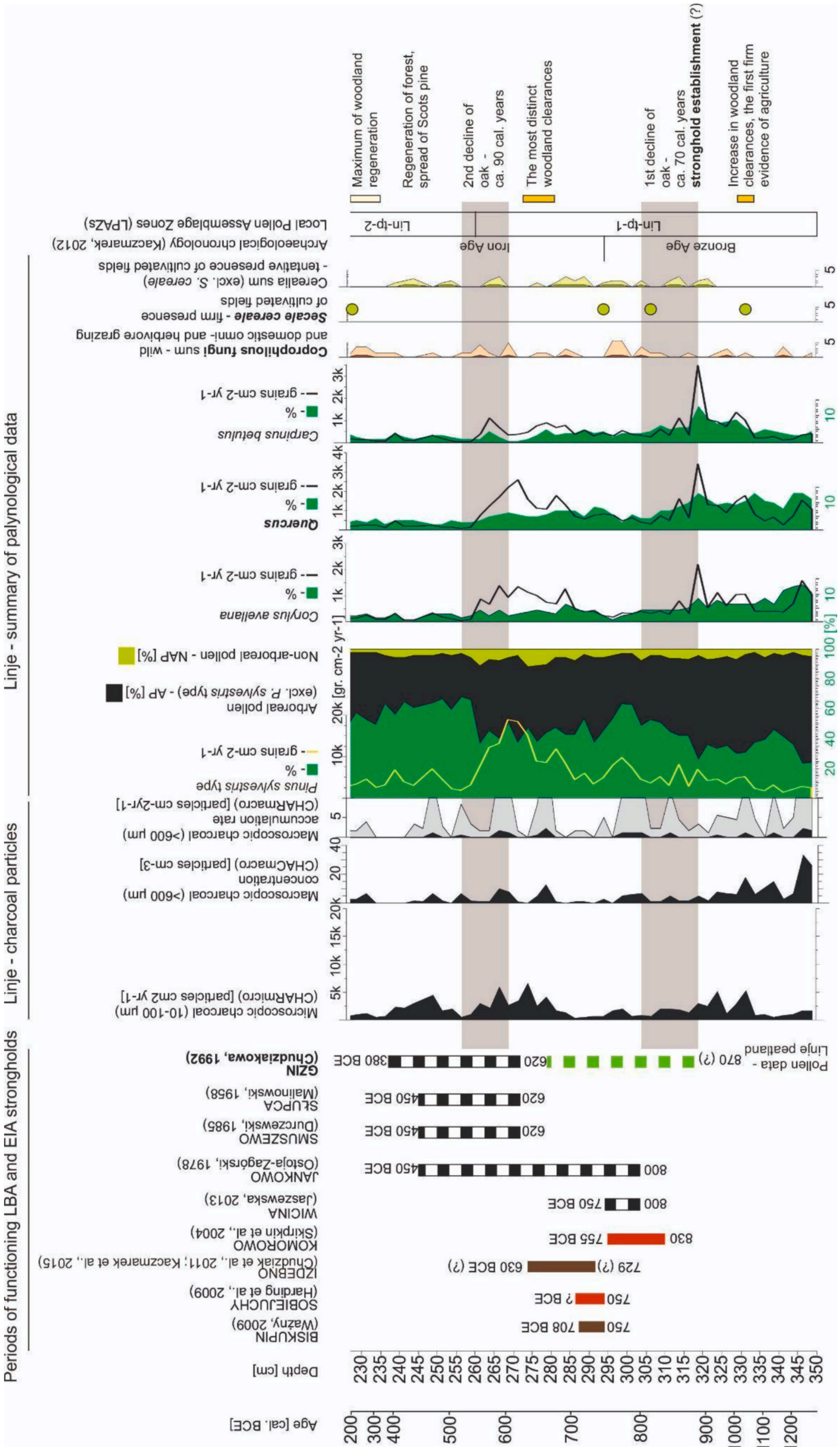

Fig. 7. Estimated Gzin stronghold operation span across other strongholds in northern and western Poland (see Fig. 1) and main woodland changes reflected by the Linje_2019 profile. Lighter colours are used in individual curves to show values magnified by 10. Dashed bar – chronology based on archaeological typochronological evidence; brown bar – chronology derived from dendrochronology; red bar – chronology estimated based on ^{14}C dates; green bar – chronology estimated by pollen data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

might have sustained a high water table. This is indicated by the twofold increase in the peat accumulation rate after ca. 860 BCE, so simultaneous with the 2.8 ka event (Fig. 4). Hence, local hydrological conditions prevented the expansion of trees on the peatland surface and kept it sensitive to more extra-local signals as the wetland remained an open area.

Unstable climatic conditions during the 2.8 ka event were manifested, i.e., by increased fluvial activity in central Europe (Macklin et al., 2006; Starkel et al., 2013) and a rise in the water table recorded in some peatlands (Słowiński et al., 2016; Gałka et al., 2015; Lamentowicz et al., 2019). However, such a rise remained undetected by the deposits of other peatlands in northern Poland such as Kusowskie Bagno and Stążki (Lamentowicz et al., 2015; Gałka et al., 2013, respectively). More frequent and/or high magnitude floods may have forced human groups that inhabited and/or were economically linked with river valleys to move to the higher terrace levels. Nevertheless, due to the indirect and imprecise chronology of sites obtained from Polish Archaeological Record, this hypothesis needs caution and further studies.

Even though woodland logging ca. 870 BCE is not unequivocal evidence of stronghold building, it may at least point to an increase in settlement activity that consumed local oak trees. The only invasive archaeological study (ceramic typochronology) performed on the Gzin stronghold enabled the dating of the beginning of this settlement to the second half of the 7th century BCE (Chudziakowa, 1992). This contrasts with our interpretation, which points to the onset of stronghold ca. 250 years earlier. According to our results, Gzin would be the oldest LUc stronghold in Polish lowlands, and taking into consideration typochronology (Chudziakowa, 1992), perhaps the one longest functioning (Fig. 7). Moreover, some other strongholds dated by dendrochronological and/or ^{14}C methods revealed the age of their onset as 9th to 8th century BCE (Fig. 7). So then, our interpretation about early construction of the Gzin stronghold at ca. 870 BCE remains realistic. All this points to the necessity of repeating studies not only on the Gzin stronghold but also on key LUc strongholds for which chronologies are not based on dendrochronology and/or ^{14}C. Such research should be supplemented with palaeoecological studies to estimate ecosystem cost of settlement activities, e.g., rapid and short-term wood consumption.

5.2. Variable human impact of Lusatian Urnfield culture recorded in the Linje peatland

Our study revealed that ca. 1040 BCE human activity increased in the wider area, and the presence of LUc crop cultivation is evident for the first time. The appearance of a single *Secale cereale* pollen grain preceding regular detection of Cerealia type pollen proves that crops were cultivated at that time, as this species might have been a crop weed then (Behre, 1992; Lityńska-Zając and Wasylikowa, 2005; Rembisz et al., 2009). The spread of cultivated fields was simultaneous to the increase in fire activity of more extra local and/or regional extent, visible through the enhanced number of microcharcoal particles (Fig. 5). This might have been a result of woodland fires, but also of various goods production with the use of fire. The beginnings of LUc in Kuyavia (central northern Poland) are dated to ca. 1550–1300 BCE (Ignaczak, 2002), i.e., earlier than palaeoecological studies suggest for the area of Linje peatland surroundings. In Kuyiavia, the LUc is recognised by small groups of people and settlements that evolved into more organised structures parallel with the development of economy and technology. In their final stage, settlement stabilisation and beginnings of local metallurgy were recorded (Ignaczak, 2002). Palaeoecological data from Linje peatland pinpoint the presence of LUc settlement from the 11th century BCE, even though previous archaeological research failed to recognise any evidence for an earlier settlement outside the area of Gzin stronghold (Chudziakowa, 1992).

The beginning of the 9th century BCE is the time of the most pronounced development and spread of LUc settlement structures. The inhabitants of the entire settlement network required natural resources to build houses and operate all infrastructure within and around the settlements. It was also the time when the intensification of agriculture in the nearest vicinity of Linje peatland took place. This is in contrast to the very low density of LUc sites recorded in the AZP mission and is probably connected with the poor availability of this area for prospection, as it is overgrown with forest. We may assume that LUc societies in this period also colonised the areas located on the plateau south of the stronghold. Still, it is impossible to find any archaeological records proving this except for a few recorded sites (Ignaczak, 2002). At the beginning of the 9th century BCE, according to pollen data (Fig. 7), a largest and rapid decline of oak was recorded, which is interpreted to be an indicator of an emerging stronghold. The effort needed to build such a considerable construction required a well-managed and well-organised community (Kóćka-Krenz, 2016). Some facilities, like workshops, might have been abandoned when construction was completed, but others probably stood inhabited. Distinct logging, associated with the acquisition of timber for construction, was also recorded in the cases of other defensive-type structures. For example, strongholds in Grodzisko – 8th–6th century BCE (Gałka et al., 2021), Manching – 3rd century BCE (Wiethold, 2013), or in later periods in Kruszwica – 9th–10th century CE (Danielewski, 2016) show comparative patterns including depletion of oaks, birches and hazels that were used for constructions and collecting resources from the nearest vicinity (Buko, 2004; Wiethold, 2013; Gałka et al., 2021).

From the middle of the 9th to the middle of the 7th century BCE., a period of stabilisation of local settlement, including the stronghold, seems to be visible in the pollen record. However, at the end of this phase, destruction and abandonment of the settlement must have taken place. Despite previous archaeological studies, hypotheses about the causes of abandonment or decline of the Gzin stronghold are still missing. Our study revealed that the weakening of agricultural activity took place ca. 550 BCE (woodland expansion indicated by an increase in arboreal pollen percentages), with a probable consequence in a decline in the local people population. However, as discussed in the previous subchapter, local processes, such as the expansion of Scots pine on the peatland surface, might have been responsible for weakening of the human record. At this research stage, owing to the aid of pollen analysis, we can detect the potential moment of erecting the stronghold, but pinpointing the end of its existence is much more challenging. This hinders unequivocal interpretation of the ecological footprint of these societal changes. More extensive, invasive archaeological studies are required to answer the question of whether local or external factors, like the Scythian invasion (Kołodziejski, 1993), were behind the downfall of the LUc stronghold in Gzin.

5.3. Gzin in LUc stronghold network and societal changes

Our study points to the first half of the 9th century BCE as the time of the foundation of Gzin stronghold. This date corresponds somewhat with the absolute (dendro)chronology of other sites: Biskupin 750–708 cal. BCE (Ważny, 2009; Kaczmarek and Szczurek, 2015), Sobiejuchy 750 cal. BCE (Harding et al., 2009; Kaczmarek and Szczurek, 2015) and Izdebno 729/630 cal. BCE (Romanowska-Grabowska, 1982, 1991; Chudziak et al., 2011). The ^{14}C date from the latter was published, but with a great uncertainty of ±140 ^{14}C years; thus, it does not seem to be applicable for dating a short-term phenomenon such as the construction of the stronghold (Romanowska-Grabowska, 1982; 1991; Chudziak et al., 2011; Kaczmarek and Szczurek, 2015). There is a single ^{14}C date for Komorowo, which also seems insufficient to narrow down the absolute chronology (830–755 cal. BCE; Skripkin and Kovaljuch, 2004). Also, archaeological typochronology based on pottery findings from different strongholds suggests approximately the same period of functioning: Wicina – 1st half of the 8th century BCE (Jaszewska and Kałagate, 2013), Jankowo – Hallstatt C/D; HaC/D (Ostoja-Zagórski, 1978), Smuszewo – HaD (Malinowski, 1961; Durczewski, 1970, 1985; Niesiołowska-Wędzka, 1974) and Słupca – HaD (Malinowski, 1958) (Fig. 7). As stated above, it is reasonable to place the Gzin stronghold as contemporary to the broader phenomenon of Early Iron Age defensive settlements in northern-central Poland.

The general function of LUc strongholds is still widely discussed (Kaczmarek and Szczurek, 2015; Dzięgielewski, 2017a). The authors suggest that: (i) the development of LUc societies resulted in collecting more goods and wealth, therefore, strongholds were needed for their protection (Ignaczak, 2002), (ii) part of them were built near the trade roots (Malinowski, 2004, 2006), (iii) at least some of them served partly as places of worship (Chudziakowa, 1978, 1992; Ignaczak, 2015; Szambelan, 2022). Nonetheless, the multifunctionality of certain strongholds was highly possible as their construction required a significant effort from the local population. Hitherto archaeological studies support the hypothesis that the Gzin stronghold establishment was a combination of 1st and 3rd reason, as no production traces were recorded (Chudziakowa, 1992). The ritual character might be supported by findings from various pits, e.g., human and animal bones, whereas weapons recovered during excavations (like spearheads; Gackowski, 2016; cheekpieces; Gackowski et al., 2024b) also point to military purposes.

In the case of Gzin, its location was not inherently associated with the presence of peatland, unlike in other LUc settlements. Most of the previously recognised strongholds were built in the vicinity of mires (Jaszewska and Kałagate, 2013), or on a lake's peninsula (Kaczmarek and Szczurek, 2015). Still, some connection to water resources is visible in the vicinity of the Vistula River flood plains. Our study suggests that the Gzin stronghold was built during the 2.8 ka event when climate instability forced people to construct settlement structures at a safe distance, preventing them from floods or increasing water levels. The withdrawal of settlements from the floodplains and lower-lying areas is a widely known phenomenon connected with this period in Europe (Trachsel, 2004; Maise, 1998; Dzięgielewski, 2017b). A decrease of human activity near the wetlands occurs at the time of erecting LUc strongholds in northern Poland (Lamentowicz et al., 2019; Fiłoc et al., 2025), the Netherlands, parallel with changes in economics (van Geel et al., 1996), England (Mercer, 1970; Jones, 2004) and Norway (Moe et al., 1988). Studies from Ireland showed opposite tendencies in settlement patterns, where people colonised previously unavailable wetland areas synchronously to the 2.8 ka event (Gearey et al., 2020). Also, in the area of north-eastern Poland, the emergence of some strongholds within the peatlands coincided with the 2.8 ka event (Żurek et al., 2022). Moreover, climate-induced socio-economic changes were recorded in the area of eastern China where military conflicts and famine forced people to migrate to new areas (Jia et al., 2022). The increase in human mobility and expansion of Scythian societies was also visible during this period, mostly in the Tuva area (van Geel et al., 2004). This might have triggered further migrations that affected the Scythian people, forcing their migration into the area occupied by LUc during the Early Iron Age (Bukowski, 1977), thus combining their history with LUc strongholds.

6. Conclusions

The reconstruction of vegetation changes based on high-resolution pollen and sedimentary charcoal data revealed that agricultural activity of people of Lusatian Urnfield culture (LUc) started in the vicinity of the peatland at least ca. 1040 cal. BCE. Even though the Gzin stronghold was situated 3 km away from the peatland, the period of significant tree decline was probably recorded in the pollen signal. As oak was presumably the main taxon providing wood for such construction, after calculating that at least ca. 3898.08 m^3 of wood were used for erecting the Gzin stronghold, we estimated that at least 11–19 ha of oak-dominated forest should have been cleared only for the rampart. Pollen data revealed that at ca. 870 cal. BCE values of *Quercus*, *Corylus avellana* and *Carpinus betulus* distinctly and synchronously declined, which might have been the footprint of this LUc project. Especially, the magnitudes of these declines were the highest in the first ca. 20 years. Our study suggests that humans were a significant factor enhancing the impact of the 2.8 ka event on the woodland ecosystem, as societal reaction to these dynamic climatic and hydrological changes required increased consumption of natural goods, among them wood.

The palynological data point to the beginning of Gzin stronghold ca. 250 years earlier than was assumed based on archaeological typochronology. However, unequivocal conclusions concerning the beginning and the end of the functioning time of the stronghold have not been drawn. Hence, complex invasive studies with reconstruction of the absolute chronology of the stronghold are still needed. Regardless of which method is closer to pinpointing the exact moment of the stronghold beginnings, palynological analysis or archaeological typochronology, a palaeoecological study may bring valuable information about long-term functioning and wood consumption by complex settlement structures in the past, as well as its consequences for the local environment.

7. Authors' contribution

WS – preparation of archaeological part of the manuscript and spatial data, conception and writing of the significant part of the draft, draft edition and review.

JN – cooperation in preparing the archaeological part of the manuscript, draft edition and review, preparation of four figures.

MK-K – non-pollen palynomorphs analysis, draft edition and review.

ML – fieldwork logistics, core retrieval, selection and identification of material for radiocarbon dating, draft edition and review.

KM – core retrieval, macroscopic charcoal analysis, draft edition and review.

KL – laboratory sampling of the cores, tephra and cryptotephra sample preparation and analysis, draft edition and review.

EP – plant macrofossil analysis, draft edition and review.

LA – fieldworks and draft edition, and review.

SV – fieldwork logistics, core retrieval and draft edition

PK – fieldworks, pollen analysis, microcharcoal analysis, preparation of depth-age model, conception and writing of the significant part of draft, preparation of four figures.

CRediT authorship contribution statement

Witold Szambelan: Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization. **Jakub Niebieszczański:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Monika Karpińska-Kołaczek:** Writing – review & editing, Investigation. **Mariusz Lamentowicz:** Writing – review & editing, Investigation. **Katarzyna Marcisz:** Writing – review & editing, Investigation. **Karolina Leszczyńska:** Writing – review & editing, Investigation. **Eliise Poolma:** Writing – review & editing, Investigation. **Leeli Amon:** Writing – review & editing, Investigation. **Siim Veski:** Writing – review & editing, Investigation. **Piotr Kołaczek:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization.

Declaration of competing interest

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.jasrep.2025.105408.

Data availability

Data will be made available on request.

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