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Human-environment interactions in the Mesolithic – The case of site Paliwodzizna 29, a lakeside site in central Poland

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ABSTRACT

Human-environmental relations before agriculture can be revealed at archaeological sites through multi-method palaeoenvironmental studies, particularly at sites which have both dryland and wetland areas. Paliwodzizna 29 is such as site, being a series of pits and hearths at the edge of Lake Grodno in Central Poland. A combination of faunal analysis, lithostratigraphy, pollen, diaspores, charcoal and sedaDNA from the site revealed seasonal *collecting*-type occupation based on the catching of pike (a superfood) in the spring in the early Mesolithic, but a different *foraging*-type pattern of occupation probably in the summer in the late Mesolithic. Subtle human impacts on the local environment are also seen, including probably burning of some woodland and reed-beds as well as localized soil erosion. This analysis reveals the potential of both such sites, and the combined methodology, for the testing of theoretical models of human mobility and activities in the Mesolithic.

1. Introduction

For a long time, the natural environment was considered only as a backdrop for human activity in the prehistoric period. Studies addressing it focused on the reconstruction of former ecosystems or the investigation of evolutionary processes in animals and plants (Pişkin and Bartkowiak, 2018, 2). This approach changed primarily due to researchers such as Grahame Clark and Julian Steward, who were two of the first to undertake an in-depth consideration of the relations between the environment and prehistoric communities (Clark, 1952; Steward, 1955). Research on this topic has now advanced in not only archaeology but many scientific disciplines and it is standard to conduct paleoenvironmental studies in the fields of palynology (e.g. Revelles, 2021; Woodbridge et al., 2018), plant macroremains (cf. Lityńska-Zając, 2018), malacology (cf. Szabó et al., 2014), sedaDNA (cf. Hudson et al., 2022), geomorphology and paleopedology (cf. Herz and Garrison, 1998), anthracology/charcoal analysis (cf. Kabukcu, 2018), and zooarcheology (cf. Gifford-Gonzalez, 2018).

However, interactions between the natural environment and groups of hunters inhabiting Europe in the early Holocene remain difficult to interpret. The most informative material for such studies is organic artefacts, unfortunately, it is extremely rare for such materials to be preserved. In the case of Mesolithic sites, paleoenvironmental studies can also be hampered by the settlement location preferences of early Holocene hunter-gatherers, who often set up camps on sandy soils which do not preserve organic materials. Unfortunately, sites of this kind constitute the overwhelming majority of sites in the European Plain. However, the situation is different with structures situated on the shores and banks of former lakes and rivers, where prehistoric artefacts made of organic raw materials can be preserved in waterlogged layers of peat and gyttja.

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Such sites as Star Carr in England (Clark, 1954; Milner et al., 2018a, 2018b), Friesack in Germany (Gramsch, 2002; Groβ, 2014; Benecke et al., 2016), Motala in Sweden (Carlsson, 2008; Molin et al., 2014; Gummesson and Molin, 2016), Šventoji in Lithuania (Rimantienė, 2005; Piličiauskas et al., 2012), Zamostje in Russia (Lozovski et al., 2013) or Bolkowo in Poland (Galiński, 2021) are, however, extremely rare and may be functionally specialized. For this reason, they can only be used as an analogy in studies for other Mesolithic settlements to a limited extent, particularly if they are located in situations with different environmental conditions and fulfilled specific purposes. As the result, every new site that can provide information on the relations between the Early Holocene hunter-gatherers and the natural environment is particularly valuable and demands in depth and multi-proxy investigation.

This article's primary goals are (1) to reconstruct the early Holocene environment around Paliwodzizna 29 (central Poland) based on the data gathered from interdisciplinary studies; (2) to expand significantly knowledge of human-environment relations in the Mesolithic of the Polish Lowlands based on the results of studies in Paliwodzizna; (3) to interpret the nature of the Mesolithic activity at Paliwodzizna, the function of the camps in different temporal phases, and the mobility of communities that used them. Particular emphasis is laid on the environmental conditions determining the presence of hunter-gatherer groups in Paliwodzizna in the Early and Late Mesolithic and the impact of their presence on the surrounding ecosystem. The data obtained is discussed in the context of similar studies on other European Mesolithic sites and finally some reflections are made on the research potential of Mesolithic sites such as Paliwodzizna 29, i.e., places where post-depositional processes result in the significant destruction of artefacts made from organic raw materials.

1.1. Site paliwodzizna 29

The Paliwodzizna 29 archaeological site is located in central Poland in the Drwęca River Valley, which separates Dobrzyń and Chełmno Lakelands (Fig. 1A; cf. Solon et al., 2018). It lies on a flat-topped ridge situated in a place where the subglacial valley of Lake Grodno and Lake Plebanka becomes the valley of the Drwęca River. The subglacial tunnel-valley of Lake Grodno and Lake Plebanka (Fig. 1B) has a N–S orientation, jutting into the flat surface of the moraine-covered upland formed during the Weichselian Glacial Stage. Its width in the southern part ranges from 400 m to 900 m in the area of Lake Plebanka, whereas in the northern part, in the vicinity of Lake Grodno, it is about 700 m wide. The immediate vicinity, as well as the floor and the walls of the tunnel-valley, stand out particularly due to their very rich diversity of glacial, fluvioglacial, denudation and erosive landscape features.

Site 29 in Paliwodzizna is one of the several Stone Age sites situated

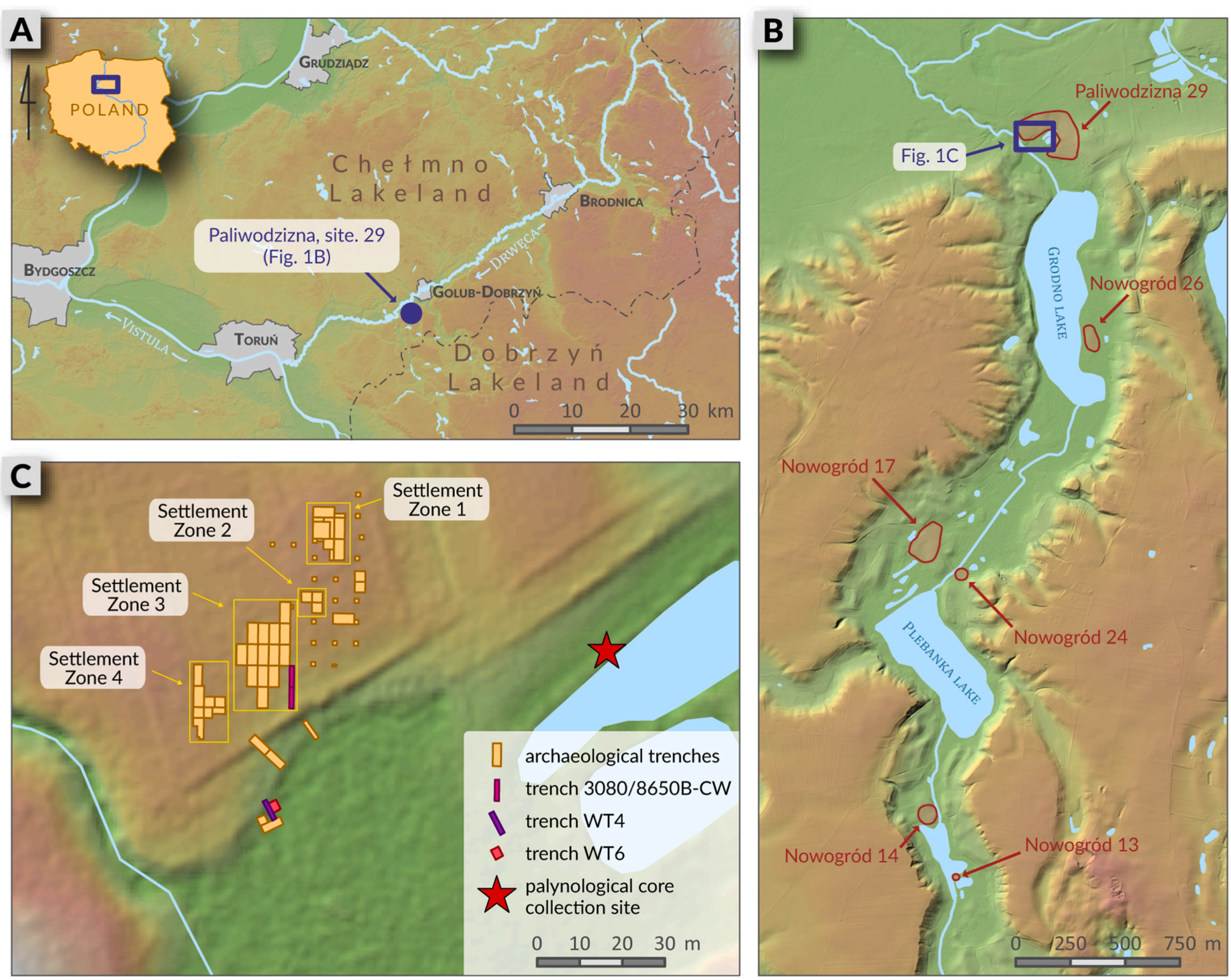

Fig. 1. Location of the site 29 in Paliwodzizna: A - location within the Chełmno-Dobrzyń Lakeland; B - location in the valley of Grodno and Plebanka Lakes; C - situational-altitude plan of the site with the archaeological trenches, settlement zones and location of the place of palynological core marked.

in the valley of Lake Grodno and Lake Plebanka that have been subject to archaeological studies (Fig. 1B), with excavations beginning in 2016. Over five years of archaeological work, an area of 468 m^2 was explored at the site, 429 m^2 of which constitute trenches situated in its sandy (dry) part, whereas 39 m^2 of excavations were made in the wetlands which are the littoral zone of the former lake. As a result of the work carried out in the dry zone of the site, four clusters of the Mesolithic features and artefacts were identified, designated here as occupation zones 1–4 (Fig. 1C). Only the archaeological materials from settlement zone 2 have been subjected to more detailed analyses so far (Osipowicz, 2021).

2. Materials and methods

2.1. Materials

From prior excavation at Paliwodzizna 29, a total of 485 samples of various types have been taken from the study area for paleoenvironmental analyses. These included 186 carbon samples intended for anthracological/charcoal analyses and radiocarbon dating, 58 samples for macroremains, 142 palynological samples, as well as 99 soil and geomorphological samples. Geomorphological and sedimentological investigations were also related to the lithofacial analysis which used sediment textural properties from 15 sediment samples collected from trench 3080/8650 B-CW (Fig. 1C). The results enable us to analyse a former lake shoreline's extent and evolution in response to the changes in its water level.

The material for palynological studies was provided by means of core drilling in the littoral zone of the prehistoric bay of Lake Grodno, in a place located directly next to an Early Holocene settlement area (Fig. 1C). The results of these studies will be discussed separately. In this paper, results of the analysis of a core sample retrieved from the profile of the trench WT4 will be discussed (sample s644; Figs. 1 and 2). The sediments from the monolith were subjected to detailed archaeobotanical analysis using pollen and plant macroremains. Seven sedaDNA samples were also collected from the trench WT6, adjacent to the east from WT4 trench. The zooarchaeological analysis included 727 bones all collected from the site in the years 2016–2020.

2.2. Methods

All the archaeological and paleoenvironmental samples are recorded three-dimensionally and their distribution analysed using ArcGIS software in order to create precise spatial models of the clusters of settlements. Kernel density estimation method, usually with a 0.5, 1, or 2 m radius determining its shape and degree of flattening, was applied to determine their range and analyse the artefact distribution (Baxter and Beardah, 1997; Beardah, 1999; Wheatley and Gillings, 2002). The chronology of the site was determined based on preliminary results of technological and stylistic analyses of the archaeological materials, as well as serial radiocarbon dating conducted primarily using the AMS method calibrated using OxCal ver. 4.4 software (Bronk-Ramsey, 2020). An attempt was made to determine the phases of the Mesolithic settlement in Paliwodzizna based on Bayesian modelling. However, it did not bring satisfactory results, and its presentation was abandoned.

The sediment grain-size distributions were determined by sieving at 1-φ intervals, and the silt and clay fractions were measured with a laser particle-size analyser (Analysette 22) at 0.25-φ intervals. The sediments were classified texturally according to the scale proposed by Udden (1914) modified by Wentworth (1922). The statistical parameters of the grain-size distribution (d_{50} - median grain diameter, GSS - mean grain-size, σ - sorting, GSK - skewness and GSP - kurtosis of the grain-size distribution) were calculated using Folk and Ward (1957).

In the geomorphological exposure (trench 3080/8650 B-CW), several lithofacies were distinguished on the base of structural and textural sediment properties sensitive to specific sedimentary environments. Additionally, soft-sediment deformation including folds and faults were distinguished and their orientations determined.

Field study of soil properties was carried out using a network of manually drilled boreholes and test pits. The study was conducted at the site and also in its immediate vicinity on adjacent terrain for a broader environmental context. Within the site area, two soil profiles representing the main landscape zones: "dry" and "wet" were identified. The profiles exposed in archaeological excavation trenches were also documented. In the immediate surroundings of the site, five additional soil test pits and a number of boreholes were made. Soil profiles were documented according to guidelines recommended by FAO (2006). Samples for laboratory testing were taken from both soil horizons in soil profiles and those exposed in the excavations. General soil properties (grain-size distribution, pH, content of organic carbon, total nitrogen and $CaCO_3$) were determined using standard pedological methods and used for classification and interpretation (Kabała et al., 2019; IUSS Working Group WRB, 2022).

The material for palynological studies and analyses of the plant macroremains was taken directly from the profile of trench WT4 (s644 in Fig. 2) into PVC trunking (U-tube), 40 cm long and 5 cm in diameter. At the laboratory, after describing the sediment approximately 50 samples were taken for the palynological analysis at a resolution of 1–2 cm. They were all subject to standard laboratory processing (Berglund

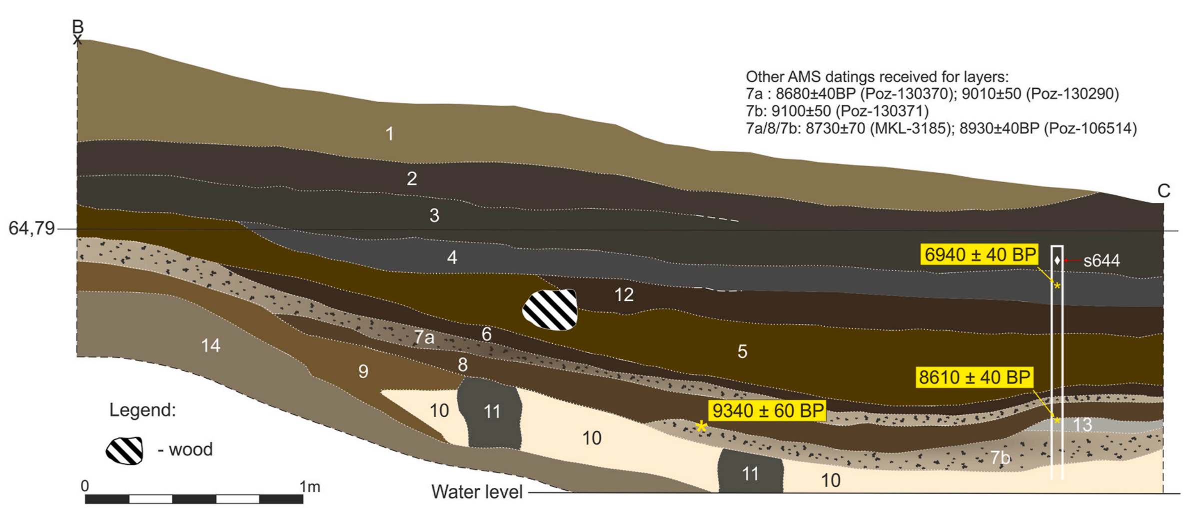

Fig. 2. Paliwodzizna, site 29, NE profile of the trench WT4. Layers: 1 – sand/gravel; 2 – boggy soil/sand; 3 – peaty muck; 4–6 – gyttja; 7 – sand with small admixture of gyttja (large charcoals, Mesolithic artefacts and ecofacts); 8–13 – gyttja; 14 – sand (natural layer). Samples: s644 – palynological/macrofossil core.

and Ralska-Jasiewiczowa, 1986). Chemical processing was performed using 10% HCl, 10% KOH and Erdtman's acetolysis method. The samples that contained clastic minerals were additionally treated with 40% HF for 48 h. To calculate the absolute sporomorphs concentration *Lycopodium* spores were added to every sample (Stockmarr, 1971). Depending on sample quality and grain frequency, at least 500 pollen grains were counted (largely above 1000) and the sum of trees (arboreal pollen AP), shrubs and terrestrial herbaceous plants (non-arboreal pollen NAP) calculated (AP + NAP = 100%). The percentage of hydrophytes, helophytes, and cryptogams, and non-pollen palynomorphs (NPP) was also calculated above the baseline sum. The POLPAL computer program (Walanus and Nalepka, 1999) was used for all calculations and diagram construction. Based on the course of the basic curves of trees, shrubs and herbaceous plants, as well as numerical analysis, local pollen levels (L PAZ - Local Pollen Assemblage Zones) were adopted from the POLPAL package.

The remaining material was divided into about 3-cm-long sections and forwarded for an analysis of macroscopic plant remains. The laboratory processing of 46 samples with a mean volume of 60 cm^3 included a brief maceration using KOH where there was a noticeably high organic matter content. Samples were washed through three sieves with the mesh size of 2.0, 0.5, and 0.2 mm and each fraction was inspected under a stereoscopic microscope. Visible plant remains (seeds, fruit, needles, tree buds, wood and charcoal) and animal remains (cocoons, chitin parts of insects) were isolated and identified. Based on the presence of remains of helophytes, hydrophytes, and after combining with pollen results, macrofossils assemblage zones (MAZs) were determined. The reconstruction of changes in the natural environment was based on bioindication characteristics of the identified plant taxa.

SedaDNA extraction followed protocols documented by Hudson et al. (2022) using the QIAGEN DNeasy Powersoil Kit. Extraction was performed in a dedicated ancient DNA laboratory at the University of Southampton on subsamples between 0.25 and 0.35 g of sediment taken from seven 50 ml tubes inserted directly into the archaeological profile. PCR amplification used generic primers of the trnL P6 loop of the plant chloroplast genome and exact PCR procedure followed Alsos et al. (2021). Two PCR negative controls and one positive control were carried out. Eight individually tagged PCR repeats for each sample aimed to increase the chance of detecting taxa represented by low quantities of DNA, and to increase confidence in the taxa identified. After library preparation using the Illumina TruSeq DNA PCR-Free protocol (Illumina Inc., CA, USA) each library was sequenced on ~10% of 2 × 150-cycle mid-output flow cells on the Illumina NextSeq platform at the Genomics Support Centre Tromsø (GSCT) at The Arctic University of Norway in Tromsø.

All next-generation sequence data were aligned, filtered and trimmed using the OBITools software package (Boyer et al., 2016) using the same criteria as Rijal et al. (2021). Resulting barcodes were assigned to taxa using the *ecotag* program and four independent reference datasets. One reference contained arctic (Sønstebø et al., 2010) and boreal (Willerslev et al., 2014) vascular plants as well as bryophytes from the circumpolar region (Soininen et al., 2015) (ArcBorBryo, n = 2280 sequences of which 1053 are unique), one the NCBI nucleotide database (January 2021 release), and finally the PhyloNorway p6loop database (Alsos et al., 2022). The relative chronology of the sedaDNA samples was established based on radiocarbon dating of material from individual layers and the results of palynological studies.

The anthracological material was analysed in line with the methodology of laboratory and microscopic works adopted in archaeobotany (Lityńska-Zając and Wasylikowa, 2005). The botanical identification of taxa was performed based on the microscopic analysis of wood elements (e.g., vessels, perforations) considered to be primary and secondary identification characteristics. The identification was performed using a plant identification field guide that contains detailed descriptions of diagnostic features and photographs for comparison with studies by Schweingruber (1990) and the Microscopic Wood Anatomy file (Schoch et al., 2004). The samples were examined in reflected light under a stereoscopic microscope (Zeiss Discovery V8) at the magnification of up to 80×, and under a metallographic microscope (Zeiss Axiotech) at the magnification of up to 500×. The investigated material was identified based on the analysis of anatomic structures visible in cross sections (CS) and longitudinal sections, the latter divided into radial longitudinal sections (RLS) and tangential longitudinal sections (TLS). Botanical names were provided in accordance with the list of vascular plants of Poland (Mirek et al., 2002).

Archaeozoological research was carried out using generally accepted techniques (Reitz and Wing, 1999) with bone debris collected from stratigraphic units subjected to macroscopic procedures. The aim was to establish the affiliation of individual items to a zoological and anatomical unit. Where possible, the age of death of the animals was assessed, and in the case of pike, the total length of individual fish was measured based on materials from the contemporary comparative collection (Makowiecki, 2003). Subfossil specimens, most often vertebrae, were compared with specimens from individuals with a known overall length.

3. Results

3.1. *Archaeological studies – the outline of the settlement phases at the site paliwodzizna 29*

The first human evidence at the site dates back to the Late Palaeolithic and is related to the activity of Swiderian hunters, although the nature of this settlement episode remains largely unclear as it is documented only by singular features, and small amounts of flint finds. The main period in which the site was used falls within the Mesolithic. Artefacts from this period were discovered both in the sandy (dry) part of the site and the peat (wetland) trenches. In the "dry' zone, these occurred both within the distinguishable flint scatters and the cloud-like structures related to numerous hearths (Fig. 3: 1–3), economic and ritual pits (up to 2 m deep), as well as other types of structures including possible remains of tar kilns (Fig. 3:4). The flint tool typology from that area (Fig. 3: 7–22) and the radiocarbon dating indicate that this part of the site was used throughout the Mesolithic (more in section 3.2.).

In the peat zone, Mesolithic materials were found in two layers of sand with a gyttja admixture containing a high number of large charcoal fragments (Fig. 2, layer 7a, b; Fig. 3: 5) and appeared to be related to the Early Mesolithic settlements exclusively. In total, during 4 research seasons, over 16,000 Mesolithic flint tools were collected from the site.

In the Neolithic, the site was sporadically visited by individuals representing such archaeological cultures as Funnel Beaker Culture, Globular Amphora Culture, and Subneolithic cultures. Most likely, settlement activity of the people of the Iwno culture (Early Bronze Age) and the Lusatian culture (Late Bronze Age/Early Iron Age) was slightly more intense. One small feature connected to the Wielbark culture (Roman period) was also identified. The final phase of the use of the site falls in the late Middle Ages and Modern Times when it was primarily croplands.

3.2. *Mesolithic settlements at the site in the context of the obtained radiocarbon dating results*

The relatively good preservation of charcoal meant that numerous samples could be taken for radiocarbon dating from the area of the Paliwodzizna site. At present, 28 of them have been dated, 15 of which are from Mesolithic contexts whereas the others are obtained from macroremains from the palynological profile (Table 3) and cultural structures outside the Mesolithic chronology.

Radiocarbon determinations obtained for Mesolithic samples indicate that the site was used throughout the entire duration of this period (Table 3; Fig. 15). The beginning of the settlement is marked by nearly identical dates obtained for wooden artefact (Poz-121,364) and charcoal

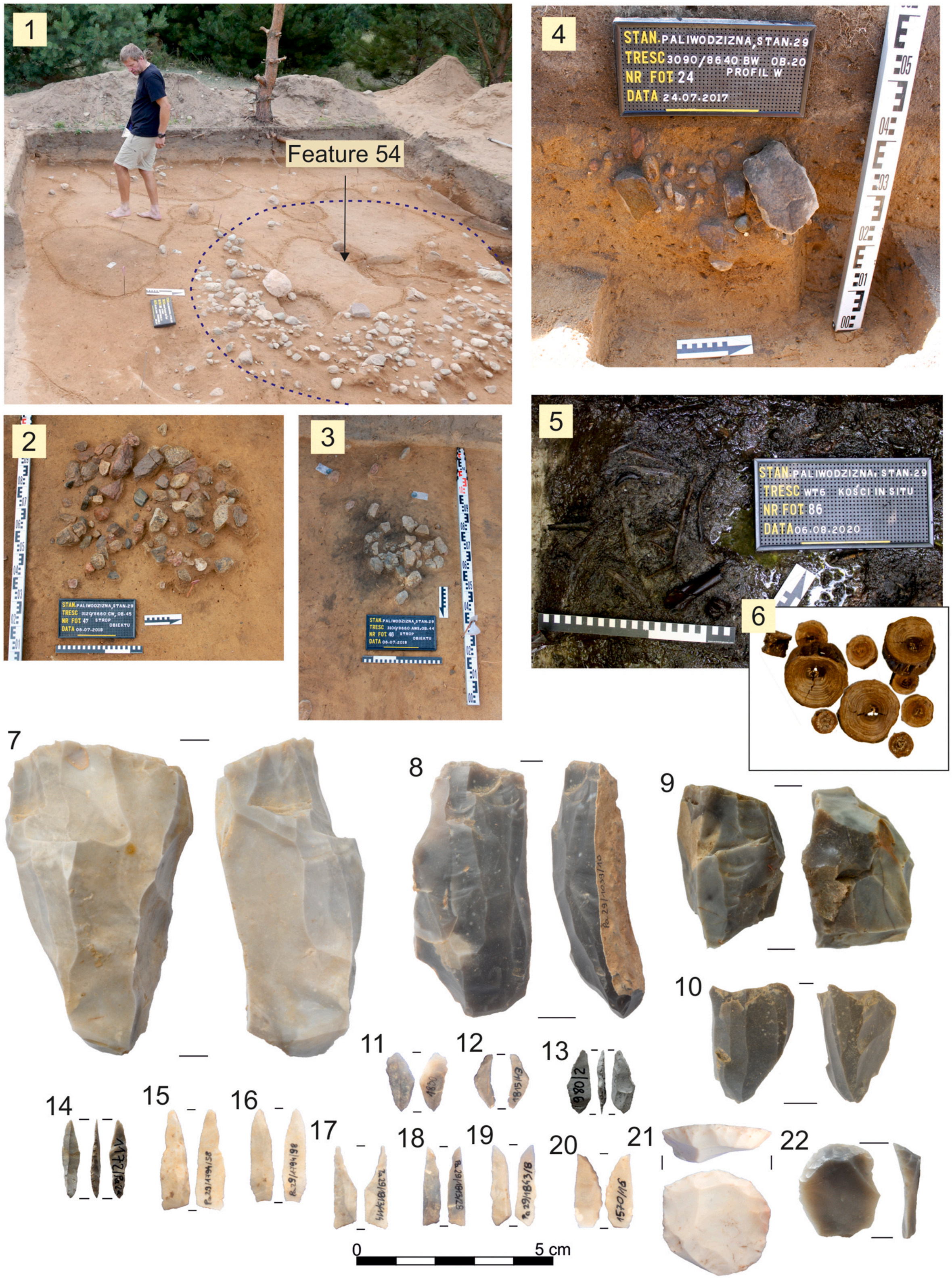

Fig. 3. Paliwodzizna, site 29. Mesolithic features and artefacts. 1–3 - hearths; 4 - remains of birch tar kiln (?); 5 - Mesolithic layer in a trench WT6 (visible bones, pieces of wood and charcoals); 6 - pike vertebrae from the "wet" trenches; 7–10 - cores; 11–20 - geometric inserts; 21–22 - end scrapers.

samples (MKL-3186) retrieved from cultural structures situated in the sand zone of the site. They date these structures to a period between 9281 and 8834 cal. BC, that is, the middle stage of the Preboreal period. Similar radiocarbon dating results for Early Mesolithic materials have already been obtained in Poland for sites such as Chwalim, site 1, Bed. 2 (Kobusiewicz and Kabaciński, 1993, Tabble 55) and Dudka, site 1 (Gumiński, 1995, Table 1). At Paliwodzizna, it is worth noting the calibration curve for the dates from the structures, as the threshold shows that they can span as far back as the beginning of the Preboreal (9634 cal BC). Therefore, this does not allow us to exclude the possibility

Table 1
Paliwodikzizna 29. Results of anthracological studies of Mesolithic charcoals from dryland zone.

Zone	Taxon	Number	Total
Settlement zone 1	*Pinus sylvestris*	113	148
	Quercus sp	9	
	Deciduous	7	
	Deciduous?	1	
	Indeterminate	18	
Settlement zone 2	*Pinus sylvestris*	27	27
Settlement zone 3	*Pinus sylvestris*	92	101
	Quercus sp	6	
	Betulaceae?	1	
	Indeterminate	2	
Settlement zone 4	*Pinus sylvestris*	22	36
	Quercus sp	6	
	Deciduous	6	
	Betulaceae?	1	
	Indeterminate	1	

that they are connected to Late Palaeolithic settlements, particularly given that similar results were obtained for materials from the same period from site Bolków 1 (Galiński, 2018, Table 1) and site Całowanie 3 (Schild, 2014, Table 2). This issue will be resolved by the technological and typological analyses of flint materials from the site currently being conducted.

Further Mesolithic settlement at the site is determined by six radiocarbon dates, five from charcoal (Poz-106752, Poz-130,371, Poz-130,290, MKL-3185; Poz-130,370) and one from bone (Poz-106514; Table 3), received for two thin denudation layers identified in the wetland zone (layers 7a and 7 b). These dates are supplemented by the AMS determination (Poz-121,823) obtained for macroremains from sample s644, taken from the border of layers 8 and 13, separating layers 7a and 7 b (cf. Fig. 2; Table 3). Both denudation levels are undisturbed, i.e. secured with strata that do not contain archaeological material. This allows us to treat them as the only stage of the Mesolithic settlement in the Paliwodzizna site that (at this stage of the research) can be distinguished as a separate settlement phase (hereinafter simply referred to as the "wetland phase "). The radiocarbon dates locate it between 8701 and 7594 cal. BC, i.e., the second half of the Preboreal and the first half of the Boreal (Table 3). It corresponds to when the Mesolithic cemetery was used at the nearby site of Mszano 14 (Marciniak, 1993, 2001). Only one radiocarbon date from the sand zone corresponds well to this phase (Poz-121,446, Table 3). It is difficult to say what causes this situation, but its reasons may be trivial and result from the fact that (due to unavailability of land) the dry part of the site in Paliwodzizna that is adjacent to the wetland digs (where sources of the "wetland phase" were discovered) has not been studied archaeologically (cf. Fig. 2C). The other two Boreal AMS dates from the sand zone (Poz-106863, Poz-106750) are later. However, from the perspective of the calibration curve, their lower dating ranges do fit within the possible range of the "wetland phase". Therefore, we cannot rule out the possibility that these dates might constitute a part of it.

Of course, there is a possibility the low amount of Early Mesolithic remains in the dryland zone is due to the fact that the Early Mesolithic "cultural layer" almost entirely eroded, and settlement waste (artefacts, charcoal, bones) ended up in the erosion layers 7a and 7 b. However, such a possibility is not very likely. The Early Mesolithic settlement structures that were found in the dry part of the site are well preserved. They consist of very deep features (many of which have perfectly preserved stone structures), numerous hearths (also with stone structures) and flint scatters, with the level of preservation allowing for spatial analysis and the precise reconstruction of utility zones related to the processing of individual raw materials. The flint scatters were dated to the Early Mesolithic from their typology and associated radiocarbon dates. It should also be noted that the oldest stage of Mesolithic settlement at Paliwodzizna is marked by two dates obtained for features from the dry zone (Poz-121,364, MKL-3186), and the presence of later Early Mesolithic structures is confirmed by the dates Poz-121,446, Poz-106750 and Poz-106863. The high number of (very concentrated) dates obtained for the "wetland phase" is probably not the result of particularly intense settlement in this period but because of a greater amount of datable material (due to the excellent preservation of the wetter conditions). Instead, these dates probably come from a small area of Early Mesolithic settlement. This small area of the site could indeed have been completely eroded, but as previously stated it has yet to be fully excavated, and the nearby Mesolithic features are well preserved. Therefore, the complete erosion of this layer is doubtful.

Late Mesolithic settlement in Paliwodzizna is dated by four AMS results obtained for charcoal samples retrieved from the cultural structures in the site's sand part (Table 3), to the period between 6220 and 5627 cal. BC. Similar early Atlantic radiocarbon dates for Mesolithic settlements were obtained in the region for sites such as Ludowice 6 (Osipowicz, 2017, 74–76) and Sąsieczno 4 (Osipowicz, 2017, 74–76).

3.3. Geomorphological studies

The Paliwodzizna 29 site lies in the transitional zone located between the Grodno Tunnel Valley (GTV) and the Drweca River Valley (DRV) where the Drwęca River terrace was transformed by the development of fan-like structure (alluvial fan) during the rapid drainage of Grodno Lake at the end of the Weichselian glaciation. The site lies in the proximal part of this fan-head, where the northern part of the GTV is bordered by two topographic levels S1 and S2. Level S1 has a high of 68.5 m a.s.l. And is correlated with the Grodno Lake rapid drainage. The lower level (S2) is located along the GTV at a height of 66.5 m a.s.l. A sedimentary succession of strand-line S2 was recognized in trench 3080/8650 B-CW. The results enable us to determine the geomorphic processes that affected the transitional zone between the bottom of the GTV and DRV. Sedimentary succession in the level S2 is represented by three units U1–U3 (Fig. 4). Unit U1 comprises medium- and fine-grained sands with d_{50} between 0.19 and 0.39 mm (samples 1–3, 4, 8–13, 15), which show the massive structure or crude horizontal lamination in the unit's upper part. Moreover, these sediments cluster into three groups in terms of organic matter content which is 18–19% (samples 10, 13 and 15), 0.22–0.27% (samples 1–3, 8 and 11) and 0.44–0.55 (samples 9 and 12). Thus, the horizontal lamination is visible due to the increased content of organic matter over 0.22% (Fig. 1B and C). Median grain diameter (d_{50}) of sediments in unit U1 ranges between 0.19 and 0.39 mm. These sands are moderately well and moderately sorted ($1.57 < \sigma < 1.87$), except sample 15, which is poorly sorted ($\sigma = 2.08$). Their grain-size distributions of sediments in unit U1 are also symmetric, positive or negative skewed as well platy- meso- and leptokurtic (GSP between 0.75 and 1.37). Moreover, sediments of unit U1 were deformed by reverse faults development with planes dipping to the north-west (Fig. 4B).

Sedimentary unit U2 has a maximum thickness of 0.9 m and consists of massive medium-grained sands with d_{50} ranging between 0.33 and

Table 2
Paliwodzizna 29. Results of anthracological studies of Mesolithic charcoals from the wetland zone.

No.	Trench	Inv. No.	Nivelation (m. a.s.l.)	Taxon	Number	Layer
1	WT4	671	63,70	*Pinus sylvestris*	8	10
2	WT4	672	63,82	*Pinus sylvestris*	21	7 b
3	WT4	673	63,89	*Pinus sylvestris*	14	13
				Indeterminate	1	13
4	WT4	674	63,96	*Pinus sylvestris*	7	8
5	WT4	675	64,02	*Pinus sylvestris*	24	7a
				Indeterminate	1	7a
6	WT4	638/18	64,02	*Pinus sylvestris*	4	7a
7	WT4	639/18	64,02	*Pinus sylvestris*	2	7a

Table 3
Paliwodzizna 29. Mesolithic settlement chronology according to the AMS datings (and other 14C datings used in the article). Calibrated using OxCal ver. 4.2 software (Bronk-Ramsey, 2020).

Name	BP date	Unmodelled (BC/AD)			Dating material	Context of the sample	
		from	to	%		Trench	Layer, feature, comments
R_Date Poz-121,444	6780 ± 40	−5731	−5625	95.4	burnt bone	3080/8630 CWS	lyr. II/mech. Lyr. 1)
R_Date Poz-106862	6810 ± 40	−5761	−5627	95.4	charcoal	3110/8660 B W	lyr. II/mech. Lyr. 2)
R_Date Poz-120,734	7030 ± 50	−6015	−5789	95.4	charcoal	3080/8630 CWS	lyr. II/mech. Lyr. 2)
R_Date Poz-106861	7260 ± 40	−6226	−6031	95.4	charcoal	3100/8660 AWS	feature 44 (cf. Osipowicz, 2021)
R_Date Poz-106863	8280 ± 40	−7477	−7179	95.4	charcoal	3120/8660 C W	feature 59
R_Date Poz-106750	8350 ± 60	−7571	−7191	95.4	charcoal	3120/8660 C W	feature 45
R_Date Poz-130,370	8680 ± 40	−7806	−7591	95.4	charcoal	WT 6	lyr. 7a
R_Date MKL-3185	8730 ± 70	−8167	−7591	95.4	charcoal	WT 1	lyr. 7a-8-7 b (flotation)
R_Date Poz-106514	8930 ± 40	−8250	−7957	95.4	bone	WT 4	lyr. 7a-8-7 b (flotation)
R_Date Poz-121,446	9000 ± 40	−8295	−7976	95.4	charcoal	3120/8660 DW	feature 69
R_Date Poz-130,290	9010 ± 50	−8300	−7967	95.4	charcoal	WT 6	lyr. 7a
R_Date Poz-130,371	9100 ± 50	−8529	−8237	95.4	charcoal	WT 6	lyr. 7 b
R_Date Poz-106752	9340 ± 60	−8762	−8353	95.4	charcoal	WT 4	–
R_Date MKL-3186	9680 ± 90	−9293	−8805	95.4	charcoal	3090/8650 A W	feature 5
R_Date Poz-121,364	9700 ± 60	−9290	−8844	95.4	wooden artefact	3120/8660 DE	feature 72
Other C14 dates used in the article							
Name	**BP date**	**Unmodelled (BC/AD)**			**Dating material**	**Trench**	**Comments**
		from	**to**	**%**			
R_Date Poz-121,822	6940 ± 40	−5968	−5729	95.4	terrain plant macroremains	WT4	S644 (palynological sample), depth 17–19 cm
R_Date Poz-112,578	8200 ± 50	−7449	−7063	95.4	terrain plant macroremains	WT4	S644 (palynological sample), depth 108–109 cm
R_Date Poz-121,823	8610 ± 40	−7736	−7578	95.4	terrain plant macroremains	WT4	S644 (palynological sample), depth 79–81 cm
R_Date Poz-112,579	9280 ± 60	−8699	−8307	95.4	terrain plant macroremains	WT4	S644 (palynological sample), depth 153–155 cm
R_Date Poz-112,580	9660 ± 60	−9259	−8824	95.4	terrain plant macroremains	WT4	S644 (palynological sample), depth 193–195 cm

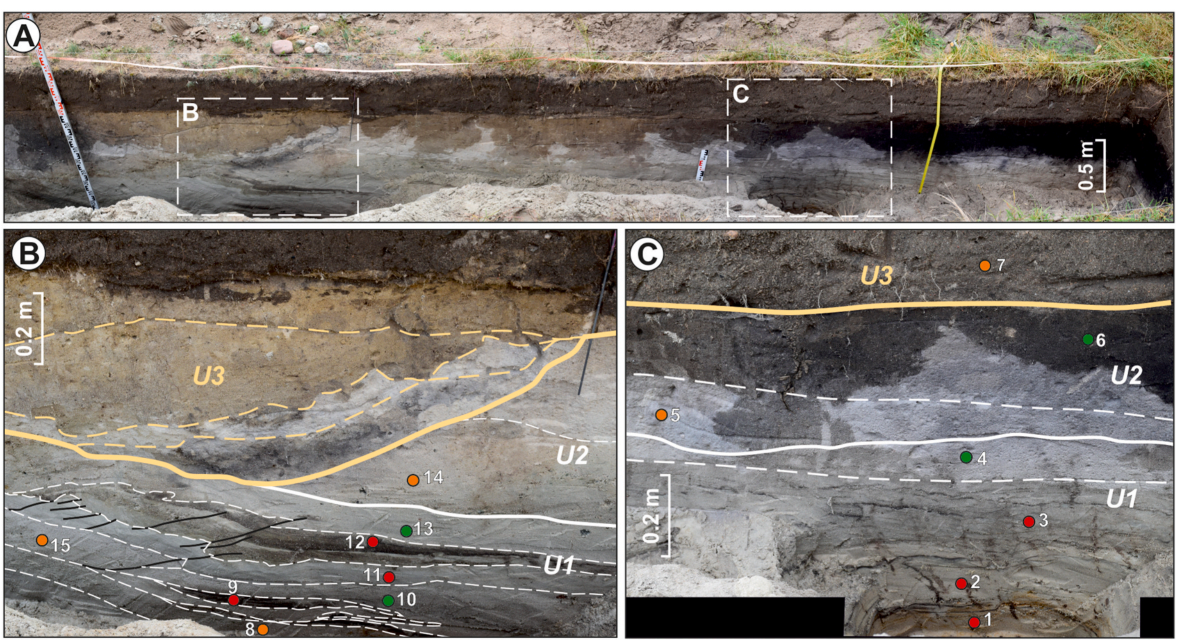

Fig. 4. Sedimentary units U1–U3 recognized in the trench 3080/8650 B-CW.

0.44 mm (Fig. 4A and B). These sediments are moderately-sorted (1.8 < σ < 1.9), while the content of organic matter varies between 0.26% (sample 5) and 1.95% (sample 6). The grain size distributions are symmetric or negative skewed (GSK from −0.03 to 0.22) and leptokurtic (GSP from 1.16 to 1.29). The uppermost sedimentary unit U3 consists of medium-grained sands (d_{50} = 0.34 mm) which are poorly sorted (σ = 2.49). Their grain-size distribution is skewed negatively (GSK = −0.16) and very leptokurtic (GSP = 1.53).

These sediments cluster into three groups in textural CM pattern (C - the one percentile and M - the median diameter), indicating the different conditions of the sedimentary environment in terms of hydrodynamic regimes and particles transport modes (Passega, 1964; Visher, 1969; Brown, 1985). The first group contains particles settled from cross-shore bedload transport (rolling particles and under saltation) in a beach sedimentary environment (segment O–P in Fig. 5) (Passega, 1964; Mycielska-Dowgiałło, 1995, 2007; Bravard and Peiry, 1999). The increasing diameter of the coarsest particles (C values; Fig. 5) characterize sediments representing a transitional setting between littoral zone and shore, affected by intense denudation. These refer to the particles with C values (first percentile of the grain-size distribution) between 1.66 and 2.33 mm indicating increased content of coarse particles transported by rolling (Fig. 5). This demonstrates the increasing role of a new type of sediment supply – most probably from lake shoreline erosion due to increasing water level and denudation caused by

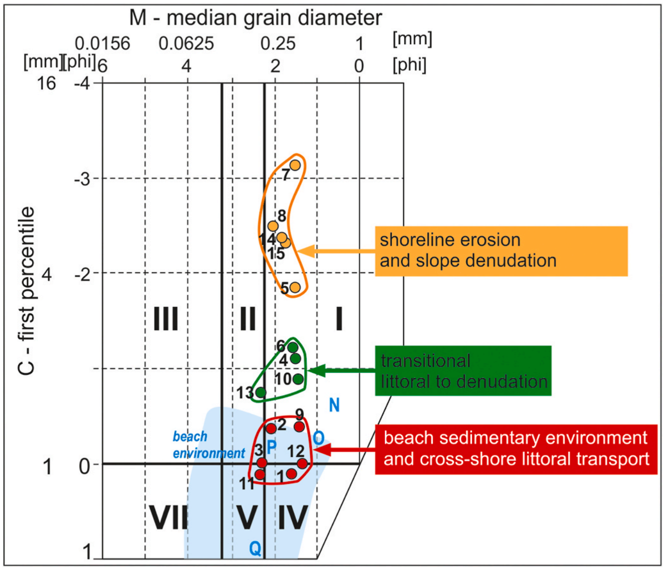

Fig. 5. CM diagram ((Passega, 1957) ; 1964) for the nearshore deposits collected from the trench 3080/8650 B-CW.

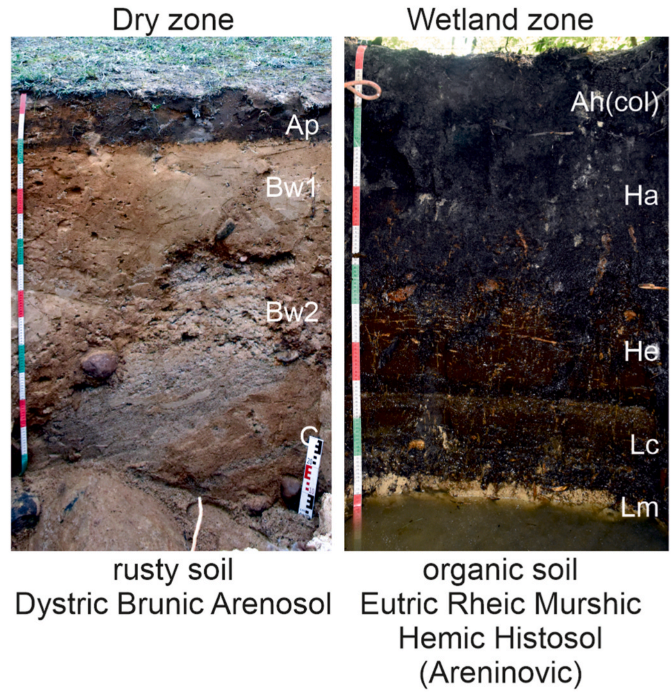

Fig. 7. Morphology of soils representing main parts of the site
Symbols of soil horizons: Ap – plough humic horizon, Bw1, Bw 2 – enrichment with iron oxides horizon, C – parent material, Ah (col) – colluvial humic horizon enriched with humus, Ha – murshic horizon, He – hemic peat horizon, Lc – limnic coprogenous earth (gittia), Lm – limnic calcarous sediments (gittia).

Mesolithic human activity (Fig. 6). The third type of sediments represents poorly-sorted deposits characterised by the largest values of C (Fig. 5). Their grain-size distribution is negatively skewed. These features indicate the active denudation processes in the zone of the former lake shoreline supplying sediments to the littoral zone (Fig. 6).

3.4. Pedological studies

A substantial part of the site at Paliwodzizna, which is situated about 67.5 m asl on a plain of the alluvial fan, is comprised of Rusty (gleba rdzawa) soils (Kabała et al., 2019; Jankowski and Bednarek, 2021), which can be classified as Dystric Brunic Arenosols (IUSS Working Group WRB, 2022). These soils consist of sandy material with the granulation of loose sand, less often slightly loamy sand mixed with skeletal fractions of gravel and stones, which is highly variable in terms of quantity, yet almost always present. The substantial permeability of those loose sediments and the relatively substantial depth at which ground water occurs (>2 m) make this part of the site a 'dry' area bereft of surface waters and wetlands.

Rusty soils (Fig. 7) comprise three main soil horizons: topsoil Ap (ploughed A horizon), accumulation horizon rich in iron oxides Bw and the parent rock C. The topsoil bears traces of repetitive ploughing, manifested in its homogenous nature and sharp lower border. The clear nature of post-farming characteristics suggests that the land must have been used for agricultural purposes in recent past, probably only a few decades ago.

The underlying accumulation horizon Bw is characterised by a typical pale-rusty colour stemming from the pedogenic accumulation of iron oxides in sandy material. In the Polish Soil Classification system (Kabała et al., 2019) it is distinguished as a diagnostic horizon *siderik*. Most archaeological structures observed are contained within this horizon. Based on the relation of these structures to the iron-rich background, it can be claimed that the *siderik* horizon is younger than they are. This horizon is characterised by acidity, with its pH level measured in H_2O ranging from 4.5 to 5.0, and in KCl ranging from 4.3 to 4.7, which has caused poor preservation of non-burned osseous remains in this part of the site. The parent material of the Rusty soils occurring at the site exhibits features of stratified fluvioglacial sand with a high content of mixed-in and interbedded gravel and stone up to several tens of centimetres in diameter.

Unfortunately, the intensity of post-Mesolithic soil formation has rendered traces of older pedogenesis completely obliterated, so the 'dry' part of the site (on the alluvial fan) has no traces of soils from the early/middle-Holocene period which makes it impossible to carry out a pedological reconstruction of soil conditions of the Mesolithic settlements.

Organic soils (Eutric Rheic Murshic Hemic Histosols) cover the lacustrine-peat plain stretching over the basin of Lake Grodno and its overgrown northern bay. The plain lies 64.8 m. a.s.l. And constitutes a heavily waterlogged terrain, about 2.5 m lower than the sandy alluvial fan. The soil at the top of those biogenic sediments shows presence of a

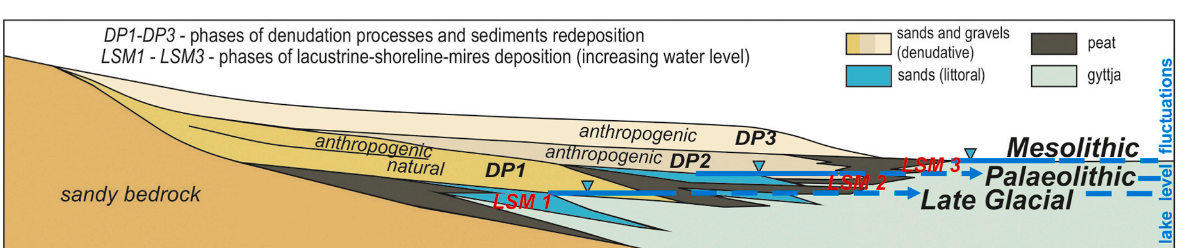

Fig. 6. Conceptual model of nearshore evolution.

muck horizon Ha (drained sapric material) up to 50–70 cm thick. This horizon constitutes a stratum of organic material with a high degree of degradation, as a result of oxidation of the former peat sediment. Below the muck horizon in the soil profile, there is a deposit of quite severely dried (hemic) peat at the medium degree of decomposition (He) up to 50 cm thick. Below these wetland formations, there are lake sediments bearing characteristics of detritus gyttja changing into calcarous gyttja (Lc – Lm). This sequence of organogenetic formations, namely, gyttja – peat – muck, constitutes a classic example of terrestrialization of bodies of water in young-glacial areas. In the contact zone of the lacustrine-peat plain and the dry part of the site, organic soils are covered with sandy colluvial (Areninovic) materials (Ah (col)) accumulated due to slope processes transforming the former border the wetland (Figs. 7 and 8).

Post-glacial valley and the Drwęca River terraces adjacent to the site are composed of sandy Rusty soils (Dystric Brunic Arenosols). It is generally believed that this soil type formed under deciduous forests and mixed forests characterised as less diverse hornbeam and oak forests (Jankowski and Bednarek, 2021; Sewerniak and Jankowski, 2021). On the Drwęca floodplain, about 2 km northwards, there are Fluvisols and Gleysols. These soils serve now and have served as habitats of riverside riparian forests occurring in the form of flooded and periodically waterlogged forests, thickets or herbaceous meadows. The upper parts of the slopes of the moraine upland that surrounds the Grodno-Plebanka tunnel valley, and kame hillocks constituting local spurs within this tunnel valley, are composed of clay-illuviated soils (Luvisols), formerly covered by rich deciduous forests. Hills and sloped aeolian mantles situated in the valley of the Drwęca River and in the marginal part of the morainic upland were composed of poorer variants of Rusty sand soils and podzolized soils (Podzols/Albic Arenosols), associated with coniferous and mixed coniferous forests.

3.5. Palynological studies

On the basis of the pollen analysis results, four local pollen assemblage zones were identified (WT4-1 - WT4-4 L PAZ). The first two are correlated with the Preboreal, the third with the Boreal and the fourth with the beginning of the Atlantic chronozone.

3.5.1. Preboreal period

3.5.1.1. WT4-1 pinus-betula-artemisia L PAZ (depth 96–107 cm). The rather high percentages of *Pinus* (pine) and *Betula* (birch) and low percentage of herbaceous plants indicates the occurrence of pine and birch forest communities (Fig. 9). However, the overall pollen assemblage indicates that these communities were not very dense, with small mid-forest clearings. The relatively high percentage and significant diversity of photophilous plants such as *Artemisia* (mugwort) Chenopodiaceae (goosefoot family) also point to the presence of some open land. The only anthropogenic indicators, is a single *Urtica* (stinging nettle)

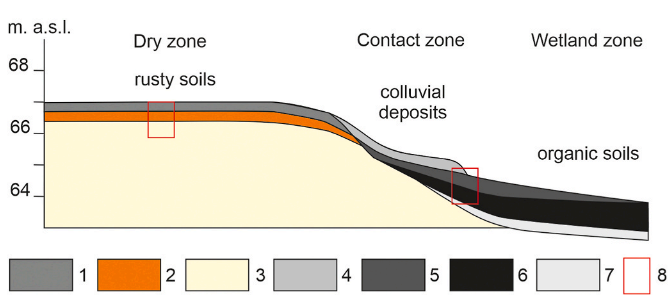

Fig. 8. Sketch of soils distribution at the site Paliwodzizna
1 – plough humic horizon Ap, 2 – enrichment with iron oxides horizon Bw, 3 – parent material C, 4 – colluvial humic deposits Ah (col), 5 – organic murshic horizon Ha, 6 – organic peat horizon Ha, 7 – limnic sediments (gittia) L, 8 – soil profiles presented at Fig. 6.

pollen, however, it can be derived from natural communities and particularly early stages of woodland succession. Of the wetland plants, *Typha latifolia* (bulrush) is abundant, indicating the development of a reed-bed around the lake which was characterised by shallow depth and a degree of eutrophication.

3.5.1.2. WT4-2 pinus-betula-ulmus L PAZ (depth 80–96 cm). Halfway up the zone, we see a distinct change in the vegetation. The forest communities expanded and became denser, as evidenced by both increased pollen concentration in the sediment (Fig. 9) and lower percentages of herbaceous plants (NAP). Gradually, *Ulmus* (elm) and *Corylus* (hazel) started spreading in forest communities. Vegetation indicating disturbance of natural forest communities was recorded in pollen spectra in the lower part of the preboreal chronozone in the form of single pollen grains of *Calluna vulgaris* (common heather), *Urtica* and *Rumex* (dock) and a continuous curve of *Artemisia*. However, although *Urtica* is the strongest indicator of human eutrophication it cannot be ruled out that is derived from natural communities that are enriched by the grazing of wild animals in naturally-formed clearings. At the same time, the body of water changed, becoming shallower and overgrown with vegetation. The open wetlands were colonised by *Filipendula* (meadowsweet), a taxa characteristic of the Preboreal chronozone (Ralska-Jasiewiczowa, 1966). Changes in the waterbody are also indicated by the considerably reduced amount of the algae *Pediastrum*, and the rapidly growing percentage of ferns such as *Thelypteris palustris* and Filicales monolete, In the upper part of the zone, the *Typha latifolia* values fall and *Equisetum* (horsetail) disappears, whilst Cyperaceae (sedges) decreases and *Cladium* appears. This is indicative of succession of the overgrown lake. The change in the nature of the sediment and the presence of a sand layer (84–90 cm) with a high percentage of organic matter suggests unstable accumulation conditions and erosion of the shores of the lake.

3.5.2. Boreal period

WT4-3 *Betula-Ulmus-Corylus* L PAZ (depth 67–80 cm).

At the turn of the Preboreal and Boreal chronozones, a multi-species forest spread in the Paliwodzizna area. There was an increase in the percentage of *Corylus* and *Ulmus* (elm), with a gradual emergence of *Quercus* (oak) and *Tilia* (lime). In the Boreal period, conditions were particularly favourable for the expansion of *Corylus*. On the one hand, this was due to its ecology, since it is the first shade-tolerant shrub among the post-glacial plants, while on the other hand, the increase in its percentage was probably caused by the lack of competition in the form of deciduous trees. At the same time moist habitats next to the *Ulmus* gradually became occupied by *Alnus*. This part of the diagram shows a significant increase in taxonomic diversity (Fig. 9) and a high frequency of microcharcoal. Of the typical anthropogenic indicators (Behre, 1981), e.g. nitrophilous and ruderal plants, those present there include *Calluna vulgaris*, *Urtica*, *Rumex* and *Pteridium aquilinum*. Such a pollen and microcharcoal pattern may indicate human disturbance of the forest in this area. However, we cannot exclude the possibility that natural climatic changes during this period were a major factor in changes to the vegetation cover. In the course of this zone, plant succession in the aquatic community occurred with the disappearance of *Typha latifolia* and replacement by *Cladium*.

3.5.3. Atlantic period

3.5.3.1. WT4-4 quercus-ulmus-fraxinus L PAZ (depth 15–67 cm). The pollen at this level indicates a continuation of the spread of mixed deciduous forests around the Paliwodzizna area. The *Betula* and *Pinus* components decreased in the woodland, which can be seen best in the pollen concentration values. In their place mixed deciduous forests developed, whose main component species were *Quercus*, *Ulmus*, *Tilia*, *Fraxinus* (ash) and *Corylus*. Favourable hydro-climatic conditions, including drainage of the shallower parts of the lake and the

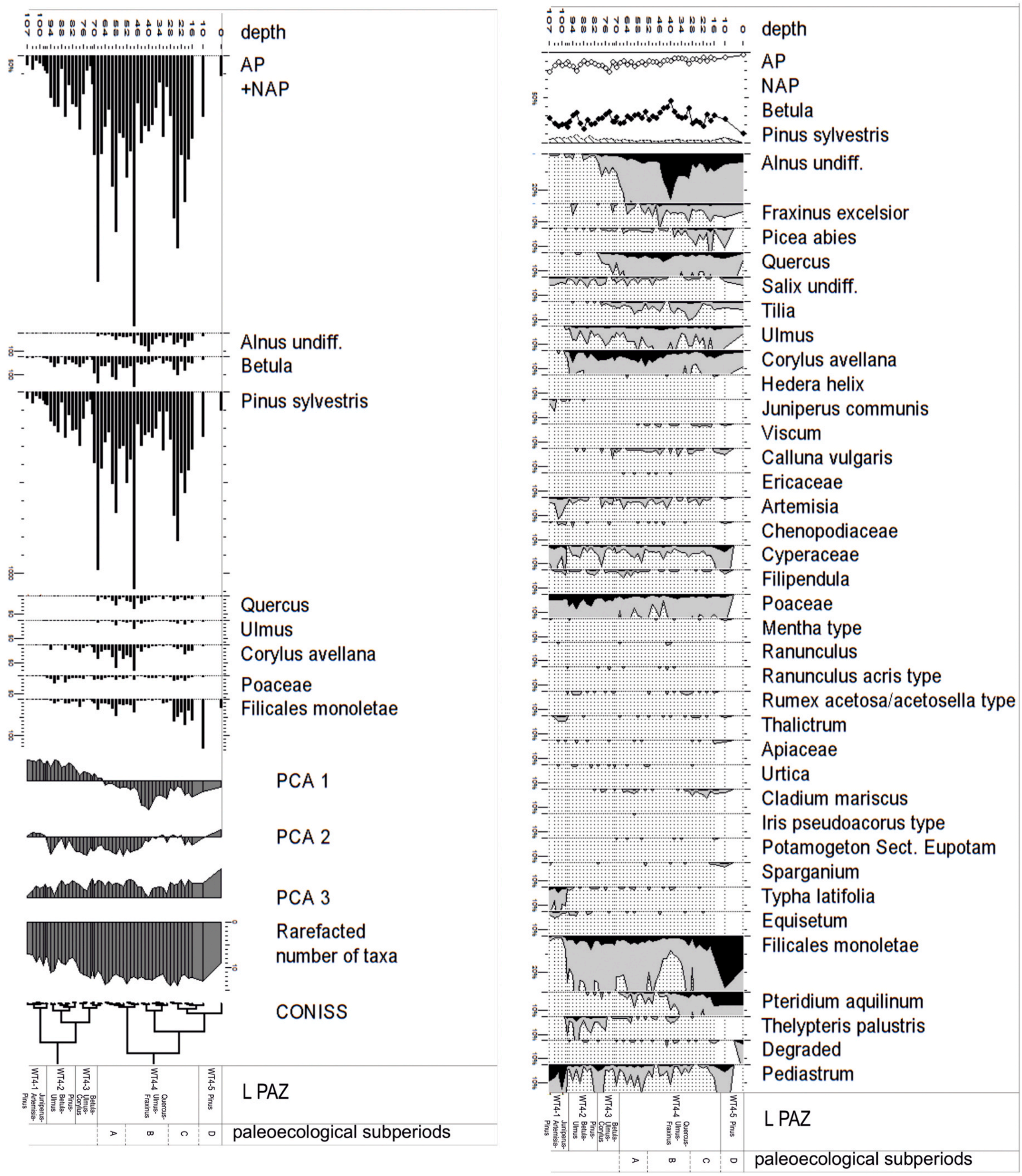

Fig. 9. Paliwodzizna 29. Palynological diagram.

development of peat bogs, resulted in the expansion of *Alnus.* In this horizon, there are systematic occurrences of *Viscum* and individual occurrences of *Hedera,* which are indicators of a warm, moderate climate (Iversen, 1944). The high taxonomic diversity, including that of plants serving as indicators of human activity, shows indirectly that these lands were exploited by human groups probably within a small clearing or forest gap. There are no plant indicators of agriculture, suggesting that the settlements were not created by Neolithic populations, and are associated with hunter-gatherer-fishers (i.e. Mesolithic peoples).

Two further samples (0 and 10 cm) coincide with the transition of the Atlantic and Subboreal periods and the end of biogenic sedimentation at this site. The proportion of both eroded sporomorphs and ferns such as *Filicales* monolete and *Pteridium aquilinum* (bracken) increases here. This may be indicative of fluctuating water levels and the invasion of ferns into new habitats. Both palynological studies and radiocarbon dating suggests an inhibition of sediment accumulation in the Atlantic period or at the transition of the Atlantic and Subboreal periods.

3.6. Macroremains

On the basis of the plant macroremains five basic zones were identified (WT4-1 - WT4-5 MAZ). The first corresponds to the Preboreal period and the second (in the form of sub-level) for the Boreal period. The Atlantic period can be linked with the one sub-level and three basic levels.

3.6.1. Preboreal period

WT4-1 *Chara-Pinus sylvestris* MAZ, depth 83–107 cm.

The analysis of the macroscopic remains suggests that in this zone, the location was dominated by macrophytes of *Chara* sp. (stonewort), however, the waterbody experienced small water level fluctuations (Fig. 10). A higher water level is also evidenced by traces of other aquatic organisms, including sponge and *Piscicola geometra* (fish leech). At the same time, *Carex rostrata*, *C. vesicaria*, *Typha* sp. And *Schoenoplectus lacustris* started growing closer to the shores. The presence of *Urtica dioica* shows that the body of water was supplied with nutrients. At the end of that period, an intense growth of rush with *Cladium mariscus* began (*Cladietum marisci*). It is a stable community that develops at the rate of the shallowing of the body of water due to the accumulating organic matter (Konieczna and Kowalewski, 2009). In this zone, single achenes of *Fragaria vesca* were found. The high percentage of pine and birch pollen is confirmed by numerous macroscopic remains of both these tree species. Also, in this zone a considerable percentage of spores of the fungus *Coenococcum geophillum* (a fly-speck fungus) were found.

3.6.2. Boreal period

3.6.2.1. WT4-2a cladium-betula-pinus MAZ, depth 67–83 cm. The macroremains diagram shows further growth of *Cladietum marisci*, which confirms the palynological observations made with respect to the body of water becoming shallower (Fig. 10). Nonetheless, periodical fluctuations in the water level could still be observed. The high percentage of the fruit of *Najas marina* (holly-leaved naiad) proves that there were parts of the body of water of a more open character. It is likely that areas with this underwater plant occurred outside the strip with *Cladietum marisci*. Atthe water's edge, in very wet places, *Eupatorium cannabinum* (hemp-agrimony) was present. Macroscopic traces indicate growth of communities that included birch with pine still present in high quantities. The potential gathering activities of the local Mesolithic communities are supported by remains of *Fragaria vesca* (wild strawberry). Local deforestation contributed to the development of probably drier-soil communities, that included grasses (Poaceae) and *Potentilla erecta* (tormentil). In this subhorizon the burnt remains show a considerable number of soft green stems, which may suggest local burning of *Cladietum marisci*.

3.6.3. Atlantic period

3.6.3.1. WT4-2 b cladium-najas MAZ, depth 53–67 cm. The macroscopic remains continue to show *Cladietum marisci* (Fig. 10), although the presence of *Najas marina* implies that the waterbody included some open water. It can be assumed that there were local changes in water level, as the percentage of remains of *C. mariscus* and *Eupatorium cannabium* is notably lower. This observation is correlated with a decreasing percentage of remains of birch and pine, as well as charred remains.

3.6.3.2. WT4-3 alnus-betula L MAZ depth 29–53 cm. In the macroremains diagram, a characteristic feature is the presence of numerous remains of *Alnus glutinosa* (common alder) (Fig. 10). Communities of this type, wet alder woodland or alder carr, require a peat and mineral substrate, as well as high ground water level with drainage impedance. Apart from *A. glutinosa*, alder carr communities can include *Urtica dioica.* These communities could have replaced *Cladietum marisci*, which exhibits a considerably lower percentage of fruit at these depths. The absence of the fruit of *Najas marina*, a typical hydrophyte, is indicative of a lack of suitable places where this macrophyte could grow. Presence of *Betula* as well *Pinus* is still observed. Across the entire horizon small charcoals can be noted.

3.6.3.3. WT4-4 alnus-betula-cladium L MAZ, depth 15–29 cm. The macroscopic data reveals a periodical rise in water levels, as indicated by the reappearance of *Najas marina* and statoblasts of Bryozoa (Fig. 10). It must have been a temporary event, though, since very shortly afterwards, *Cladietum marisci* reappeared. Significant swamping of the immediate surroundings is indicated by the percentage of the fruit of *Alnus glutinosa,* which is still high, and that of *Urtica dioica*. More distant changes in vegetation must have taken place as the percentages of *Betula*, *Pinus*, and charcoals rise again. The Atlantic phases are separated based on plant macroremains corresponding with the results of the palynological analysis in WT4-4 L PAZ regarding changes in the local vegetation.

3.6.3.4. WT4-5 chara-cladium-alnus-filicales L MAZ, depth 5-15. The last LMAZ of the profile is connected with a sudden outbreak of *Chara* oospores accompanied by *Cladium maricus* fruits. Swamping known from

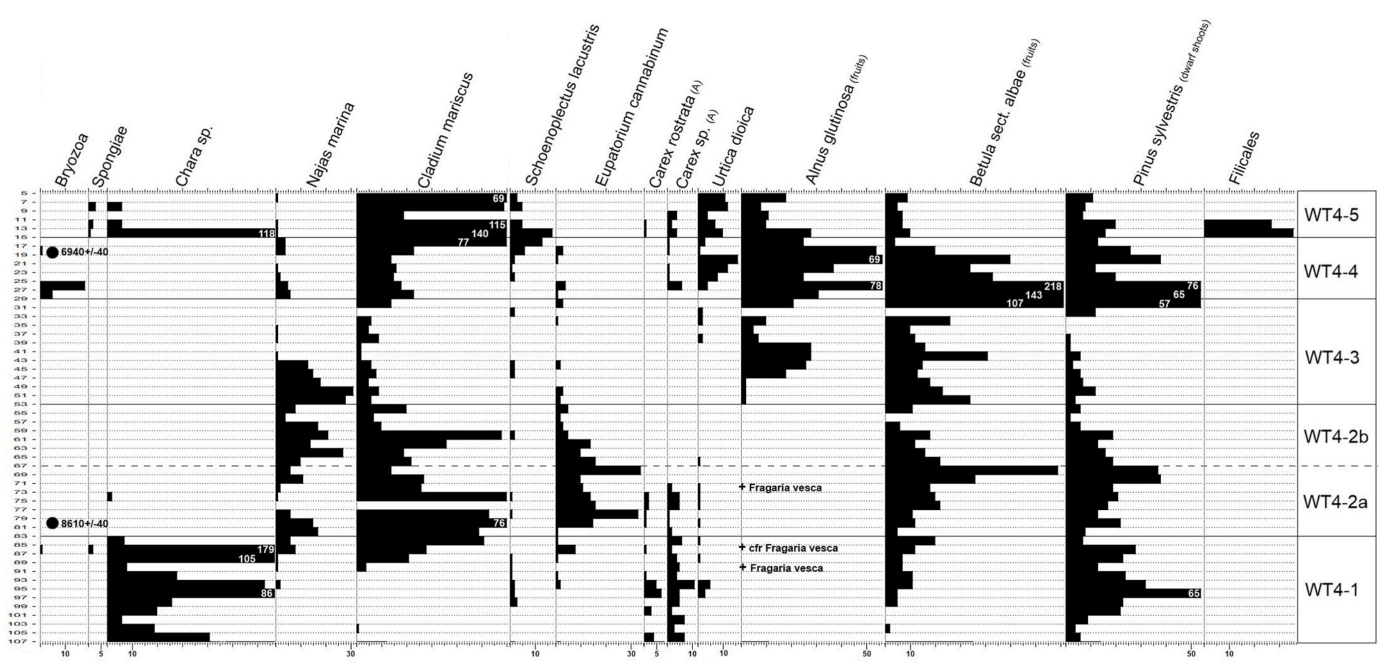

Fig. 10. Diagram of selected plant macrofossils: A - achenes.

the previous phase still persists. It must be permanent enough that remains of herbaceous plants requiring drier conditions, earlier present in a small number do not develop nearby. A characteristic component of the phase is the appearance of sporangia of ferns from the *Filicales* group.

3.7. Plant sedaDNA

The seven samples (P770–P776) produced 4,667,031 raw reads. After pre and post-identification filtering this was trimmed to 2,546,348 reads with 34 accepted taxa- 8 to tribe, family or above, 18 to genus and 8 to species level (Fig. 11). DNA data quality was fairly good-an average of 57 % reads remaining after pre-identification filtering (P772–P776), with the exception of the two samples from the Lateglacial contexts (P770–P771), which were of poor quality (<15% of reads remaining after pre-identification filtering) and are discounted from further interpretation. Plant sedaDNA has been shown to represent mostly local species (Alsos et al., 2018; Edwards et al., 2018) and as such the assemblage likely represents species growing around and in the immediate area of the lake and particularly near lakeside archaeological sites (Brown et al., 2022).

3.7.1. Preboreal period (sample P772; depth 98 cm)

In the basal black gyttja a variety of woodland taxa are identified; with the wetland taxa *Salix* and *Alnus* likely forming carr-woodland around the lake edge and stands of *Populus* (Poplar), *Betula* and *Pinus* situated on dryer ground. Graminoids include *Typha latifolia*, *Schoenoplectus* (club-rush) and *Phragmites australis* (common reed) dominates overall read percentages (57%), though *Thelypteris palustris* is also found in high numbers (18% of total reads). These species represent the reed-beds present both within and around the water at the lake edge, with marsh fern likely inhabiting both the willow-alder carr and persisting with *Phragmites* to form more open fen closer to the water. Aquatic taxa include Nymphaceae, and the pondweeds *Stuckenia* (fennel pondweed) and *Potamogeton* (pond weed), with the latter growing in open water not exceeding 2 m in depth. Forbs are limited and represented mainly by wetland taxa such as *Eupatorium cannabinum* and Lamiaceae (mint family), along with *Sphagnum* (bog moss), these formed components of the open fenland around the lake.

3.7.2. Second half of the preboreal period/beginnings of the boreal period (sample P773; depth 90 cm)

The layer of basal grey gyttja where from sample P773 comes from was dated with two AMS datings to (cf. Table 3): 8762 - 8353 cal BC (Poz-106752) and 8529 - 8237 cal BC (Poz-130,371). Sample P773 is similar in composition to P772, with all woodland taxa maintaining their presence at similar levels. However, graminoids expand further, with the common reed increasing to 69% of total reads. Notably, aquatic taxa decrease in diversity alongside this, possibly reflecting succession of areas of the lake to reed-bed. This is supported by increases in forb diversity-with the taxa *Vicia* (violet), Solanoideae (nightshade family) and *Urtica* appearing in moderate amounts of reads and repeats, indicating some disturbed ground and dryer areas.

3.7.3. First half of the boreal (samples P774, depth 84 cm; P775, depth 78 cm)

Sample P774 shows slightly increased levels of woodland taxa, willow expand, at the expense of alder which disappears. *Cornus* (dogwood) appears in low levels for the first time. Ferns such as *Athyrium* increase slightly, supporting a small expansion of woodland and shaded areas. Graminoids maintain high numbers of reads and repeats, and *Carex* and *Cladium mariscus* appear, most likely forming *Cladium-Phragmites* fen around the lake along with marsh fern. Aquatic taxa expand to similar levels as P772, alongside the appearance of *Equisetum*, and disappearance of *Urtica*, *Solanum* (nightshade) and *Vicia* (vetch), this suggests increases in moisture levels and fenland expansion.

Sample P775 shows similar woodland taxa to P774, but with increased read percentages (36% of total reads), mainly from birch (16%) and pine (17%). Together with an expansion of ferns (40% of total reads), the complete disappearance of aquatic taxa and the expansion of forb taxa – *Hypericum* (St John's wort), *Rumex*, and the dry ground taxa *Hypochaeris* (hairy cat's ear) is visible.

3.7.4. Early atlantic period (sample P776; depth 78 cm)

The assemblage from P776 shows slightly reduced levels of woodland and ferns, both *Cornus* and *Salix* (willow) disappear, with *Alnus* reappearing as the dominant wet woodland taxa. Graminoids expand in read percentages from P775 (23%–39% of total reads). Forbs decrease in diversity but maintain similar read percentages (2–3%). An expansion of

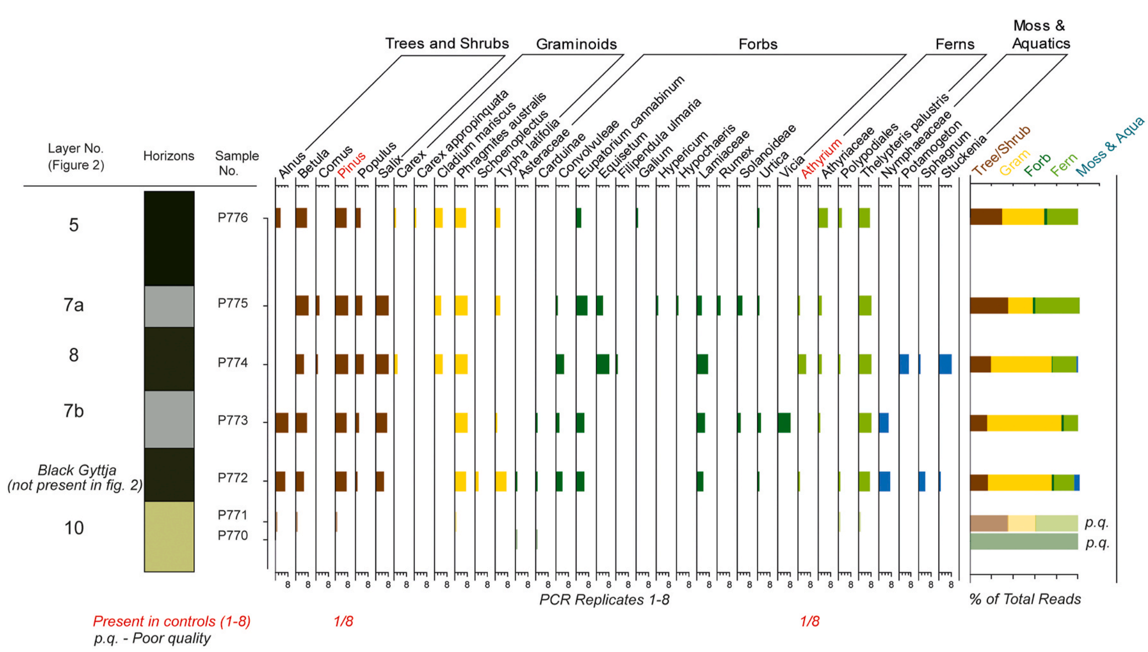

Fig. 11. Paliwodzizna, site 29. Plant sedaDNA results.

the *Cladium-Phragmites-Thelypteris* reed-bed is indicated, at the expense of the forb species seen in P775. Aquatic taxa are not present.

3.8. Anthracological studies

Of the 394 charcoal samples from Mesolithic contexts that were subject to anthracological studies, the by far most numerous species is *Pinus sylvestris* (Scots pine), the remains of which account for over 84% of all the analysed material (cf. Table 1). At the same time, it is the only taxa that was identified in the strata related to Early Mesolithic settlement discovered in the peat zone of the site (Table 2). The second most numerous species represented in the collection is *Quercus* sp. This taxon has been linked to 5.3% of the charcoal. In turn, 4% of all the analysed samples were classified into the more general group of deciduous trees (*Deciduous*), suggesting *Betula* in two cases. Other charcoal remains are of unidentified material.

The species composition of the charcoal collections from specific settlement zones varies. In settlement zones 2 and 3, only pine wood charcoal occurred (Table 1). The highest amount of charcoal from deciduous trees (including oak) was found in settlement zone 4, where it accounted for 36.1%. In settlement zone 1, remains of this type make up 11.5%, whereas in settlement zone 3 it is 5.9% of the entire collection.

The charcoal assemblage discovered at the site in Paliwodzizna is damaged and fragmented, and therefore it is difficult to draw broader conclusions about the properties of the wood it originated from. Only in a few cases was it possible to make such suggestions. The pine charcoal discovered in the Late Mesolithic hearth found in settlement zone 2 (Feature 44) was formed as a result of burning fine twigs up to approximately 1 cm in diameter. As for the Early Mesolithic hearth from settlement zone 3 (Feature 5), these were larger twigs around 5 cm in diameter.

3.9. Results of archaeozoological studies

Due to the very high levels of destruction of animal remains, the amount that could be identified to specific taxa was small, amounting to only 24%. (Fig. 12) and it is lowest in the dryland zone, where only 18.6% of bones have been assigned a taxonomic affiliation (Fig. 13A). Nevertheless, the list of taxa identified in the collection from this area is extensive and consists of 11 taxa identified to the species or higher taxonomic levels (e.g., mussels, carp, birds, deer). In the peat zone, the materials were much better preserved, hence the percentage of identified specimens was 91.1%, but the faunal list is shorter, consisting of only five taxa (Fig. 13B).

Most of the identified bones are fish remains, the predominant species of which is unquestionably the pike (*Esos lucius.*). It constitutes the most numerous taxa at the site with 8.2% of the classified bones included in this category (Fig. 12). In the fish group there were also individual occurrences of vertebra of the common perch (*Perca fluviatilis*) and the carp (*Cyprinidae*). The second most numerous species is the European pond tortoise (*Emys orbicularis*). Its remains account for 2.7% of the analysed collection (Fig. 12). The number of bones of roe deer (*Capreolus* – 2.5% of the collection) is not much lower, followed by less commonly occurring remains identified as belonging to red deer (*Cervus elaphus* – 1.1% of the collection). There were individual instances of bones of hare (*Lepus* sp.), beaver (*Castor fiber*) and an unidentified bird, as well as remains of shells of bivalves.

Attention is drawn to the differences in the structure of the bone collections from the dry zone of the site (dryland - Fig. 13A) and the trenches in the peat zone (wetland - Fig. 13B). Among the remains for which species identification was completed, the predominant bones in the peat zone were those of pike, accounting for over 52% of this collection. The second most numerous are mammal bones (27.3%), predominantly remains of roe deer (18.2%). In the dry zone, dominated by fragmented mammal bones not identified by species (Fig. 13A), remains of the European pond tortoise predominate (3.2% of the collection). These were followed by bones of pike (1.3%), red deer (0.3%) and roe deer (0.3%). A distinctly higher percentage of the European pond tortoise is particularly clear in one of the clusters of settlements (settlement zone 4), from which nearly all bones of this species are derived (Fig. 13C). In the case of pike remains, the total length for this species was estimated based on the vertebrae size. The graphical distribution obtained of this parameter is indicates a natural population, with classes ranging from 50 to 100 cm being the most abundant (75.5%) and located in the middle of the histogram (Fig. 13D). Smaller and larger specimens only accounted for 12.2% and 12.3% respectively.

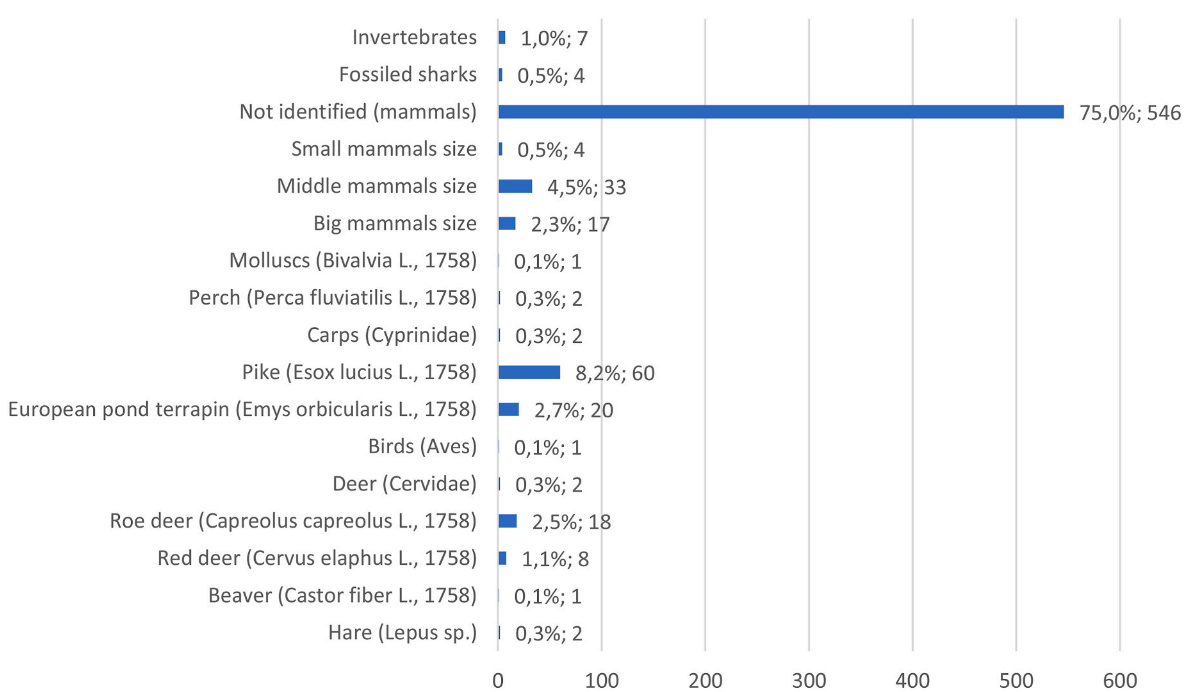

Fig. 12. Paliwodzizna 29. Species structure of animal bones.

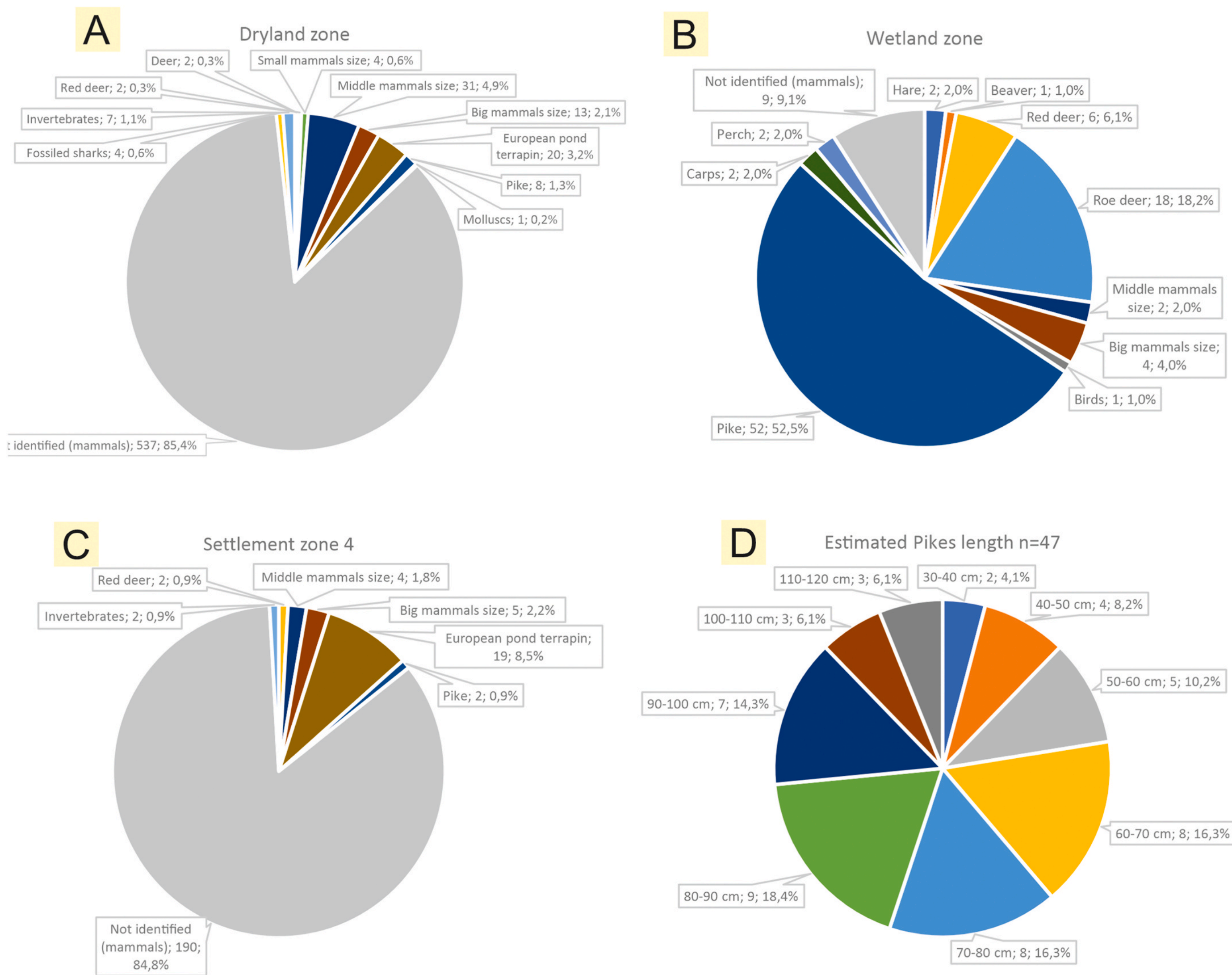

Fig. 13. Paliwodzizna 29. Results of the archaeozoological research: A-C - species structure of bone remains in distinguished zones of the site; D - estimated pike length.

4. Discussion

4.1. A brief history of plants in the vicinity of the site paliwodzizna 29 in the mesolithic

Understanding the history of plants in the vicinity of the site is based on the results of the pollen analysis supported by data from macroscopic remains and sedaDNA data. As can be seen from Fig. 14 the results of these palaeobiological techniques correlate well with each other and with the archaeological settlement phases based on AMS dating.

While palynological results allow us to describe the wider area, the results of the other two analyses primarily reflect very local conditions (Sugita, 1993; Sugita et al., 1999; Sobkowiak-Tabaka et al., 2020; Alsos et al., 2018). It can be assumed that in the older Preboreal period, forest communities with birch and pine spread in the vicinity of the site. This is evidenced by both the significant percentage of pollen of both trees, as well as numerous remains of their macroscopic remains. The faster growth of *Betula* than *Pinus* is due to its high tolerance to light and habitat conditions as a pioneer species (Latałowa et al., 2004; Ralska--Jasiewiczowa et al., 2004). This results in the initiation of faster migration of *Betula* and *Pinus* into newly exposed areas that may have been created by fires, caused by people living in the Paliwodzizna area. In the younger part of the Preboreal, *Ulmus* and *Corylus* began to encroach on the forests in the vicinity of the site. The traces of sedaDNA as well as single fruits of *Alnus* show the presence of this wetland tree already at that time, although it is not confirmed in the pollen with only a sporadic single pollen grain appearing in the profile. This suggeststhat whilst *Alnus* may have been present, it did not spread around the lake and site until the Boreal period. The shore of the lake was overgrown with reed beds, and the presence of traces of submerged aquatic plants indicates that this community was not well developed. At the end of the period *Cladium mariscus* began to appear and it is possible that its presence increased the attractiveness of the site to local hunter-gatherer groups (Regnell et al., 1995; Out, 2009). At the turn of the Boreal period, a high-growing, heterogenous forest began developing in the vicinity of the site and *Tilia* and *Quercus* appear in the Paliwodzizna area. This may have hindered the growth of the photophilous *Pinus*. Mixed forests began to form on the most fertile sites, where *Ulmus*, *Corylus, Tilia* and *Quercus* had already appeared in addition to *Pinus*. On the wettest sites, forests with *Alnus* and *Ulmus* spread. At that time, the shores of the lake were overgrown with fully developed *Cladium* rushes. Presence of forbs at this time suggests increasing succession of the lake body to open fen and carr-woodland, with increased levels of *Pinus* and *Betula* woodland in the surrounding area and some dryer areas. However, early Mesolithic hunters also encountered periodic changes in the water level in the lake.

Fluctuations in the water level were certainly also evident in the

Chronology	Paliwodzizna 29: Peatbog L PAZ	Archaeological trench WT4: L PAZ	Archaeological trench WT4: L MAZ	Archaeological trench WT4: Arch. levels/layers	sedaDNA	Charcoal	Bones	Radiocarbon dates	Mesolithic settlement phases
Subboreal	TP-8 *Pinus-Quercus*	WT4-5 *Pinus*	WT4-5 Cadium-Alnus -Urtica	-	-	-	-		-
Atlantic	TP-7 *Quercus-Ulmus -Tilia*	WT4-4 *Quercus-Ulmus -Fraxinus*	WT4-4 *Alnus -Betula Cladium*	3, 4	-	+	-	6940±40BP (Poz-121822)*	
			WT4-3 *Alnus-Betula*	12,5	-	+	-		
			WT4-2b *Cladium*-Najas	5	P776	+	-		Late Mesolithic *(not legible in wetland zone)*
Boreal	TP-6 *Betula-Ulmus -Corylus*	WT4-3 *Betula-Ulmus -Corylus*	WT4-2a *Cladium-Betula -Pinus*	6		+	-		
				7a	P775	**+**	**+**	8680±40BP (Poz-130370) 9010±50BP (Poz-130290)**	„Wetland phase”
Preboreal				8	P774	+	+?	8610±40BP (Poz-121823)*	
	TP-5 *Pinus-Betula -Ulmus*	WT4-2 *Pinus-Betula -Ulmus*	WT4-1 *Chara-Pinus*	13		+	-		
				7b	P773	**+**	**+**	9100±50BP (Poz-130371) 9340±60BP (Poz-106752)***	
		WT4-1 *Pinus -Betula-Artemisia*		10	P770, 771	-	+?		

Charcoal/bones:
+ - large amount + - small amount
+? - bone at layer boundaries **-** - absent

Radiocarbon dates:
* - terrain plant macroremains from S644
** - charcoal denudated from older settlement levels?
*** + datings from flotation (layers 7a/8/7b): 8730±70BP (MKL-3185), 8930±40BP (Poz-106514)

Mesolithic settlement phases:
- - - - chronological boundaries of Mesolithic settlement
----- - distinguished settlement phases

Fig. 14. Paliwodzizna 29, wetland zone. Correlation of the palaeobiological studies results with the Mesolithic settlement chronology based on the AMS dates.

Atlantic period. On the less fertile soils, *Pinus* and *Pinus-Quercus* forests spread at this time, while the more fertile and humid sites were occupied by mixed forests with *Pinus*, *Ulmus*, *Corylus*, *Tilia* and *Quercus*. The pollen and sedaDNA data may suggest the formation of large areas of significant wetland on which *Alnus* has spread. This may be due to the progressive terrestrialization of the lake.

4.2. Settlement conditions at the paliwodzizna site in mesolithic

Unquestionably, the multifaceted palaeoenvironmental studies reported in this paper provide us with valuable and otherwise inaccessible data providing a more in-depth picture of the life of hunters inhabiting the valley of Lake Grodno and more generally the Polish Lowlands. In this respect, indicators of human presence and impact on the environment are especially valuable, as when compared to other data, they allow us to interpret natural and economic conditions that appertained to the settlements of the early Holocene hunter-gatherer communities. Obviously, it should be noted that data acquired from the site of Paliwodzizna 29 will be affected by different states of preservation of organic material from specific periods. In particular, the presence of calcium carbonate, particularly in the floor of Histosols, contributed to the formation of alkalinity which combined with the high humidity level had a preserving effect on the organic materials deposited synchronically within lake sediments and the lower parts of the peat layer. In turn, the presence of deep muck soils and (on the margin of the biogenic plain) mineral colluvial deposits overlying these soils led to the advanced stage of decomposition of organic matter under aerobic conditions, as well as the poor preservation of sporomorphs and other plant/animal remains. This situation had a decisive impact on the fact that at the site, artefacts made of organic raw materials of early Mesolithic affinity (deposited in the deep-seated denudation layers in the littoral zone of the former bay of Lake Grodno) were well preserved, whereas this type of artefacts from the Atlantic period were very poorly preserved. This obviously makes it much more difficult to formulate a claim on the interactions between a man and the environment in subsequent phases of the Holocene.

The findings of the palaeoenvironmental studies clearly show that the location of site Paliwodzizna 29 is not accidental. Its situation at the intersection of a large river valley oriented latitudinally and a glacial gutter with a meridional orientation was most likely of key importance for transport and communication with other human groups, and provided the possibility of monitoring the 'migration' of animals over a large area. However, there were probably more reasons for choosing this location. Above all, as shown by the results of the pedological studies, the significant diversity of habitats and natural ecosystems in the vicinity of the site combined with considerable topography, reaching up to 40 m, created high-levels of biodiversity and accessibility of diverse natural resources (plant raw materials and game) within a small distance from the camp.

Moreover, at Paliwodzizna and in its immediate surroundings, many plants associated with human settlement occurred, including what we now call human-related and ruderal species typical of small gaps and opening in mixed forests. As indicated by the results of the palynological studies, in the early Preboreal chronozone, the hydrophytes were represented in relatively high numbers by, for instance, *Typha latifolia* and *Equisetum*. Both these plants have a wide use as the shoots, roots, and stem bases of the cattail are edible as vegetables, whereas its leaves and floral stems are used for making mats and wickerwork. The fibre obtained from the leaves can also be used for making cordage as can the fibres from *Urtica* (stinging nettles). Bulrush/cattail is also considered a medicinal plant (Podbielkowski and Sudnik-Wójcikowska, 2003, 343). Such properties, as well as cosmetic properties, are also attributed to the field horsetail (Podbielkowski and Sudnik-Wójcikowska, 2003, 428), that could have been an element of the Mesolithic diet (cf. Kubiak--Martens, 2016). Nowadays, it is collected from May to September and used for treating cancer and eye diseases, amongst other conditions, and it is also believed to have a strengthening effect on blood vessels as well as an anti-haemorrhagic and diuretic effects (Górnicka, 2003, 255–257).

At the end of the Preboreal period, the littoral zone of the bay of Lake Grodno above which the site is located started developing reed beds. These reeds could have been used by early Holocene hunters for basketry, wickerwork, cordage, and mats and they could have also served as excellent bedding material (Podbielkowski and Sudnik-Wójcikowska, 2003, 489). Leaves of the fen-sedge, which is clearly identifiable in the pollen profile from the site in the Boreal period, could have been used for a similar purpose. The use of this plant for thatching has been suggested for the late Mesolithic site Bökeberg III in southern Sweden (Regnell et al., 1995) and is known from the Middle Stone Age site Sibudu in

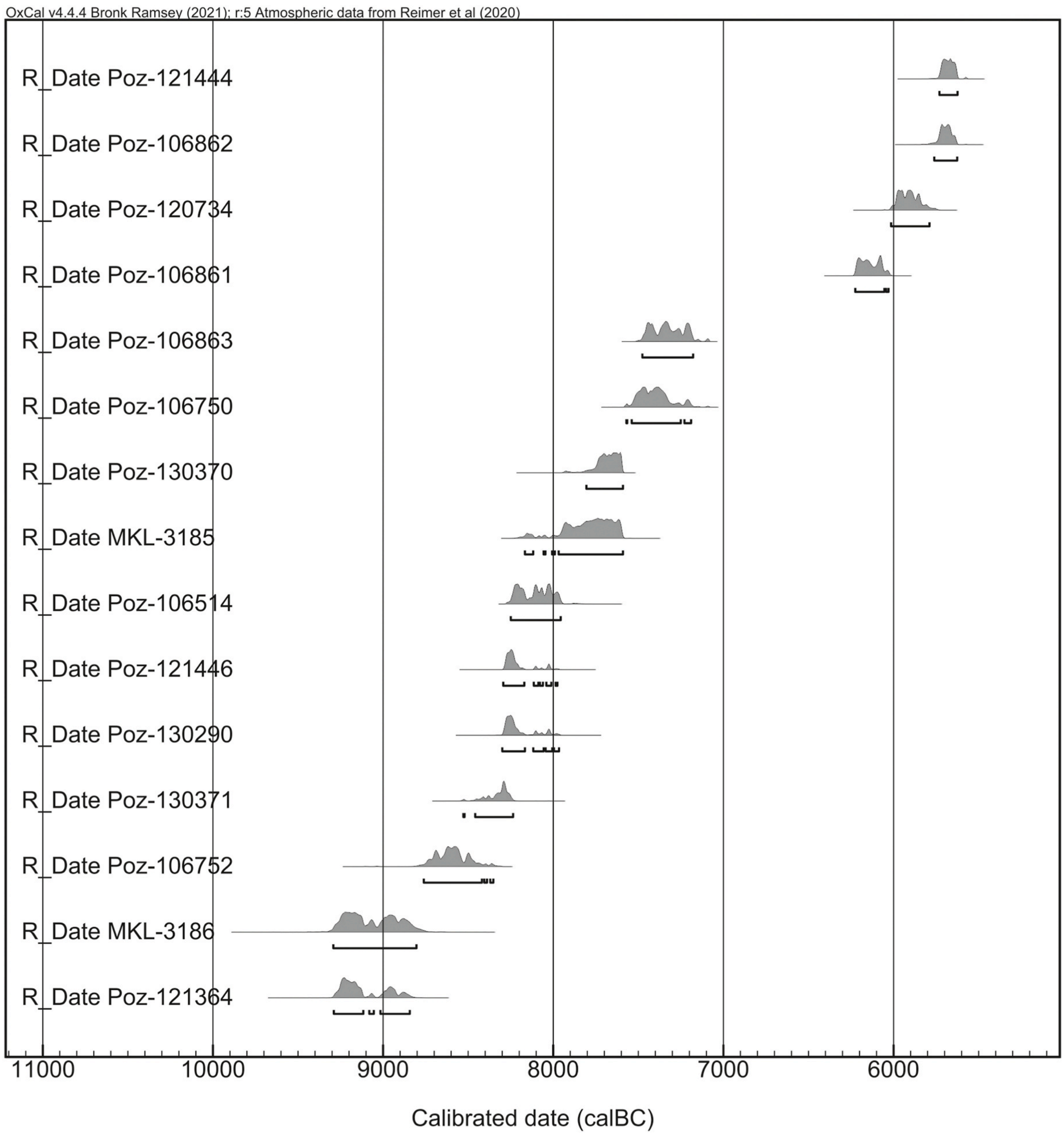

Fig. 15. Paliwodzizna 29. Mesolithic settlement chronology according to AMS dates.

South Africa, where leaves were used as "bedding" - an informal floor covering for various activities (Sievers, 2015). Also, the Cladiums sedge nutlets, corms, tubers and rhizomes are widely reported as food in archaeological and ethnographic contexts (e.g. Van Wyk and Gericke, 2000; Mason and Hather, 2000, 424; Simpson and Inglis, 2001; Kubiak-Martens, 2016; Bishop, 2021; Bishop et al., 2023).

Another species represented in a high number in the Preboreal and the Boreal periods in the pollen diagram is *Corylus avellana*, and hazelnuts constituted a valuable protein source in the Mesolithic almost throughout Europe (cf. Holst, 2010; Woldring et al., 2012, 387; Bishop et al., 2013, 2015; Jacomet and Vandorpe, 2022). Its nutshells were found in high quantities on many sites from that period, among others, e.g., Staosnaig in Scotland (Mithen et al., 2001) and the site complex in Duvensee, northern Germany – which was most likely connected to the seasonal gathering of this fruit for about 700 years (Holst, 2010, 207). We also have ample evidence of hazelnut consumption in the Mesolithic in Poland. Hazelnut shells were discovered at sites in Dudka (Gumiński, 1995, 27), Pobiel (Bagniewski, 1990, 180–181), Krzyż Wielkopolski (Kabaciński, 2016) and Bolków (Galiński, 2014). Given the above, it seems interesting that they did not occur among the remains collected at the site in Paliwodzizna, not even individually, despite the excellent state of preservation of the early Mesolithic sources made from organic raw materials in the 'wet' zone of the site.

From the beginning of the Boreal period, the palynological profile from Paliwodzizna also shows traces of ferns. Ferns, and particularly bracken (*Pteridium aquilinum*), were used in the Mesolithic (Makohonienko, 2000, 53) for human consumption (Göranson, 1986; Divišová and Šída, 2015; Kubiak-Martens, 2016). Edible parts of bracken include starch-rich rhizomes and young leaves and shoots. Its shoots are also used for making fabrics and cordage that are particularly appreciated for their high water resistance (Makohonienko, 2000, 54). Ferns can also have medicinal properties. The male fern (*Dryopteris*) is less versatile in terms of its application, though some of its species were used until recently as a remedy against worms and tapeworms (Stichmann-Marny and Kretzschmar 1994, 404; Podbielkowski and Sudnik-Wójcikowska, 2003, 313) and in the Mesolithic, it could have been also used for mattresses (Grøn, 1995, 48).

In view of the above list, in the context of the early Holocene vegetation from the site in Paliwodzizna, we note a broad spectrum of plants potentially useful for hunter-gatherers. All the species could have been used and could have served as attractive elements that determined the location of the settlements. Nonetheless, as yet, no arguments that would provide a more convincing support for this claim have been found, as was the case with the Late Mesolithic site Ludowice 6 situated nearby (Osipowicz, 2018). It is possible that evidence in this respect will be provided by provenance studies of stone products from the site.

The pedological studies and observations made in the course of the archaeological research at Paliwodzizna indicate that an important and even decisive reason for choosing this location by the early Holocene peoples probably lies in the properties of the soils covering the site. In this respect, characteristic distribution of skeletal fractions in the soil profile are the most important. Chips of gravel and stone clusters occur in the parent rock C and in the lower part of horizon Bw – *siderik* of modern (Rusty) soils, which form the Mesolithic cultural layer. The upper part of the soil, that is, arable topsoil Ap and the roof part of horizon Bw, have either a low share of gravel fractions and stones or contain neither and post-date the archaeology (cf. Fig. 7). This factor combined with the high state of preservation of the archaeological structures show that in the Late Palaeolithic and Mesolithic, the terrain surface of the site was characterised by gravelly-boulder pavement, created as a result of intensive outwash of fine fraction resulting in the separation of sands from gravels and boulders during a Froude-supercritical flow regime (Weckwerth et al., 2019, 2021). This boulder pavement (lag deposits) could have been the determining factor for the settlements, serving as a source of stone used for building hearths and other structures that involved stone components (cf. Fig. 3:1–4). The overlying sand layer was probably formed after the Mesolithic settlement period in the lower-middle Holocene, preserving the older surface.

The gravelly-boulder pavement present at the site was likely not only a source of stone; it could have been also used for obtaining erratic flint occurring within its borders. Easy access to flint could have even been the main reason for early Holocene settlement at Paliwodzizna, but confirmation of this suggestion would require additional analyses.

4.3. The function of the mesolithic camps and the mobility of the communities that used them

Important arguments regarding the possible structure of the diet of Early Mesolithic hunters during their stay at the site, and probably even one of the key reasons why they used this area, were provided by the zooarchaeological studies. The predominance of pike remains among animal bones dating back to the second phase of settlement at the site (52.5% of all the bones from the 'wetland' zone, 92.8% of the fish bones) clearly indicates that this species could constitute the main reason for visiting this place in the early Mesolithic (i.e., at the turn of the Preboreal and Boreal periods). This suggestion is also supported by the results of the geomorphological research and the data obtained in the course of the palaeobiological analyses. Based on these findings, it can be concluded that the terrain around the site and the characteristics of Lake Grodno were highly conducive to hunting/trapping this fish when it was spawning in early spring (cf. Makowiecki, 2003). The structure of the pollen profile and the discovered macroremains indicate that the water level in the lake was high. This is confirmed also by the results of the geomorphological studies, which suggest that it was responsible for the development of a small valley that linked the Drwęca River and Lake Grodno (cf. Fig. 1). This small valley is up to 30 m wide and characterised by a single terrace level of a high 65.7–66 m a.s.l. Which corresponds to the highest water level recognized in trench 3080/8650 B-CW. This terrace is up to 12 m wide in the meandering reaches of the small valley. Moreover, this valley widens at the contact with the Grodno Tunnel Valley forming in the past a funnel-shaped bay of a former lake. Probably, the rising of the lake water level during the springtime caused an increase of water flow through the small valley, with the bottom located at the terrace level of a high 65.7–66 m a.s.l. These conditions represent places favored by pike, where shallow water bodies have sufficient oxygen content. These conditions were also favourable for the Early Holocene fishermen who could catch the pike in this type of marsh without major obstacles, often using very simple methods including traps (cf. Makowiecki, 2003; Robson and Ritchie, 2022; Gumiński, 2012).

The evidence of the importance of fish for Early Mesolithic Europe is plentiful (cf. Meadows et al., 2018). Pike remains predominate among bones of the identified ichthyofauna on Early Mesolithic sites in Denmark (Robson and Ritchie, 2022) and, for instance, in materials of this chronology from Friesack 4, Germany (Robson, 2016). They are also represented in high numbers at sites such as, among others, Norje Sunnansund in Sweden (Early Mesolithic; Boethius et al., 2021) or Beregovaya 2 in Russia (Boreal/Atlantic; Zhilin and Savchenko, 2020). They prevail among fish bones in the Mesolithic and Neolithic collections from Estonia (Lõugas, 1997, 25; Robson and Ritchie, 2022). In Poland, pike remains were numerous (often predominant) at Mesolithic sites such as: Dudka (Gumiński, 1995), Szczepanki (Gumiński, 2003), Pobiel (Bagniewski, 1990), Miłuki 4, Tłokowo 2 and Mszano 14 (Makowiecki, 2003), Krzyż Wielkopolski 7 (Zabilska-Kunek et al., 2015) and Dąbki 9 (Makowiecki, 2003; Zabilska-Kunek et al., 2015). In this context it is highly relevant that pike is a so-called 'superfood' – that is a food that supplies a very high amount of nutrients, including highly beneficial fatty-acids, required for not only human survival but the successful procreation and raising of children, making this almost certainly a 'good place' to be or to visit for the group (Brown et al., 2013).

In the context of the presented conclusions, it is worth considering the character and the permanence of the Early Mesolithic settlement at the site in Paliwodzizna. This issue should be looked at from two perspectives, namely, (1) the long-term perspective (that is, the frequency at which this place was used) and (2) the short-term perspective (that is, the possible mean duration of a one-time stay). The information is of key importance for assessing the degree and character of the mobility of Early Holocene peoples using this site. Obviously, multifaceted spatial studies and high-precision analyses of archaeological sources (e.g. provenance determinations from flint products), which are still in progress, will be of fundamental importance for these studies. However, at this stage of the research, this problem can be approached from the perspective provided by the dating results and the paleoenvironmental findings presented here.

First of all, it should be stated that in the light of the radiocarbon dating results, it is not possible to determine whether in the course of the Early- and Middle-Mesolithic (which covers over one thousand calibrated radiocarbon years – Table 3), occupation was systematic or of a long-term nature. The structure of the ^{14}C dating results possibly indicates a series of short duration settlement episodes completely independent of one another, scattered along a long timeline, and therefore the absence of continuous settlements in the meaning of cyclical, or seasonal use of the site by a specific group of hunters. However, the presence of this type of seasonal settlement is indirectly supported by the characteristics of the deposits that mark the early Mesolithic "wetland phase" of the settlement.

From the perspective of stratigraphy, this phase is documented by two homogeneous denudation layers, recorded, for instance, in the profile of the trench WT4 (layers 7a and 7 b – Fig. 2). In some places, their thickness reaches over 10 cm, while the cultural substrate in the form of artefacts (flint products and bones) and organic remains (predominantly burned wood) is very high.

It is worth looking at the origin of these stratigraphic levels at this point. The presence of certain artefacts indicates that they are related to some extent to human activity. The huge amount of large charcoals (with diameters up to 5 cm) discovered in these strata are most likely of anthropogenic origin, and apart from flint artefacts and bones, they are (and this should be emphasised) the only component absent in other Early Holocene horizons. The charcoals found in layers 6, 8 and 13 (cf. Figs. 2 and 14) are generally charcoal dust and small charcoals that may be associated with natural reed-beds and forest fires. Apart from the boundary zone with layers 7a and 7 b, burnt wood and larger charcoals were not identified in these stratigraphic horizons. The fact that this component has been discovered exclusively in the layers containing artefacts, allows for the suggestion that its presence there can also be connected (with a high degree of probability) with human activity (of course, not excluding that some of the charcoals are the result of natural forest fires).

Layers 7a and 7 b are largely composed of sand and are relatively thick. The strata with these characteristics could have been formed only as a result of partial deforestation of the area. It is likely, that this process was caused to some extent by the erosion of the lake bank caused by natural forest fires. However, the presence of a relatively large number of diverse artefacts in these (and only in these) layers seems (again) to indicate that they relate to human activity. This activity was most likely long-term, intense exploitation of the area (in either a continuous or a seasonal manner), leading to permanent damage of the turf (which is essential for launching runoff processes). Additionally, it is worth recalling here that the boulder pavement (lag deposits) present at the site in Paliwodzizna were used by the Mesolithic people to extract stones and probably flint. Some of the pits dug for this purpose are up to about 2 m deep and about 5 m in diameter. Conducting such large groundworks undoubtedly could have also impacted the initiation of denudation, and it can be evidence of a more permanent (continuous or a seasonal) settlement itself.

The presence of the gyttja layer containing burned charcoals that separates both denudation layers (layer 8 – Fig. 2) is unclear. It might reflect a longer discontinuation of the settlement or merely a relocation to a different part of the site.

Looking at the data from a short-term perspective, we can ask whether the occupation at Paliwodzizna occurred only at the time most conducive to catching pike or whether these settlements were of a more fixed and long-term nature. In this regard, the lack of conclusive remains of more permanent dwelling structures and in general a relatively low number of artefacts (particularly in the 'wet' zone of the site) may suggest short-term settlements. Much more convincing evidence in this respect has been provided by the results of the archaeobotanical studies. In this regard, the absence of hazelnut shells in the archaeological context and among the macroremains discovered in the denudation layers in the wet part of the site seems particularly important as it suggests that occupation was not during the late summer to autumn, indirectly supporting early spring occupation.

As already noted above, these nuts served as an extremely valuable protein source in the Mesolithic, and their shells occur on a mass scale at sites from that period where suitable preservation conditions exist. However, in Paliwodzizna, they are not present at all despite the Early Mesolithic wood remains that have been very well preserved there, and from the palynological and sedaDNA studies we know that the hazel grew in the vicinity of the site in that period. This situation probably means that in the fruit season, that is, around September (Larsson, 1983, 120; Gumiński, 1995, 27), the area of the site was not in use. However, in the macroremains from the Early Mesolithic denudation layers of the wet zone, remains of wild strawberry were found, a plant that bears fruit in the summer, most likely gathered by Mesolithic people (Bos and Urz, 2003; Robinson, 2007, 367; Jahns and Wolters, 2021). It is not confirmed though whether its origin at the site in Paliwodzizna is anthropogenic, as it could have been deposited in animal faeces or may simply have grown nearby. This last hypothesis is supported by the fact that remains of wild strawberries were also identified in the place where the core sample was retrieved from for palynological study, which is a small distance from the area of the early Holocene settlements (and about 100 m away from WT4).

In summary, the Early Mesolithic settlements related to the most pronounced "wetland phase" of human activity at Paliwodzizna, were probably limited to the early-spring period of pike fishing, after which this area was deserted. Considering the high thickness of denudation layers that are a consequence of these settlements, it may be suggested that numerous occupations of seasonal nature must have taken place.

The picture of Mesolithic settlement at the site changes radically in the Atlantic phase of the Holocene. The activity of the hunter-gatherer communities from that period was not marked in any clear fashion in the peat-gyttja deposits. The tiny number of discovered artefacts and the considerable drop in the quantity of charcoal fragments in the strata show that the nature of settlement changed to be even more occasional. This is perhaps supported by a significant dispersion of radiocarbon dating results obtained for the objects from that stage (Table 3). During this period the human impact on the forest communities in the area of Paliwodzizna was unquestionably small and possibly limited to gathering wild resources, with no enhancement of productivity or substantial destabilizing effect.

The character of Mesolithic settlement at the site in Paliwodzizna in the Atlantic period of the Holocene is reflected in the results from settlement zone 2 (Fig. 2c), which is the only concentration of early Holocene artefacts for which the analysis has been fully completed (cf. Osipowicz, 2021). The findings of the spatial research, as well as technological and provenance analyses of the flint products derived from this settlement structure show it to be a brief, one-time camp with an open hearth, most likely a hunters' camp in a place where human activity was focused on preparing or repairing hunting equipment and processing the hunted game.

Nonetheless, the relationship between the Mesolithic settlements and Lake Grodno is still clear (Fig. 6). Considering the poor state of preservation of the bones from the Late Mesolithic, the share of fish in the collection from this period may be underestimated. It can be suggested however that the changes taking place in this body of water - gradual eutrophication – probably made it unsuitable for spring-time pike fishing but had no negative influence on tortoise catching. Remains of specimens of this species (mainly fragments of pond tortoise shells) account for about 56% of all the taxonomically identified animal remains in settlement zone 4 (Fig. 13C), which was radiocarbon dated to the Atlantic period. Similar large percentages of tortoise remains have been already observed in Poland for the Mesolithic. At the site in Pobiel dating back to the late Boreal and early Atlantic, pond tortoise remains account for about 30% (Bagniewski, 1990), whereas in the materials from site Mszano 14, connected most likely with the Atlantic period, they account for as much as 41% of the identified animal remains (Makowiecki and Rybacki, 2001). Pond tortoise is also represented in great numbers in similarly dated collections from sites in Dudka and Szczepanki (Gumiński, 2003, 62; 2014) and it was confirmed at Ludowice 6, not that far from Paliwodzizna (Osipowicz et al., 2014). In the Mesolithic, pond tortoises were collected not only for their meat but also for their shells, which were used for various purposes (Larsson, 1982, 119, Figg. 81; cf. Jonsson, 1988, 72; Jger, 1988, 245, Fig. 1; Gramsch, 1992, 68; Gumiński, 2012, 104; 2014; Grünberg, 2013).

At this stage of research, we are unable to explain the reason for the hiatus observed in the radiocarbon dating of Mesolithic settlements at the site, covering the period between 7200 and 6200 cal. BC. Perhaps this is an apparent gap resulting from archaeological research covering only a tiny part of the site, or the hiatus could be related to the changes taking place in the lake and the natural environment. This problem will be discussed in more detail in the following article (currently being prepared), which will focus only on the cultural and chronological aspects of the Mesolithic settlement in Paliwodzizna. Further research will include the results of morphological/typological analyses of flint artefacts, some results of spatial and traceological analysis, as well as Bayesian modelling of the radiocarbon dates (taking into account the results of typological analyses). It is hoped that the data obtained through these analyses will allow us to more thoroughly understand the chronology of the site and explain this hiatus.

4.4. Other evidence of mesolithic human activity identified in the palaeobiological sources

The overall picture of the relationships of early Holocene hunter-gatherer communities and their environment provided by the palaeobiological studies of Paliwodzizna can be complemented by the anthracological analyses. The charcoal analysis shows consistencies in the type of firewood used during the different phases of activity at the site. The early Mesolithic charcoal discovered in denudation layers 7a and 7 b in the wetland area come exclusively from pine (Table 2) indicating that this type of wood was the main (if not the only) raw material used as firewood in that period, as it was the most common and the most easily accessible source of fuel. This also supports the suggestion of Carcaillet (2017) that pine was preferred due to its high abundance. Additionally, the large size of some of the charcoal discovered both in the denudation layers and the early Mesolithic hearths indicated that they came from more massive wood pieces, which may have been obtained by tree felling.

In the hearths discovered in the 'dry' part of the site, dating back to the Atlantic period, oak wood charcoal also occurred in small quantities (Table 1). This species was identified in the 'Atlantic part' of the palynological profile from Paliwodzizna, and therefore, it was probably obtained in the immediate surroundings of the site. At the same time, the charcoal discovered in the late Mesolithic hearths come from small-diameter branches (up to 5 cm). It all seems to be indicative of a very opportunistic approach to firewood used by the people of that period, that is, collecting easily available, small pieces of wood (most likely branches lying on the ground) regardless of the tree species (cf. Shackleton and Prins, 1992; Thery-Parisot, 2002; Thery-Parisot et al., 2010). This is indirectly supported by the occasional nature of the late Mesolithic settlements at the site.

Some of the large charcoal discovered in the early Mesolithic denudation layers of the peat part of the site can be also related to intentional burning of forests in the vicinity. The possibility that this kind of 'land-clearing' practices were applied in Paliwodzizna by early Holocene peoples can be suggested indirectly by a clear increase in the percentage of spores of the bracken (*Pteridium aquilinum*) in the palynological profile starting from the Boreal period. This fern covers areas disrupted due to mass-scale burning of forests (Simmons, 1996; Pokorný, 1999; Kuneš et al., 2008; Pokorný et al., 2008). The burning of forests, and reed-beds, was apparently quite a common phenomenon in the Mesolithic, though the intentionality of this practice and its scale is still being discussed (Brown, 1997; Divišová and Šída, 2015, 97–98; Bell and Noble, 2012; Warren et al., 2014; Bishop et al., 2015; Selsing, 2016). It is believed that practices of this sort were probably used for many purposes, e.g., to increase the growth of edible understory plants (such as herbaceous berry producers and edible wild grasses), to increase growing season (quantity and nutritional quality of food of herbivores), to improve the visibility and mobility in woodlands (to increase the hunting success) and to reduce the forest undergrowth to facilitate the collection of wild edible plants, such as hazelnuts and acorns (cf. Bos and Urz, 2003; Gumiński and Michniewicz, 2003; Bishop et al., 2015). In Poland, traces of Mesolithic probably intentional forest fires were observed at the site in Dudka (Gumiński, 1995).

Among the burned remains discovered in denudation layers 7a and 7 b a considerable number of soft green stems was also identified, possibly suggesting burning and regeneration of *Cladietum marisci*. The practices of burning wetland vegetation in the early Mesolithic have already been observed at many European sites (i.a. Day, 1993; Day and Mellars, 1994; Groenewoudt et al., 2001; Bos and Urz, 2003; Innes and Blackford, 2023).

5. Conclusions

The paleoenvironmental studies conducted in Paliwodzizna have produced more data than expected, this date is robust and illustrates the relations between the early Holocene hunter-gatherers who inhabited the area and the natural environment that surrounded them. Indisputably, these relations were based on a substantive symbiosis, a conscious and skilled utilization of nature and the acquisition of high-quality food and other goods it offered without dramatic ecosystem-change. The traces of possible human activity that possibly had a far-reaching impact on the surrounding environment that were successfully observed in the course of the analyses are (most likely) intentional burning of the forest and the reedbed in the vicinity of the site.

Nonetheless, as a result of this research, possible reasons why the Early Holocene hunter-gatherers visited the site in Paliwodzizna in specific periods can be determined and the character of their settlements interpreted. The results reveal early Mesolithic communities as highly mobile groups that relocated between multiple sites where the resources that they sought were available on a seasonal or sub-seasonal basis and in the case of Paliwodzizna, this resource was the pike. It is difficult to clearly determine whether the observed picture of settlements is a result of a cyclical presence of a migrating tribal/familial group (*foragers*), or perhaps seasonal expeditions of a small and highly specialized task-based group of hunters (*collectors*) (cf. (Binford, 1977, 1979, 1980)). However, given the fact that the early Mesolithic settlement was intense enough to lead to alteration of the plant cover and trigger slope movements, the former of the two mentioned mobility models is probably more likely.

The picture of the settlements, and mobility of late Mesolithic hunters is completely different as Paliwodzizna was repeatedly visited by small groups of hunters who occasionally used it for opportunistic hunting purposes as can be concluded from the assemblage of the collected bone fragments. This corresponds to the mobility typical of *collectors*, although likewise, this suggestion requires further research in order to be confirmed.

The interpretation of a site like Paliwodzizna at this level of detail clearly shows how such sites are 'worthy of thought' even where the artefactual and environmental evidence might at seem at first glance to be slight. This, however, depends upon the methodology and particularly the application of multi-technique palaeonvironmental analyses which can be used to test hypotheses, and which can be applied together for more complete reconstructions of human activities and environmental impacts. This is particularly the case in peat and organic sediments that may be low in artefacts, being peripheral to the main areas of activity, but which can provide both time-depth and high-quality ecofacts due to conditions conducive to the preservation of bone, plant macroremains, pollen, spores, charcoal and sedaDNA.

Author contributions

Grzegorz Osipowicz: Conceptualization; Supervision; Validation; Funding acquisition; Investigation; Methodology; Project administration; Resources; Writing – original draft; Writing – review & editing; Visualization; Monika Badura: Investigation; Resources; Writing – original draft; Visualization, Tony Brown: Investigation; Resources; Writing – original draft; Visualization, Samuel Hudson: Investigation; Resources; Writing – original draft; Visualization, Michał Jankowski: Investigation; Resources; Writing – original draft; Visualization, Daniel Makowiecki: Investigation; Resources; Writing – original draft; Agnieszka M. Noryśkiewicz: Investigation; Resources; Writing – original draft; Writing – review & editing; Visualization, Justyna Orłowska: Resources; Writing – review & editing; Visualization, Marcin Sykuła: Resources; Visualization, Piotr Weckwerth: Investigation; Resources; Writing – original draft; Visualization

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.

Data availability

No data was used for the research described in the article.

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