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

Michał Słowiński¹ • Krzysztof Szewczyk¹ • Jerzy Jonczak² • Tomasz Związek¹ • Dominika Łuców¹ • Agnieszka Halaś¹ • Milena Obremska³ • Sandra Słowińska¹ • Dominik Róg⁴ • Agnieszka Mroczkowska¹ • Agnieszka Maria Noryśkiewicz⁵ • Aleksandra Chojnacka⁶ • Tomasz Ważny⁷ • Barbara Gmińska-Nowak⁷ • Mateusz Kramkowski⁸ • Vincenzo Barbarino⁹ • Sebastian Tyszkowski⁸ • Bogusława Kruczkowska² • Anna Kowalska¹ • Ewa Kołaczkowska¹ • Paweł Swoboda¹⁰ • Cezary Kardasz¹¹ • Michał Niedzielski¹ • Michał Konopski¹ • Dariusz Brykała⁸

¹ Institute of Geography and Spatial Organization
Polish Academy of Sciences
Twarda 51/55, 00-818 Warsaw: Poland
e-mail: michał.slowinski@geopan.torun.pl
(corresponding author)

² Department of Soil Science
Warsaw University of Life Sciences
Nowoursynowska 159, 02-776 Warsaw: Poland

³ Institute of Geological Sciences
Polish Academy of Sciences
Twarda 51/55, 00-818 Warsaw: Poland

⁴ Institute of History
The John Paul II Catholic University of Lublin
Al. Racławickie 14, 20-950 Lublin: Poland

⁵ Institute of Archaeology
Nicolaus Copernicus University
Szosa Bydgoska 44/48, 87-100 Toruń: Poland

⁶ Department of Biochemistry and Microbiology
Warsaw University of Life Sciences
Nowoursynowska 159, 02-776 Warsaw: Poland

⁷ Centre for Research and Conservation of Cultural Heritage
Nicolaus Copernicus University
Sienkiewicza 30/32, 87-100 Toruń: Poland

⁸ Institute of Geography and Spatial Organization
Polish Academy of Sciences
Kopernika 9, 87-100 Toruń: Poland

⁹ Department of Agriculture, Food and Environment
University of Pisa, Italy

¹⁰ Institute of Polish Language
Polish Academy of Sciences
al. Mickiewicza 31, 31-120 Kraków: Poland

¹¹ Faculty of History
Nicolaus Copernicus University
ul. Bojarskiego 1, 87-100 Toruń: Poland
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 19th and 20th centuries (Łukasiewicz, 1977).

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.
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 (Zabko-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 (Ważyń & 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 (Ważyń & 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; Mastroionardo 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;
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 (CHR) 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 CHR 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](image-url)
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 km²). 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,
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 Lithhauen 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
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 (Ważyński, 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).
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. Onomastics 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,

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
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; Zierhoff & 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 m³ 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 palaeoecological 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). Palaeoecological 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).

**Acknowledgements**

The research was funded by the National Science Centre project, “Impact of charcoal production on environmental changes in Northern Poland – a novel ‘multi-proxy’ approach”. Project no. 2018/31/B/ST10/02498.

Editors’ note: Unless otherwise stated, the sources of tables and figures are the authors’, on the basis of their own research.
References

Augustyn, M. (2000). Wpływ produkcji potażu na stan lasów nad górnym Sanem i Solinką w XIX wieku. Roczniki Bieszczadzkie, 8, 325-332.

Bailie, M. G. L. (1982). Tree-ring dating and archaeology. London: Croom Helm. https://doi.org/10.4324/9781315746689

Bartczak, A., Słowińska, S., Tyszkowski, S., Kramkowski, M., Kaczmarek, H., Kordowski, J., & Słowiński, M. (2019). Ecohydrological changes and resilience of a shallow lake ecosystem under intense human pressure and recent climate change. Water, 11(1). https://doi.org/10.3390/w11010032

Bartlett, R. (1993). The making of Europe: Conquest, colonization and cultural change, 950-1350. London: Allen Lane.

Birks, H., Felde, V. A., & Seddon, A. W. (2016). Biodiversity trends within the Holocene. The Holocene, 26(6), 994-1001. https://doi.org/10.1177/0959683615622568

Blackbourn, D. (2007). The conquest of nature: Water, landscape and the making of modern Germany. London: Pimlica.

Bonhage, A., Hirsch, F., Schneider, A., Raab, A., Raab, T., & Donovan, S. (2020). Long term anthropogenic enrichment of soil organic matter stocks in forest soils – Detecting a legacy of historical charcoal production. Forest Ecology and Management, 459. https://doi.org/10.1016/j.foreco.2019.117814

Bonk, A., Słowiński, M., Żarczyński, M., Oliński, P., Kupryjanowicz, M., Fiłoc, M., & Tylmann, W. (2022). Tracking fire activity and post-fire limnological responses using the varved sedimentary sequence of Lake Jaczno, Poland. The Holocene, 32(6), 515-528. https://doi.org/10.1177/09596836221080755

Brauer, A., & Casanova, J. (2001). Chronology and depositional processes of the laminated sediment record from Lac d’Annecy, French Alps. Journal of Paleolimnology, 25(2), 163-177. https://doi.org/10.1023/a:1008136029735

Braun-Blanquet, J. (1964). Pflanzensoziologie, Grundzüge der Vegetationskunde. Springer-Verlag. https://doi.org/10.1007/978-3-7091-8110-2

Bridge, M. (2020). ELM Dendrochronology. Vernacular Architecture, 51(1), 94-102. https://doi.org/10.1080/03055477.2020.1794245

Broda, J. (2000). Historia leśnictwa w Polsce. Poznań: Wydawnictwo Akademii Rolniczej im. Augusta Cieszkowskiego.

Bronk Ramsey, C. (2001). Development of the radiocarbon calibration program. Radiocarbon, 43(2A), 355-363. https://doi.org/10.1017/S0033822200038212

Carrari, E., Ampoorter, E., Bottalico, F., Chirici, G., Coppi, A., Travaglini, D., Verheyen, K., & Selvi, F. (2017). The old charcoal kiln sites in Central Italian forest landscapes. Quaternary International, 458. https://doi.org/10.1016/j.quaint.2016.10.027

Carrari, E., Ampoorter, E., Bussotti, F., Coppi, A., Garcia Nogales, A., Pollastrini, M., Verheyen, K., & Selvi, F. (2018). Effects of charcoal hearth soil on forest regeneration: Evidence from a two-year experiment on tree seedlings. Forest Ecology and Management, 427, 37-44. https://doi.org/10.1016/j.foreco.2018.05.038

Chapin, F. S., Matson, P. A., & Vitousek, P. M. (2012). Principles of terrestrial ecosystem ecology. New York: Springer. https://doi.org/10.1007/978-1-4419-9504-9

Cogos, S., Östlund, L., & Rotorurier, S. (2019). Forest fire and indigenous Sami land use: Place names, fire dynamics, and ecosystem change in Northern Scandinavia. Human Ecology, 47(1), 51-64. https://doi.org/10.1007/s10745-019-0056-9

Cole, L. E., Bhagwat, S. A., & Willis, K. J. (2014). Recovery and resilience of tropical forests after disturbance. Nat Commun, 5, 3906. https://doi.org/10.1038/ncomms4906

Conedera, M., Vassere, S., Neff, C., Meurer, M., & Krebs, P. (2007). Using toponymy to reconstruct past land use: A case study of ‘brüsáda’ (burn) in southern Switzerland. Journal of Historical Geography, 33(4), 729-748. https://doi.org/10.1016/j.jhgc.2006.11.002
Czaja, R. (2008). Wykorzystanie energii w Starym Mieście Elblągu na początku XV. *Kwartalnik Historii Kultury Materialnej*, 56(3-4), 361-366.

Czerwiński, S., Guzowski, P., Lamentowicz, M., Gałka, M., Karpińska-Łołaczk, M., Poniat, R., Łokas, E., Diazza, A.-C., Schwarzer, J., Miecznik, M., & Kołaczek, P. (2021). Environmental implications of past socioeconomic events in Greater Poland during the last 1200 years. Synthesis of paleoecological and historical data. *Quaternary Science Reviews*, 259. https://doi.org/10.1016/j.quascirev.2021.106902

De Palma, A., Sanchez-Ortiz, K., Martin, P. A., Chadwick, A., Gilbert, G., Bates, A. E., Börger, L., Contu, S., Hill, S. L. L., & Purvis, A. (2018). Challenges with inferring how land-use affects terrestrial biodiversity: Study design, time, space and synthesis. In *Next Generation Biomonitoring: Part 1* (pp. 163-199). https://doi.org/10.1016/bs.aecr.2017.12.004

Dearing, J., Acma, B., Bub, S., Chambers, F., Chen, X., Cooper, J., Crook, D., Dong, X., Dotterweich, M., Edwards, M., Foster, T., Gaillard, M. J., Galop, D., Gell, P., Gil, A., Jeffers, E., Jones, R., Anupama, K., Langdon, P., ... & Zhang, K. (2015). Social-ecological systems in the Anthropocene: The need for integrating social and biophysical records at regional scales. *The Anthropocene Review*, 2(3), 220-246. https://doi.org/10.1177/2053019615579128

Dearing, J. A. (2006). Climate-human-environment interactions: Resolving our past. *Climate of the Past*, 2(2), 187-203. https://doi.org/10.5194/cp-2-187-2006

Dupin, A., Girardclos, O., Fruchart, C., Laplaige, C., Nuninger, L., Dufrasne, A., & Gauthier, E. (2017). Anthracology of charcoal kilns in the forest of Chailluz (France) as a tool to understand Franche-Comté forestry from the mid-15th to the early 20th century AD. *Quaternary International*, 458, 200-213. https://doi.org/10.1016/j.quaint.2017.03.008

Eckstein, D., Baillie, M. G. L., & Egger, H. (1984). *Dendrochronological Dating*. Strasbourg: European Science Foundation.

Edwards, M., Foster, T., Gaillard, M. J., Galop, D., Gell, P., Gil, A., Jeffers, E., Jones, R., Anupama, K., Langdon, P., ... & Zhang, K. (2015). Social-ecological systems in the Anthropocene: The need for integrating social and biophysical records at regional scales. *The Anthropocene Review*, 2(3), 220-246. https://doi.org/10.1177/2053019615579128

FAO. (2006). *Guidelines for soil description*.

Gałka, M., Tobolski, K., Görka, A., & Lamentowicz, M. (2016). Resilience of plant and testate amoeba communities after climatic and anthropogenic disturbances in a Baltic bog in Northern Poland: Implications for ecological restoration. *The Holocene*, 27(1), 130-141. https://doi.org/10.1177/0959683616652704

Gmińska-Nowak, B., D’Agostino, A., Özarslan, Y., Orsi, V., Christopoulou, A., Mazzoni, S., Akkemik, Ü., & Ważny, T. (2021). Dendrochronological analysis and radiocarbon dating of charcoal remains from the multi-period site of Uşaklı Höyük, Yozgat, Turkey. *Journal of Archaeological Science: Reports*, 38. https://doi.org/10.1016/j.jasrep.2021.103078

Górnowicz, H. (1977). O możliwości rekonstrukcji dawnego krajobrazu, flor i fauny na podstawie toponimii [On the possibility of reconstructing the former landscape, flora and fauna on the basis of toponyms]. *Poradnik Językowy*, 8, 337-344.

Haneca, K., Katarina, Č., & Beeckman, H. (2009). Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *Journal of Archaeological Science*, 36(1), 1-11. https://doi.org/10.1016/j.jas.2008.07.005

Hardy, B., Cornelis, J. T., Houben, D., Lambert, R., & Dufey, J. E. (2016). The effect of pre-industrial charcoal kilns on chemical properties of forest soil of Wallonia, Belgium. *European Journal of Soil Science*, 67(2), 206-216. https://doi.org/10.1111/ejss.12324
A novel multiproxy approach to detect the impact of charcoal production on the natural...
Kukulak, J. (2014). Charcoal in alluvium of mountain streams in the Bieszczady Mountains (Polish Carpathians) as a carrier of information on the local palaeoenvironment. *Geochronometria*, 41(3), 294-305. https://doi.org/10.2478/s13386-013-0155-0

Kulakowski, D., Bebi, P., Rixen, C. (2011). The interacting effects of land use change, climate change and suppression of natural disturbances on landscape forest structure in the Swiss Alps. *Oikos*, 120(2), 216-225. https://doi.org/10.1111/j.1600-0706.2010.18726.x

Kulumbegov, R. P. (2020). Toponymija kak istochnik svedenij o zemledel’cheskom byte Osetin [Toponymy as a source of information about the agricultural life of Ossetians]. *Vestnik Vladikavkazskogo nauchnogo centra*, 20(4), 53-57.

Kutrzeba, S., Duda, F. (1915). *Regestra thelonei aquatici Wladislaviensis: saeculi XVI*. Nakładem Akademii Umiejętności.

Lamentowicz, M., Kołaczek, P., Mauquoy, D., Kittel, P., Łokas, E., Słowiński, M., Jassey, V. E. J., Niedziółka, K., Kajuka-Drygalska, K., & Marcisz, K. (2019). Always on the tipping point – A search for signals of past societies and related peatland ecosystem critical transitions during the last 6500 years in N Poland. *Quaternary Science Reviews*, 225. https://doi.org/10.1016/j.quascirev.2019.105954

Lamentowicz, M., Marcisz, K., Guzowski, P., Gątka, M., Diaconu, A.-C., & Kołaczek, P. (2020). How Joannites’ economy eradicated primeval forest and created anthroecosystems in medieval Central Europe. *Scientific Reports*, 10(1), 1-13. https://doi.org/10.1038/s41598-020-75692-4

Łuców, D., Küttim, M., Słowiński, M., Kołaczek, P., Łokas, E., Marcisz, K., Obremska, M., Tyszkowski, S., & Słowiński, M. (2021). Pine forest management and disturbance in Northern Poland: Combining high-resolution 100-year-old paleoecological and remote sensing data. *Frontiers in Ecology and Evolution*, 9. https://doi.org/10.3389/fevo.2021.747976

Łukasiewicz, J. (1977). Drogi rozwoju rolnictwa na ziemiach polskich. In S. Kieniewicz (Ed.), *Konfrontacje historyczne. Polska XIX wieku. Państwo, społeczeństwo, kultura* (pp. 13-55). Wiedza Powszechna.
Marszałek, E., & Kusiak, W. (2013). Wypał węgla drzewnego w Bieszczadach w przeszłości i obecnie. *Roczniki Bieszczadzkie, 21*, 164-183.

Mastrodonardo, G., Francioso, O., & Certini, G. (2018). Relic charcoal hearth soils: A neglected carbon reservoir. Case study at Marsiliana forest, Central Italy. *Geoderma, 315*, 88-95. https://doi.org/10.1016/j.geoderma.2017.11.036

Miles, D. (1997). The interpretation, presentation and use of tree-ring dates. *Vernacular Architecture, 28*(1), 40-56. https://doi.org/10.1179/030554797786050563

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications, 17*(8), 2145-2151. https://www.ncbi.nlm.nih.gov/pubmed/18213958

Mastrolonardo, G., Francioso, O., & Certini, G. (2018). Relic charcoal hearth soils: A neglected carbon reservoir. Case study at Marsiliana forest, Central Italy. *Geoderma, 315*, 88-95. https://doi.org/10.1016/j.geoderma.2017.11.036

Miles, D. (1997). The interpretation, presentation and use of tree-ring dates. *Vernacular Architecture, 28*(1), 40-56. https://doi.org/10.1179/030554797786050563

Mroczkowska, A., Kittel, P., Marcisz, K., Dolbunova, E., Gauthier, E., Lamentowicz, M., Mazurkevich, A., Obremksa, M., Płocieński, M., Kramkowski, M., Łuców, D., Kublitskiy, Y., & Stawiński, M. (2021). Small peatland with a big story: 600-year paleoecological and historical data from a kettle-hole peatland in Western Russia. *The Holocene, 31*(11-12). https://doi.org/10.1177/09596836211033224

Müller, F., Baessler, C., Schubert, H., & Klotz, S. (Eds.) (2010). *Long-term ecological research*. Springer Dordrecht Heidelberg London New York, 10(1007). https://doi.org/10.1007/978-90-481-8782-9

Pearson, G. W. (1986). Precise calendrical dating of known growth-period samples using a “curve fitting” technique. *Radiocarbon, 28*(2A), 292-299. https://doi.org/10.1017/S0033822200007396

Poraj-Górska, A. I., Bonk, A., Żarczyński, M., Kinder, M., & Tylmann, W. (2021). Varved lake sediments as indicators of recent cultural eutrophication and hypolimnetic hypoxia in lakes. *Anthropocene, 36*. https://doi.org/10.1016/j.ancene.2021.100311

Rinn, F. (2011). *TSAP – Time Series Analysis and Presentation for Dendrochronology and related applications. Version 4.64 for Microsoft Windows – User Reference*. Heidelberg, Germany.

Raab, A., Bonhage, A., Schneider, A., Raab, T., Räslér, H., Heuußer, K. U., & Hirsch, F. (2019). Spatial distribution of relict charcoal hearths in the former royal forest district Tauer (SE Brandenburg, Germany). *Quaternary International, 511*, 153-165. https://doi.org/10.1016/j.quaint.2017.07.022

Raab, A., Takla, M., Raab, T., Nicolay, A., Schneider, A., Räslér, H., Heuußer, K. U., & Bönisch, E. (2015). Pre-industrial charcoal production in Lower Lusatia (Brandenburg, Germany): Detection and evaluation of a large charcoal-burning field by combining archaeological studies, GIS-based analyses of shaded-relief maps and dendrochronological age determination. *Quaternary International, 367*, 111-122. https://doi.org/10.1016/j.quaint.2014.09.041

Rinn, F. (2011). *TSAP – Time Series Analysis and Presentation for Dendrochronology and related applications. Version 4.64 for Microsoft Windows – User Reference*. Heidelberg, Germany.
Szal, M., Kupryjanowicz, M., Wyczółkowski, M., & Tylmann, W. (2014). The Iron Age in the Mrągowo Lake District, Masuria, NE Poland: The Salęt settlement microregion as an example of long-lasting human impact on vegetation. *Vegetation History and Archaeobotany, 23*(4), 419-437. https://doi.org/10.1007/s00334-014-0465-z

Szewczyk, K., Hałaś, A., Tyszkowski, S., Łuców, D., Jonczak, J., Mroczkowska, A., Kruczkowska, B., Związek, T., Brykała, D., & Słowiński, M. (2021). Charcoal hearths – mapping and spatial distribution in northern Poland. In *AGU Fall Meeting Abstracts* (Vol. 2021, pp. PP35D-1018).

Thom, D., & Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological Reviews, 91*(3), 760-781. https://doi.org/10.1111/brv.12193

Tobolski, K. (2000). *Przewodnik do oznaczania torfów i osadów jeziornych*. Warszawa: Wydawnictwo Naukowe PWN.

Wacnik, A., Gumiński, W., Cywa, K., & Bugajska, K. (2020). Forests and foragers: Exploitation of wood resources by Mesolithic and para-Neolithic societies in north-eastern Poland. *Vegetation History and Archaeobotany, 29*, 717-736. https://doi.org/10.1007/s00334-020-00778-y

Warde, P. (2006). Fear of wood shortage and the reality of the woodland in Europe, c.1450-1850. *History Workshop Journal, 62*(1), 28-57. https://doi.org/10.1093/hwj/dbl009

Warde, P., & Williamson, T. (2014). Fuel supply and agriculture in post-medieval England. *The Agricultural History Review, 62*(1), 61-82. http://www.jstor.org/stable/43697953

Warner, B. G., Kubiw, H. J., & Hanf, K. I. (1989). An anthropogenic cause for quaking mire formation in southwestern Ontario. *Nature, 340*(6232), 380-384. https://doi.org/10.1038/340380a0

Ważyński, T. (1991). *Dendrochronologia obiektów zabytkowych w Polsce*. Gdańsk: Muzeum Archeologiczne w Gdańsku.

Ważyński, T., & Eckstein, D. (1987). Der Holzhandel von Danzig/Gdańsk—Geschichte, Umfang und Reichweite. *Holz als Roh- und Werkstoff, 45*(12), 509-513. https://doi.org/10.1007/bf02611458

Whitlock, C., Colombaroli, D., Conedera, M., & Tinner, W. (2018). Land-use history as a guide for forest conservation and management. *Conservation Biology, 32*(1), 84-97. https://doi.org/10.1111/cobi.12960

Williams, M. (2000). Dark ages and dark areas: Global deforestation in the deep past. *Journal of Historical Geography, 26*(1), 28-46. https://doi.org/10.1006/jhge.1999.0189

WRB, I. W. G. (2015). *World Reference Base for Soil Resources 2014: International soil classification system for naming soils and creating legends for soil maps. Update 2015*. World Soil Resources Reports, (106). Rome: Food and Agriculture Organization.

Zientara, B.-P. (1954). *Dzieje małopolskiego hutnictwa zelaznego XIV–XVII*. Państwowe Wydawnictwo Naukowe.

Zierhoffer, K., & Zierhofferowa, Z. (2008-2009). Refleksy gospodarki żarowej w polskim nazewnictwie. *Onomastica*, 53, 93-117.

Żabko-Potopowicz, A. (1954). Zagadnienie lasów w Polsce przed rozbiorami od schyłku XV do połowy XVIII wieku. *Sylwan*, 98*(5), 363-388.

Żabko-Potopowicz, A. (1972). *Las w dziejach Polski przedrozbiorowej*. Warszawa: Szkola Glosna Gospodarstwa Wiejskiego.