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A NOVEL MULTIPROXY APPROACH TO DETECT THE IMPACT OF CHARCOAL PRODUCTION ON THE NATURAL ENVIRONMENT IN NW POLAND – PROJECT CONCEPT AND PRELIMINARY RESULTS

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Abstract

Agriculture has been the major driver of deforestation in Europe in the last 1000 years. In the past, forests were also exploited for charcoal production; however, the spatial scale/extent of this activity and its impact are unknown. LIDAR data can be used as a noninvasive tool to investigate the small-scale diversity of the land relief, including forested areas. These data can reveal the extent anthropogenic modifications of topography present-day as well as in the past. One of the activities that can be analyzed based on LIDAR data is spatial distribution of charcoal production. A preliminary LIDAR data analysis indicated the intensity of this practice and its potential impact on the natural environment. This prompted us to analyze the environmental impact of charcoal hearths in northern Poland. As it turned out, this topic exceeded the scope of earth sciences and became a transdisciplinary one. In this work, we will use the research methods typical of biogeography, dendroecology, paleoecology, soil science, biology, botany, history, onomastics, as well as art history, in order to thoroughly understand not only the natural consequences but also the social and economic consequences of charcoal production. This paper presents the assumptions of our project, the research methodology, and the preliminary results. We have identified using LIDAR data more than 73 thousand relief forms which can be remnants of charcoal hearths. Our preliminary results confirmed large scale impact of past human activity related to charcoal production and suitability of the methods used for detecting and reconstructing charcoal hearths as well as determining the distribution and magnitude of past forest use for charcoal production in NW Poland.

Key words

anthropopression • relict charcoal hearths • legacy effects • deforestation • LIDAR • multi-proxy • Central Europe

Introduction

During the last 1000 years, humans have transformed the natural environment to varying degrees through burning of forest, hunting, animal domestication, species reproduction, and cultivation. According to Ellis et al. (2021), the loss of biodiversity (an indicator of the naturalness of ecosystems) is the result of degradation, colonization - and above all – excessive use of already existing cultural landscapes. Abandoning or changing the type of human-made cultural landscapes, such as farmlands, has severe implications and may lead to a significant loss of biodiversity. On the other hand, forest ecosystems or clearings and meadows rapidly "run wild" and regenerate spontaneously when human activity has ceased. The natural forest ecosystems are characterized by complex interrelationships that make them resistant to short-term disturbances (Chapin et al., 2012; Müller, 2010 Łuców et al., 2021). Therefore, knowledge concerning resilience of these ecosystems to past disturbances is essential for their current management (Thom & Seidl, 2016; De Palma et al., 2018; Bartczak et al., 2019; Kruczkowska et al., 2021; Łuców et al., 2022). In this regard, the response and resistance of various types of ecosystems to disturbances caused by both human activity and climate change have been widely studied in the last decade (Kirilenko & Sedjo, 2007; Cole et al., 2014; Ratcliffe et al., 2017; Sabatini et al., 2018; Whitlock et al., 2018).

Rapid dynamics of changes in the landscape (including forested areas) is directly related to human activity (Ellis et al., 2021). In Polish territories, intensity of this factor increased only since the Middle Ages, as evidenced, for example, by the progressive deforestation, draining of wetlands, and adaptation of new areas for farming purposes (Bartlett, 1993; Słowiński et al., 2019; Lamentowicz et al., 2020). However, such mechanisms did not intensify until the 19^{th} and 20^{th} centuries (Łukasiewicz, 1977). Initially, these processes were closely linked with a rapid rise of the population and the dynamic development of settlement structures, for which forests were used as the primary source of energy resources and construction materials (Żabko-Potopowicz, 1954, 1972). The progressive exploitation of forest areas in Polish territories was primarily related to the inclusion of Kingdom of Poland economy in the range of Western European markets in the Late Middle ages (Ważny & Eckstein, 1987; Kutrzeba & Duda, 1915; Małowist, 2006; Czaja, 2008; Kardasz, 2021). After the grain trade, the export of wood in various forms (e.g., staves, raw logs, or firewood) and the production of charcoal and other forest goods became the most lucrative branches of the agricultural and forest economy (Ważny & Eckstein, 1987). Industrial development from late 18th cent. led to an increased demand for high-energy fuel needed for operating forging and smelting furnaces (Warde, 2006; Warde & Williamson, 2014; Smil, 2017). The abundance of high-energy wood contributed to the widespread burning of charcoal in Polish lands, which was the dominant energy source until the early 19th century. Hence, we assumed that charcoal-burning practices must have had a significant impact on the forest environment, leaving long-term traces related to the processes discussed.

Until now, this type of multidisciplinary study has not been conducted not only in Poland but also in Europe. Although forests covered over 80% of Central Europe at the beginning of the Middle Ages (Broda, 2000; Williams, 2000), the effect of charcoal hearths – and thus human activity – on the transformation of forest ecosystems in this period has been underestimated so far. Studies have explored the charcoal hearths and associated forms in other states such as Germany (Raab et al., 2015; Hirsch et al., 2018; Schneider et al., 2020), Belgium (Hardy et al., 2016), Italy (Carrari et al., 2017; Carrari et al., 2018; Mastrolonardo et al., 2018), and France (Dupin et al., 2017). Research on charcoal hearths in Poland focused only on their inventory and characteristics of objects, taking into account the technique used for obtaining products (Kałagate et al., 2012). The main studies carried out in Poland explored the areas in the southern (Augustyn, 2000; Marszałek, 2013; Marszałek & Kusiak, 2013; Rutkiewicz et al., 2019) and eastern part of the country (e.g. Samojlik, Jędrzejewska, et al., 2013; Samojlik, Rotherham, et al., 2013). Kukulak (2014) analyzed the alluvial sediments of the Carpathian rivers and reconstructed an increased erosion pattern of the catchment, which confirmed deforestation and activities of "charcoal hearth". Previous studies on changes in the natural environment mainly investigated specific points, analyzing the local changes and relations between the main drivers of changes recorded in biogenic sediments.

The goal of this project is to expand the current knowledge obtained from spatial and temporal analysis of the impact of charcoal hearths functioning along with growing anthropopressure leading to selective deforestation from the Middle Ages and to determine their effects on the natural environment. We aim to accurately predict the reactions of the natural environment by performing high-resolution paleoecological analyses. It has been assumed that the collected data on the reaction of peatland and lake ecosystems to human impact can be used to create a model specific to charcoal hearths. The proposed project is a unique opportunity to fully utilize the potential of a multidisciplinary team, focused on analysis of an impact of the production of charcoal, tar, or potash on environmental changes in NW Poland. Hence, it is important to determine whether the functioning of charcoal hearths caused only a short-term disturbance to ecosystems or had the potential to alter their trajectory.

Undoubtedly, information in the literature on the impact of charcoal production on the environment is insufficient and the long-term direct and indirect effects of the charcoal hearth operation on environmental evolution have been underestimated (e.g. Raab et al., 2015; Dupin et al., 2017; Hirsch et al., 2018; Hirsch et al., 2020; Bonhage et al., 2020;

Schneider et al., 2020). In a similar study, we attempted to find answers to several questions regarding the relations between the influences on charcoal hearth and ecosystems (forest, vegetation composition, microclimate, hydrology, general deforestation, soil properties, and related climate changes). All these environmental components are interconnected and interact with each other indirectly and directly, as well as in a cascading manner (e.g. Słowiński et al., 2018; Lamentowicz et al., 2019; Słowiński et al., 2019; Szewczyk et al., 2021; Bonk et al., 2022). We will use the archives such as peat, gyttja and soils. Only by performing results of paleoecological and geochemical analyses, one may study and reconstruct the past events and attempt to interpret the causes and effects recorded in the cores and soil profiles (Lamentowicz et al., 2019; Kittel et al., 2020; Kruczkowska et al., 2021; Łuców et al., 2021; Mroczkowska et al., 2021). A great advantage is working in an area that has a wealth of historical archives from maps to church sources, and information on tax and ownership.

This paper discusses the main concepts of our project and presents the results obtained from the preliminary analysis of the impact of "charcoal hearths" on the natural environment, particularly on soil processes and vegetation cover in NW Poland from the Middle Ages.

Methods

Study site

In this project, identification and measurements of the charcoal hearth remains (CHRs) will be carried out in the Polish lowland and upland, excluding the mountain ranges. So far, the remains have been identified in almost a quarter of the country. In the first phase of the project, we focused on NW Poland, where 73,133 of CHRs was identified (Fig. 1).

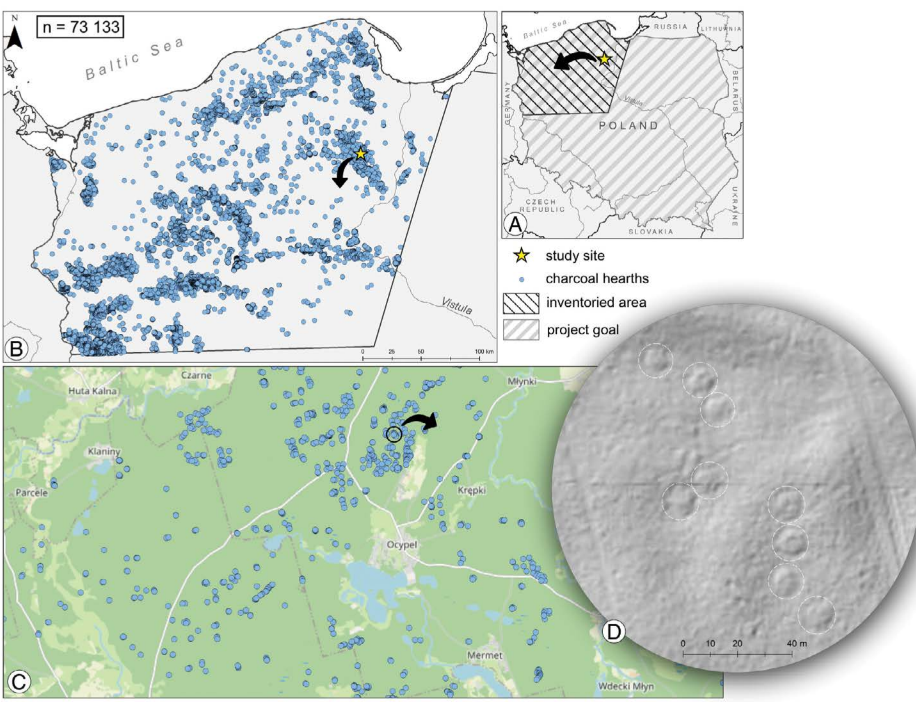

Figure 1. Research locations, (a) setting up of the project area, (b) distribution of charcoal hearths in the already investigated area, (c) distribution of charcoal hearths in NW Poland and (d) examples of LIDAR visualization of charcoal hearths in Tuchola Forest

Research methods adopted and availability of data

The project comprises seven work packages to verify the research questions (Work Package (WP) 1-7, Fig. 2). WP1 includes the analysis of airborne laser scanning (ALS) data and materials, as well as the counting of all existing charcoal hearth residues in NW Poland (in the area of approximately 73,000 km^2). The ALS data were collected from the Central Office for Geodetic and Cartographic Documentation. Shaded relief models were obtained using ArcGIS and QGIS software. CHRs were identified based on the ALS lidar data.

More than 73 thousands of CHRs have been identified in NW Poland. The use of LIDAR data allows us to recognize the objects remnants hidden under the forest litter. The residues remaining after the burning of charcoal are clearly visible in the form of CHRs, appearing like circles sticking out slightly above the ground level and often surrounded by a ditch.

To identify CHRs, first a semitransparent grid of squares with sides measuring 500 m was applied on the underlay of the LIDAR map of the entire area of Poland. The grid proved very useful in the search of CHRs on LIDAR, ensuring that no area was overlooked and that every charcoal burning area was found. The CHRs were marked only on forest areas because their remains were damaged and made invisible on LIDAR due to tillage and other agricultural practices, erosion and construction of buildings over time. Each charcoal hearth was marked as a single point with division into pile size as follows: small—diameter <10 m, medium—diameter 10-15 m, and large—diameter >15 m. After the area was verified, the grid was removed and a set of points representing the piles on the given area was visible.

The CHRs were piles of wooden trunk arranged on a circle plan, covered with litter, soil, and turf (Radwan, 1959). In some cases, they could also be covered with brushwood and wet sand (Zientara, 1954). To construct a CHR, a single wooden pole was driven in, allowing the diameter to be outlined. Then,

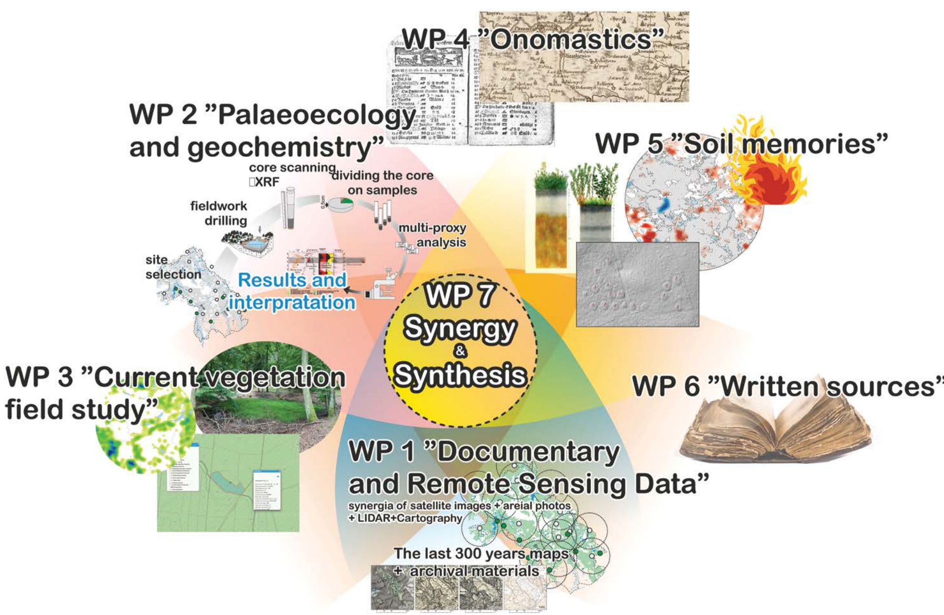

Figure 2. The concept of project work packages and their interaction

the prepared pieces of wood were arranged around the it in a vertical position. Subsequently, the CHR was covered with a casing that prevented excessive inflow of air, favoring dry distillation of wood and its transformation into charcoal (Zientara, 1954). Nowadays, only remnants of CHRs can be found, surrounded by a ditch and with a minor land elevation, which are often invisible to the naked eye (Kałagate et al., 2012). Additionally, on the available archive maps of the territory of NW Poland one can see a perfect coincidence between the distribution of settlements occupied by charcoal burners and the accumulation of relics of CHRs relics (Fig. 3).

Based on the results obtained from WP1, the study sites were selected for paleoecological and palaeopedological analyses, implemented as a part of WP2. The working group of WP2 will focus on analyzing the response of lake and peat ecosystems to human activity related to CHRs (selective deforestation, erosion, and fires). In this package, we will attempt synchronizing our positions using the results of Accelerator Mass Spectrometry (AMS) radiocarbon dating and dendrochronology.

The preserved fragments of charcoals found in CHRs will be analyzed following a six-stage procedure: (1) wood identification based on the microscopic observation of the wood anatomical features; (2) recording characteristic wood structure features and selection of samples suitable for dendrochronology; (3) dendrochronological analysis; (4) extraction of samples for radiocarbon dating; (5) AMS radiocarbon dating and (6) calibration of C14 ages and wiggle-matching the results (Fig. 4).

Both wood identification and the analysis of wood structure provide information concerning past environment. Moreover, wood

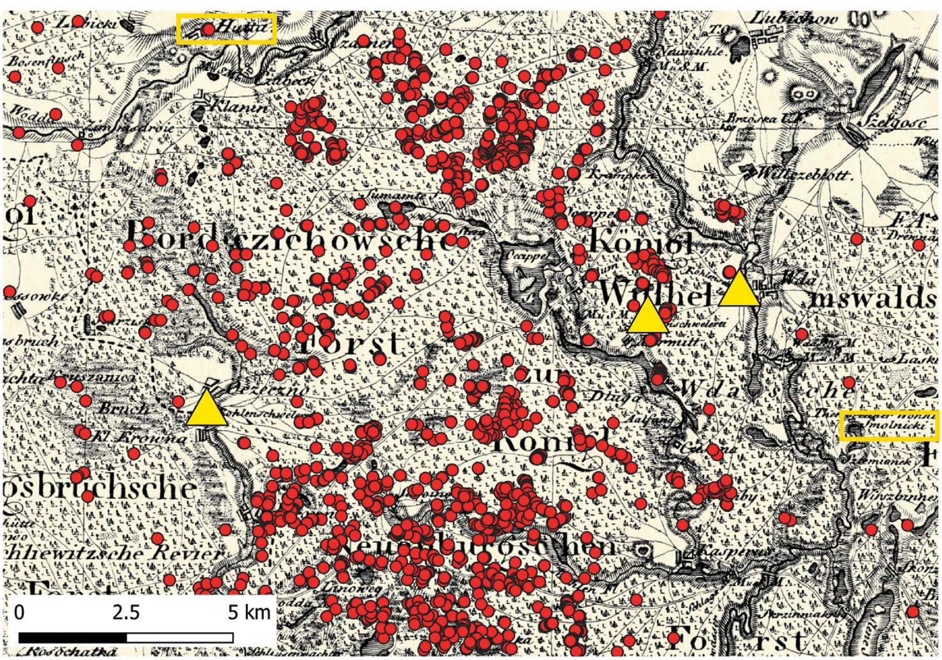

Figure 3. A piece of the Leopold Schrötter's map of the Ost- and West-Preussen from 1796-1802 with charcoal hearts (red dots), coal burners settlemets (yellow tringles) and some onomastic indicators connected with forest industry (settlement names like *Huta* or *Smolniki*)

Source: Karte von Ost-Preussen nebst Preussisch Litthauen und West-Preussen nebst dem Netzdistrict aufgenommen unter Leitung des Königl. Preuss. Staats Ministers Frey Herrn von Schroetteer in den Jahren von 1796 bis 1802, scale 1: 150,000, Berlin

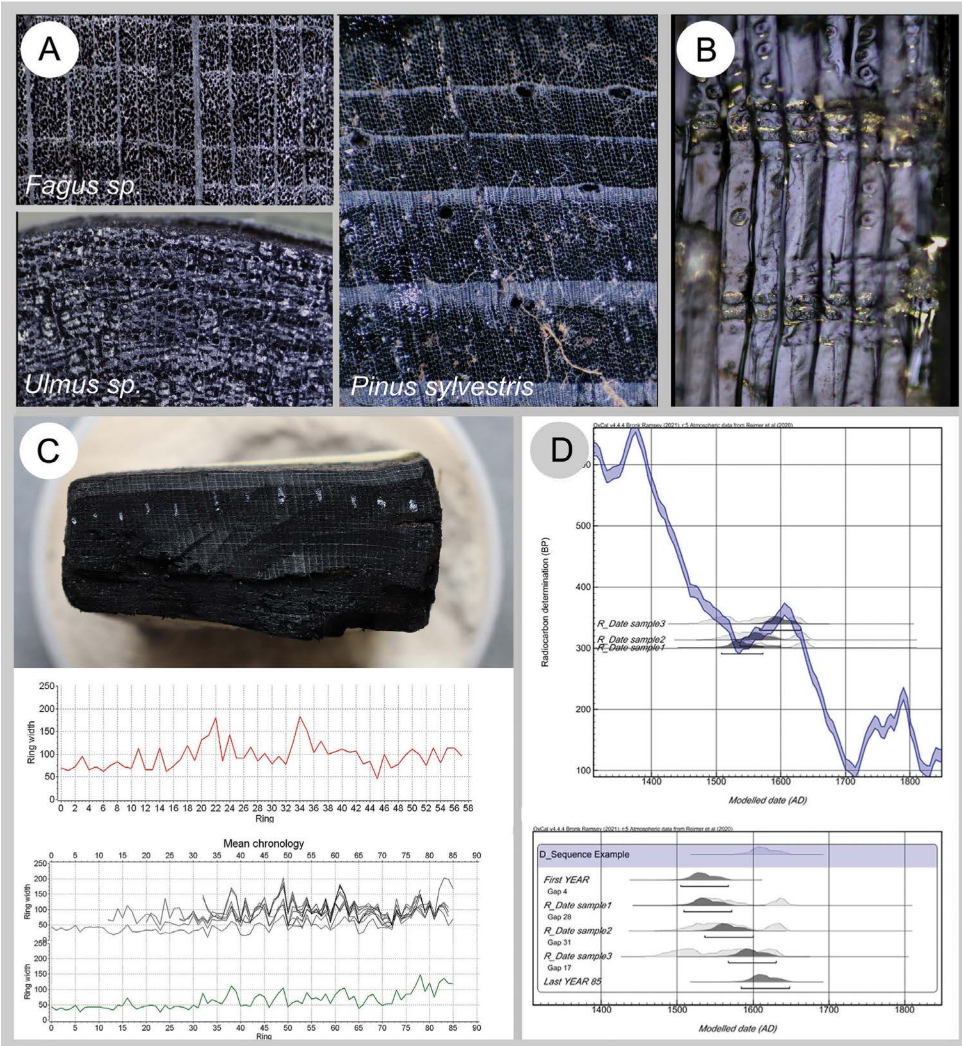

Figure 4. Analysis of charcoals fragments found in charcoal hearths: A: tree species identification based on macroscopic observation of cross section – beech (*Fagus sp.*), elm (*Ulmus sp.*) and pine (*Pinus sylvestris*); B: microscopic observation of the wood anatomical features – radial section of pine (*Pinus sylvestris*); C: dendrochronological analysis. Example: measuring a single sequence representing one charcoal sample, development of a mean chronology representing eight synchronizes charcoal pieces (TSAP-Win; Rinn (2011)); D: calibration of C14 ages using wiggle-matching (OxCall v 4.4.2). Example: modelling of three samples (C14 dates) of an ascertained age difference: curve plot (Reimer et al., 2020) and multiple plot (Bronk Ramsey, 2001)

identification is of key importance when selecting a dating method. Not all tree species can be dated using methods of dendrochronology. The most commonly used species in timber dating are several conifers and deciduous oaks (Edvardsson et al., 2021). In some cases, oak chronologies may serve as reference material to date other deciduous species e.g. elm (Bridge, 2020) and beech (Hollstein, 1973; Klein & Bauch, 1983).

Dendrochronological analysis of charcoal remains found in CHRs will be performed using the traditional methods of dendrochronology applied for the dating of historical timber and archaeological materials (Baillie, 1982; Eckstein et al., 1984; Schweingruber, 1988). Dendrochronology is the most accurate known dating method. When the bark and / or waney edge are preserved the exact felling date can be determined with annual precision. However, one of the crucial requirements for successful use of the method is a number of tree rings preserved in a sample – at least 50 rings are needed to avoid accidental cross dating against reference chronology (Ważny, 1991; Miles, 1997; Haneca et al., 2009). Suitable charcoal samples will be employed to develop tree ring chronologies. Subsequently, these will be cross dated against regional reference chronologies of the same or other species with similar growth responses to environmental conditions to determine the age of tested charcoals.

Radiocarbon dating and wiggle-matching modelling will be applied for the samples with limited potential for dendrochronological dating: charcoal pieces with insufficient number of tree rings (Gmińska-Nowak et al., 2021), charcoals synchronized with reference chronologies on the basis of interspecies correlation and charcoals representing tree species that cannot be dated using the method of dendrochronology.

Calendar age is calculated from the radiocarbon date using the OxCal v 4.4.2 program (Bronk Ramsey 2001) and the calibration curve IntCal20 (Reimer et al., 2020). The accuracy of the method depends on the age of the tested organic matter and the type and quality of the material itself (Walanus & Goslar, 2009). The wiggle-matching method provides higher precision than calibration of the C14 age of a single sample. It can be used when there are at least two samples of an ascertained age difference, thus it can be successfully applied for wood with distinguishable tree rings. While modelling, ^{14}C dates of selected rings with specified positions in the sequence are fitted simultaneously to the shape of the calibration curve giving narrowed range of dates (Pearson, 1986; Bronk Ramsey, 2001).

WP2 involves collecting lake and peat sediments from sites where the CHRs functioned in catchments (Fig. 5). We managed to select a dozen positions that have been checked in the field. Ultimately, the lake and peatland sediments will be subject to a multiproxy analysis of high resolution (from 1 to 5 cm, depending on the sedimentation rate). In addition, pollen analysis will be conducted to reconstruct regional vegetation cover and human impact. It is also planned to carry out microscopic and macroscopic charcoal analysis of morphotypes to reconstruct fires as well as plant macrofossil analysis to reconstruct local vegetation and geochemical analysis to determine geochemical changes and assess the impact of CHRs on vegetation cover. Finally hydrological variability on peatlands will be reconstructed by the means of testate amoebae analysis.

WP3 includes analysis of floristic composition in plots located on the CHRs and corresponding reference areas (controls) within selected test catchments in forest ecosystems of diverse age (Fig. 6). We are planning to collect phytosociological relevés using the methodology after Braun-Blanquet (1964) and measure the DBH of trees at the plots with a dimension of 10 × 10 m on CHRs and controls. The research sites will be selected adopting the following criteria: (1) habitat is fresh pine forest on rusty and podzolic soils; (2) the age of stand is no less than 70 years (the so-called maturing and mature stands); (3) the CHR situated distantly from roads, trails, or edge of the forest; (4) the diameter of the CHR is over 14 m (to designate a 10 × 10 m plot in the center to execute a phytosociological relevé); (5) it is possible to determine the reference plot in the same forest subdivision at a distance equal to the diameter of the CHR; (6) there are no disturbances, such as foraging traces of wild boars, fallen trees, new tree plantings, or clearings, in the continuity of the vegetation cover; and (7) the reference plot of 10 × 10 m is located within the same forest unit, at a distance equal to the diameter of the respective CHR. Soil and plant samples will be gathered from three selected CHRs and their respective

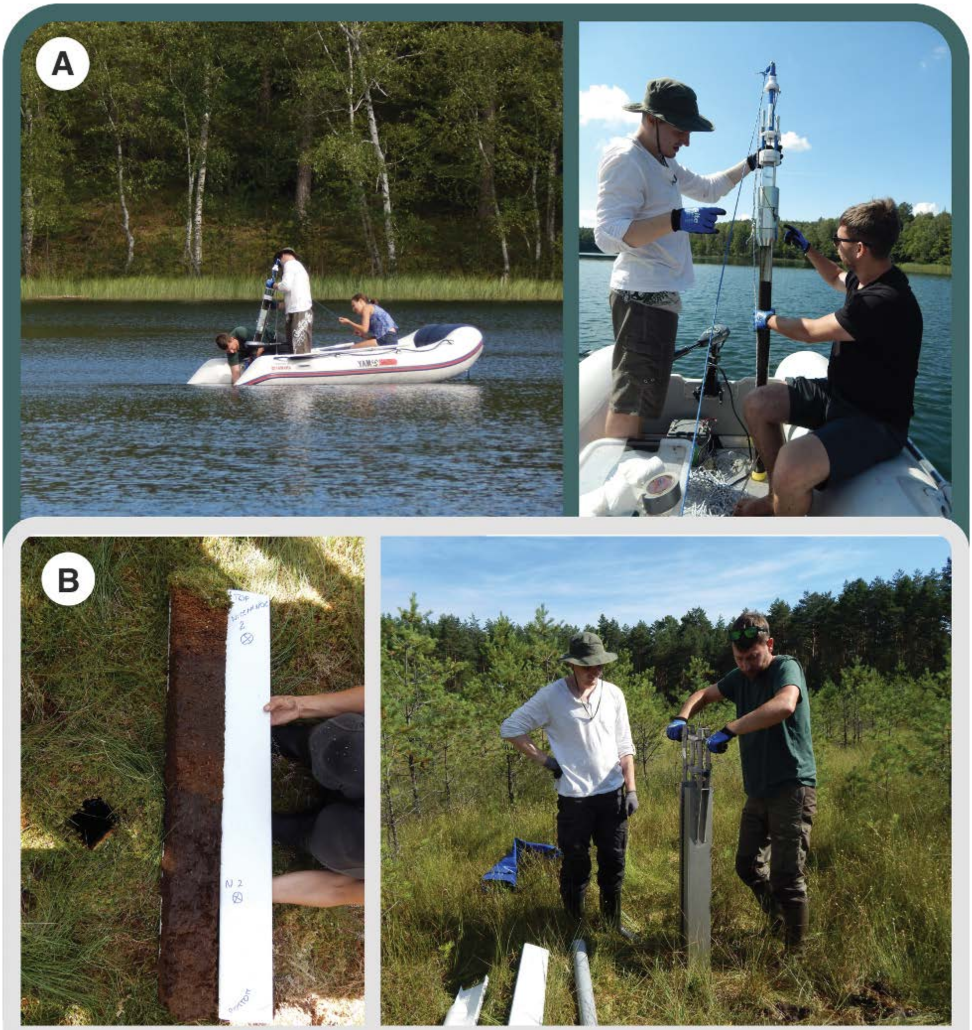

Figure 5. Field work in NW Poland as a part of WP2. A: Lake core extraction using UWITEC. B: Peat core extraction using Wardenaar sampler

controls for elemental composition analysis. After removing the litter layer, the soil will be collected (to a depth of 10-15 cm) from 10 locations within each CHR using a soil corer; the same procedure will be followed for the control. Samples of Vaccinium myrtillus bilberry (aboveground and underground parts of plants) will be taken from the same places as the soil samples. Soil and biomass specimens will be analyzed using dry combustion (Vario MacroCube, Elementar, Germany) and inductively-coupled plasma atomic emission spectrometry (ICP-OES, Avio 200, Perkin Elmer, USA) methods.

WP4 includes an onomastic analysis. Onomastic is a subdiscipline of linguistics that deals with various aspects of the functioning of proper names, including geographic names (toponyms), which are the products of language. However, when studying these names, it is important to consider the extralinguistic factors accompanying their creation and influencing the variability of their form or function using data from fields such as geography, history, or archeology. Sometimes, it is the opposite — in the absence of geo- or archeological artifacts or written source materials, onomastics (based on a proper linguistic interpretation of a name) can provide information on historical reality. In recent years, numerous articles on the acquisition and management of forest and agricultural areas have been published, presenting such a research approach (e.g.: Conedera et al., 2007; Zierhoffer & Zierhofferowa, 2008-2009; Cogos et al., 2019; Kulumbegov, 2020). However, the possibilities and needs of onomastic research in this area were recognized much earlier (see e.g.: Górnowicz, 1977).

Such a situation may arise, for instance, in the case of research on forest settlements, which are mostly transitory in nature. Often, the only trace of a former forest settlement and the type of activity carried out there is its name (in the event of a change settlement function). When a settlement disappears, the name of the place (e.g., forest clearing) where it was once located may reveal its existence in the past. This may be indicated by the form of the name itself, being typical for oikonyms (names of inhabited places), or by its content, referring to economic or cultural issues unrelated to the environment. Intensive geographical, noninvasive, or historical research can certainly provide much more precise information about the time and nature of settlement in a given area, but onomastic research is useful – and in some cases – indispensable for the initial definition of the studied site.

WP5 focuses on charcoal production impact on soil system. A wide spectrum of soil characteristics will be determined at several stands representing various landscapes – aeolian, fluvioglacial and moraine. Each landscape type will be represented by three locations (Fig. 7). The stands in aeolian landscape

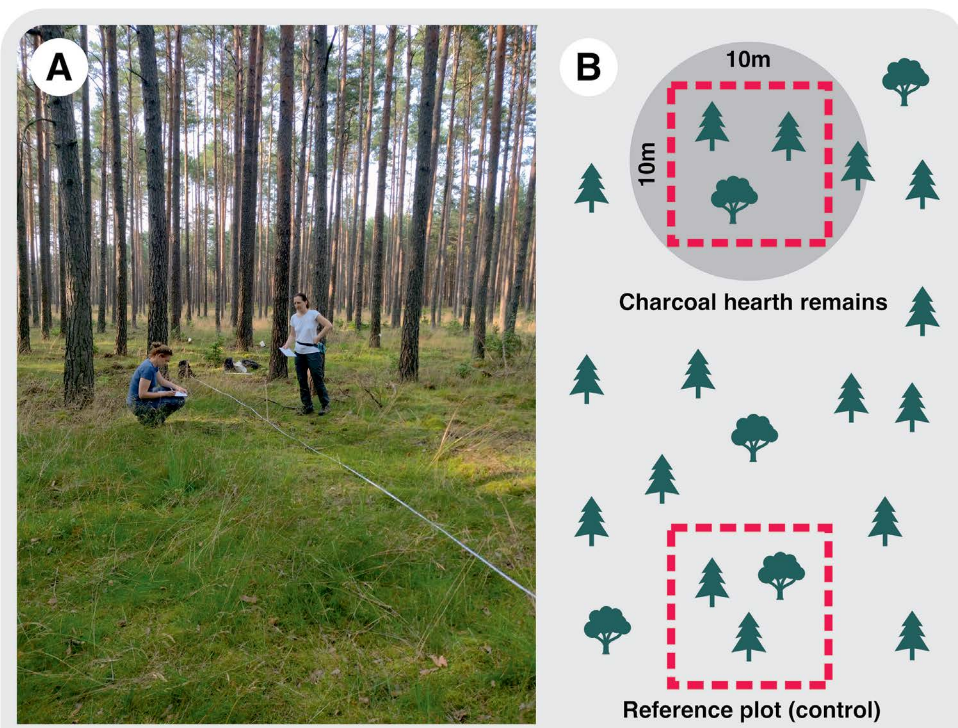

Figure 6. A: Field work in the NW Poland as a part of the WP3 (collection of phytosociological relevés). B: Scheme of phytosociological research on the CHRs and reference plots

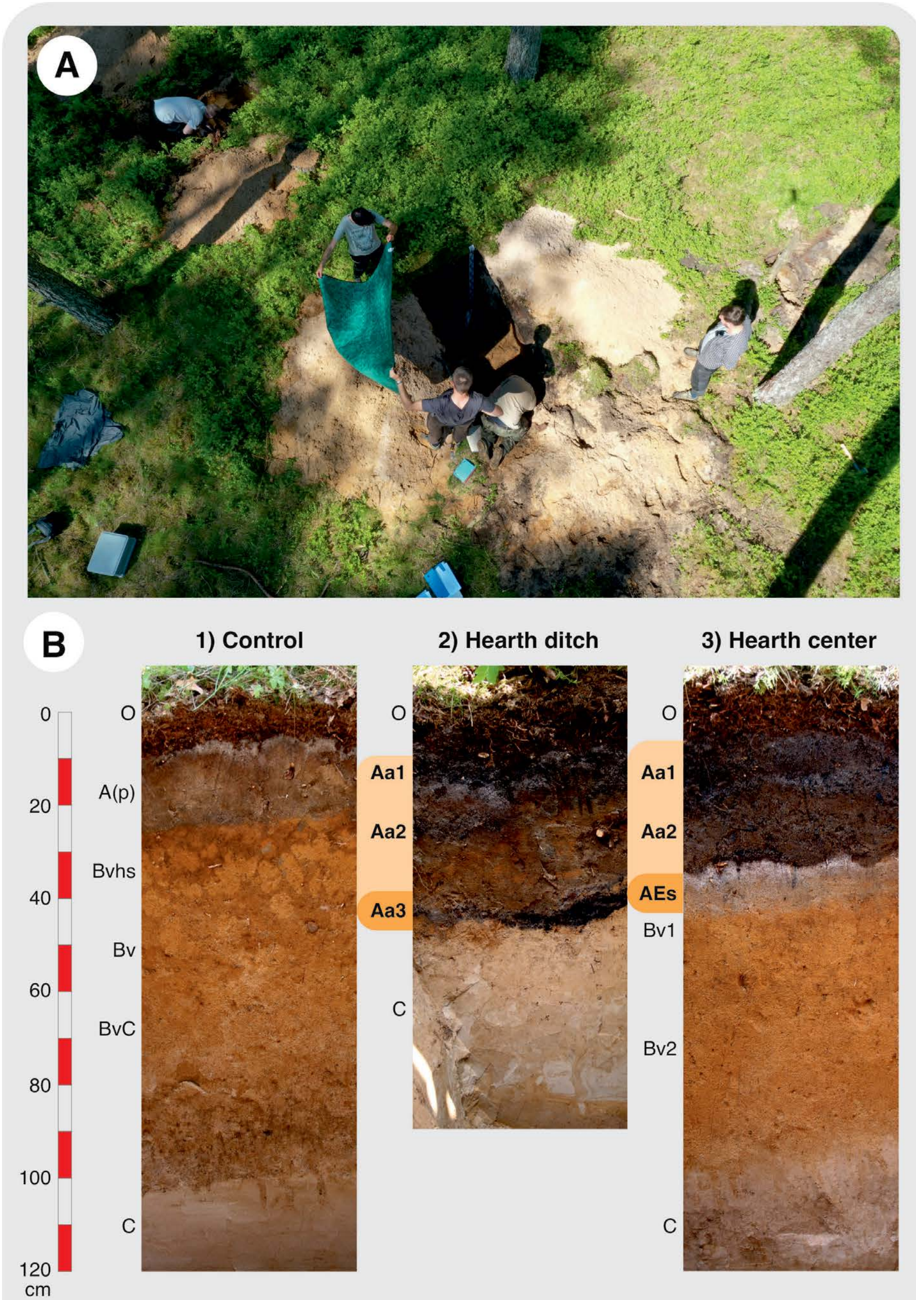

Figure 7. A: Field work in the north of NW Poland as a part of the WP5 (analysis of soil profiles). B: Morphology of exemplary soils of the fluvioglacial environment transformed as a result of charcoal production in the past. 1) Control—Brunic Arenosol, postagricultural soil without traits of human-derived transformations related to the production of charcoal, with a typical sequence of genetic horizons. 2) Hearth ditch – Aggerosol, formed as a result of the removal of A and Bv horizons from the primary Arenosol, followed by adding mixed soil material with charcoal; residues of tar and other pyrolysis products can also be found in ditch soils. 3) Hearth center – Brunic Arenosol with retained primary sequence of genetic horizons, backfilled with a layer of human-derived material consisting of a mixture of soil material used to cover wood during burning and residues of charcoal; soil in the primary top layer has a characteristic white horizon (AEs) formed under the influence of a high temperature. A clearly less advanced process of podsolization can be observed in comparison with the control soil

will cover location on a top of small dune with Brunic Arenosols, mid-dunal depression with Podzols and flat deflation niche with Arenosols affected by wind erosion. The fluvioglacial landscape will cover three locations on Brunic Arenosols, whereas moraine landscape three locations on moraine hills with Cambisols or Luvisols. Three soil profiles will be performed at each location, including CHR center, ditch and control. The soils will be described using the Food and Agriculture Organization (FAO) of the United Nations criteria (FAO, 2006), and classified according to the World Reference Base (WRB) system of the International Union of Soil Sciences Working Group (WRB, 2015). Then undisturbed and disturbed soil samples will be taken from distinguished horizons for further analysis. Laboratory analysis will cover a wide spectrum of physical and chemical characteristics, including particle-size distribution, bulk density, particle density, porosity, pH, total contents of elements (C, N, S, P, K, Ca, Mg, Fe, Al, Mn, Cu, Zn, Ni, Pb, Cr, Ti, Zr, Ba, Li, Sr), contents of "free" and amorphous Fe oxides and sorptive characteristics (exchange acidity, basic cations, cation exchange capacity). Moreover, sequential extraction of soil phosphorus will be performed for selected locations using the Hedley et al. (1982) procedure. A wide spectrum of analysis shall allow to define not only morphological changes clearly visible within the soils of CHRs, that have already been a subject of prior studies (Schmidt et al., 2016; Hirsch et al., 2017; Mastrolonardo et al., 2018), but also modifications in chemistry and eco-chemical state, as key factors affecting the functioning of forest vegetation. That aspect is poorly represented in the literature. Absolutely innovative will be the research on soil microbiome composition (bacterial and fungal community) based on DNA sequencing and toxicity of the relict CHR soils. Our studies will considerably expand the knowledge in the fields of widely understood soils science (soil genesis, soil-forming processes, soil evolution, soil biodiversity, soil contamination), forest ecology and landscape biogeochemistry. More effective and more sustainable management of soil resources in areas affected by historical charcoal production, as more utilitarian outcome of the project should be also expected.

WP6 uses written sources, archive maps, and cartographic material. The primary archival search (in both written and cartographic sources) will significantly supplement the results obtained from the paleoecological analysis. We will investigate economic materials demonstrating the scale of past exploitation of forest ecosystems. Furthermore, our research will be focused on the technological, social, and energy transformations that occurred in the late 18th and early 19th centuries. We are working on issues related to: (1) the question of forest settlement, (2) the development of forest management in the 19th century, and (3) the environmental consequences associated with increasing industrialization and modernization processes.

WP7 deals with the technical, scientific, administrative, and financial aspects of the project and its overall effective management.

Discussion

Synergy of paleoecological and historical research

Our transdisciplinary approach to the scientific question has allowed us to take a scholastic view of the research problems and opened up a whole new level of collaboration. Through joint events, frequent conversations, and intensive fieldwork, we are able to understand research workshops from other scientific disciplines in a better and deeper informed manner. The use of written sources in paleoecological research enables us to obtain a profound insight into past landscapes and their transformations (Latałowa et al., 2015; Samojlik et al., 2020; Słowiński et al., 2021). This contributes to filling in material gaps that can be bridged within a single discipline. Lacking written sources, paleoecological data serve to supplement history and vice versa. The effectiveness of this approach has been demonstrated, among others, by studies undertaken to date on Polish lake and peat bog sites (Lamentowicz et al., 2019; Czerwiński et al., 2021; Słowiński et al., 2021). The methodological solutions used in this project, however, go much further in revealing the environmental complexity of preindustrial charcoal production. To date, we have been able to link toponomastic relics to particular types of past forest industry (Słowiński et al., in rev.). This has contributed to a more in-depth understanding of the regionalization of production and the mechanisms behind forest product trade. Analysis of available written sources allowed to state that the environmental datasets used in the project may be integrated into a broader narrative context related to the raw material utility of forest products in the past. This would allow us to focus on the issues concerning Enlightenment empires' pattern of subjugation of nature in the late 18th and early 19th centuries (Blackbourn, 2007; Samojlik et al., 2020) and to connect the landscape changes of that time with the new patterns of forest management imposed by the partitioning states at the turn of the 18th and 19th centuries (Barański & Broda, 1965). This gives rise to new research questions primarily concerning silviculture of managed forests on Polish territories since the end of the 18th century and the deliberate practices to ensure that young trees reach felling age as soon as possible, which would allow obtaining the raw material necessary for charcoal firing.

CHRs constituted an important part of the economy in many areas during the Middle Ages and Early Modern times. Life in the preindustrial period was unimaginable without products such as charcoal, wood tar, oil tar, potash, and slime. Depending on whether the CHRs would be used for producing oil tar, coal, wood tar, turpentine, or potash, the following parameters were varied: a) the material used, b) the size of the hearths, and c) the production technique. Certain tree species were selected based on the product of interest, such as potash or tar. According to Augustyn (2000), about 30 kg of clean potash could be obtained from 1 m^3 of beech wood, which was a valued product and transported over vast distances before the 19th century. Usually, after the most mature trees had been used, woodland was left vacant in the sites occupied by the CHRs and huts inhabited by people engaged in this activity. These sites were often used for grazing. However, settlements were introduced there over time.

Biogenic sediments as a source of knowledge about the past

Peat and lake sediments are considered archives of past environmental changes all around the world. Therefore, high-resolution palaeoecological analyses of biogenic sediments are increasingly becoming common (e.g., Brauer & Casanova, 2001; Marcisz et al., 2015; Lamentowicz et al., 2016; Słowiński et al., 2016; Łuców et al., 2021; Bonk et al., 2022). Tobolski (2000) stated that ecological issues, especially paleoecological ones, devoted to Poland's lake and peat bog ecosystems are little known. However, in the last decade, there has been an increase in the number of works focusing on the reconstruction of environmental changes in northern Poland (Szal et al., 2014; Pędziszewska et al., 2015; Gałka et al., 2016; Wacnik et al., 2020; Poraj-Górska et al., 2021; Słowiński et al., 2021; Izdebski et al., 2022). Nonetheless, the functioning of lake and peatland, in particular associations between abiotic, biotic and human activities in these valuable ecosystems, is unclear (Tobolski, 2000). Paleoecological studies have shown that lake–peat ecosystems are sensitive indicators of deforestation, and their functioning is directly influenced by changes in the structure of vegetation (Warner et al., 1989; Lamentowicz et al., 2007; Łuców et al., 2021). Therefore, works on the perforation of forests during the functioning of "charcoal hearths", which anthropogenically deforested a large part of the direct catchments of selected objects (lake and peat bog), will aid in the comparison and analysis of this undeveloped process (Samojlik, Rotherham, et al., 2013; Straka, 2014; Dupin et al., 2017; Raab et al., 2019). Therefore, further research is needed to investigate how disturbances caused by human activities, which were undoubtedly a result of the formation of CHRs, have affected the functioning of ecosystems. There is still a lack of understanding of issues related to forest exploitation in the preindustrial period. This type of multidisciplinary research has not been undertaken before and in particular the effect of CHRs- and thus human activity – on the transformation of forest ecosystems in the period has been underestimated to date. Disturbances can alter the existing structure and function of an ecosystem, as well as cause changes in neighboring ecosystems through cascading effects (Kulakowski et al., 2011; Lamentowicz et al., 2019; Mroczkowska et al., 2021). Some disturbances can be beneficial to the ecosystems in rare cases when the right balance is achieved between the disturbance and the ecosystem's sustainability (Keane et al., 2002; Kershaw & Mallik, 2013; Dearing et al., 2015). Disorder of insufficient magnitude can decrease the diversity of an ecosystem, while events of greater intensity can completely change the trajectory of another ecosystem or even result in its extinction (Millar et al., 2007; Karavani et al., 2018). Eventually, disturbance may also influence productivity, which is directly associated with biodiversity (e.g. Dearing, 2006; Kirilenko & Sedjo, 2007; Birks et al., 2016).

We assume that the findings of our project will shed new light on the forest ecosystem's response to human impact and shall aid in developing a model describing the cascading significance of CHRs on ecosystem functioning. We aim to determine whether the consequences associated with the functioning of CHRs in the forest ecosystem were of a short-term nature or if they could lead to long-lasting changes in the ecosystem's trajectory. The possible impact on the ecosystem can be demonstrated by the large number of identified CHRs. Given their large spatial density in the studied area, we believe that CHRs had a remarkable impact on the functioning of the entire ecosystem, directly affecting the soil and vegetation structure both during and after their operation, and indirectly influencing other processes associated with these environmental components.

Recently, analytical and statistical works have been focusing on analyzing the data obtained from archeological and historical sources and ALS, as well as field, cartographic, and photogrammetric materials. The results will be useful to determine the spatial distribution of CHRs in NW Poland. Using advanced multidimensional statistical analyses, relation between the occurrence of CHRs and the variables of the natural environment (such as morphology, soil, potential vegetation, and the historical settlement network) will be determined. Based on the results of the statistical analyses, we will select three test areas differing from each other in terms of environmental parameters. Our findings will contribute to a more in-depth understanding of the environmental and historical context of CHRs. One may observe how these facilities, which served the basic energy needs of the protoindustry, significantly affected entire forest ecosystems (forest stands, soils, vegetation structure).

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