Spatial and temporal patterns in Neolithic and Bronze Age agriculture in Poland based on the stable carbon and nitrogen isotopic composition of cereal grains.

Aldona Mueller-Bieniek[1], Marek Nowak[2], Amy Styring[3], Maria Lityńska-Zając[4], Magdalena Moskal-del Hoyo[1], Agnieszka Sojka[1], Beata Paszko[1], Krzysztof Tunia[4], Amy Bogaard[5]

[1] W. Szafer Institute of Botany, Polish Academy of Sciences, Lubicz St. 46, 31-512 Kraków, Poland
[2] Institute of Archaeology, Jagiellonian University, Gołębia St. 11, 31-007 Kraków, Poland
[3] Abteilung III: Vor- und Frühgeschichte, Institut für Archäologische Wissenschaften, Sprach- und Kulturwissenschaften Fachbereich 09, Goethe-Universität Frankfurt, Frankfurt am Main, Germany
[4] Institute of Archaeology and Ethnology, Polish Academy of Sciences, Sławkowska St. 17, 31-016 Kraków, Poland
[5] School of Archaeology, 36 Beaumont Street, University of Oxford, Oxford, UK

Corresponding author: A. Mueller-Bieniek, a.mueller@botany.pl

Abstract

In this study the stable nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) isotopic compositions of carbonised cereal grains from 18 archaeological sites in Poland, dating from the Early Neolithic to the turn of the Bronze Age and the Iron Age, were determined. There were two main aims of this study. The first aim was to test the archaeologically accepted model of a change from intensive 'horticulture' in the Early Neolithic in Lesser Poland to more extensive cultivation in the Middle Neolithic, which is expected to be evidenced by decreasing levels of manuring and labour input, reflected especially in a shift to lower cereal grain $\delta^{15}N$ values. The second aim was to assess how cereal grain $\delta^{13}C$ values reflect crop watering conditions and landscape openness regionally and through time. Despite the limited plant material, the study showed that all cereal plots potentially received some inputs of manure (including household waste), but there seems to be a clear regional difference in the intensity of manuring practice in the Early Neolithic, with greater manure application on plots in southern Poland than in northern Poland. Moreover, cereal plots in southern Poland in the Early Neolithic seem to have been located on soils with higher water retention and/or within denser vegetation than plots in northern Poland. In the Middle Neolithic, however, plots in southern Poland seemed to have expanded into areas with lower water availability or that were more open, supporting the evidence from former archaeological interpretations that agriculture spread into different, usually elevated areas at this time.

Key words: carbon isotopes; nitrogen isotopes; cereals; agriculture; Neolithic

1. Introduction

Reconstructions of early plant husbandry practices are mostly based on studies of archaeobotanical macro-remains and weed ecology (Bogaard, 2004; Jones et al., 2010, 2000; Kreuz and Schäfer, 2011; Wasylikowa, 1989). The value of archaeobotanical data, i.e. the taxonomic composition of plant assemblages, their ecological and economic interpretation, as well as physical analysis of the plant remains, is still not sufficiently exploited in studies of past societies and landscape development. The current data show some general trends but it is clear that there was considerable local and temporal diversity in subsistence strategies, including both intensive garden-like cultivation on permanent plots and potentially more extensive cultivation with use of fallowing, grazing and burning in different parts of the landscape (Bogaard et al., 2016, 2013; Ehrmann et al., 2014; Fraser et al., 2011; Jacomet et al., 2016; Kowalska-Lewicka, 1961; McClatchie, 2014; Rösch et al., 2014; Styring et al., 2017, 2016).

In the last decade the stable carbon and nitrogen isotopic composition of plant remains has been used to identify the intensity of agriculture practices, including manuring and crop water status, thus allowing insights into the type of cultivation, ecological conditions and – indirectly – possible changes in landscape (Bogaard et al., 2016, 2013; Fraser et al., 2011; Styring et al., 2017, 2016). Experimental studies have shown a significant increase in the nitrogen isotope ($\delta^{15}N$) values of cereal grains (similar in both wheat and barley) grown in intensively manured fields compared with unmanured ones (Bogaard et al., 2007; Fraser et al., 2011). High $\delta^{15}N$ values of Neolithic grains, as well as the ecological properties of weed spectra accompanying Neolithic crops, suggest that crops were grown under intensive garden-type conditions at many sites across Europe (Bogaard, 2004; Bogaard et al., 2016, 2013). Studies of the stable N isotopic composition of plants growing in forested areas also indicate a significant increase in ^{15}N concentration in the first few years following clearance of vegetation by fire (Szpak, 2014), but cereals grown on plots in recently cleared forest were still found to have markedly *low* $\delta^{15}N$ values (< 1‰; Styring et al., 2017), despite clearance by burning. Some palaeoecological analysis and experimental data point to the potential importance of shifting cultivation with the use of fire (slash-and-burn) in the Neolithic of central Europe (Ehrmann et al., 2014; Rösch et al., 2017, 2014), though this is contested (Jacomet et al., 2016). Additionally it must be mentioned that human-induced fires were observed in the Central European Lowlands since Mesolithic times through sedimentary charcoal composites and pollen analyses (Dietze et al., 2018).

It is known that the carbon isotope ($\delta^{13}C$) values of plant tissues are strongly influenced by their photosynthetic pathway. The majority of plants in temperature Europe, including the most important cultivars wheats and barley, follow the C_3 photosynthetic pathway. Where water is the main limit on photosynthetic rate, C_3 crop $\delta^{13}C$ values can reflect their water status and thus the availability of water, which could be influenced by the amount of rainfall as well as the water-holding capacity of the soil (e.g. Farquhar and Richards, 1984). Light intensity can also influence the assimilation of carbon dioxide, with plants growing under dense canopies having relatively low $\delta^{13}C$ values (Bonafini et al., 2013; Broadmeadow and Griffiths; 1993; Tieszen, 1991). Crop $\delta^{13}C$ values therefore offer the possibility of identifying the cultivation of crops in locations with distinct environmental conditions (e.g. Fraser et al., 2013).

The aim of this paper is to present new stable carbon and nitrogen isotopic data originating from crop samples derived from Polish Neolithic and Bronze/Early Iron Age sites and to contextualize these within a background of archaeological and environmental data. The large spatial and temporal span of the material presented here makes it possible to investigate some general trends in the changes in plant isotopic composition, which should reflect differences in growing conditions characterised by manuring intensity and water availability/light intensity.

The main objectives to be addressed using the isotopic data are:

1) to test the archaeologically accepted model for the region, especially for Lesser Poland (Kruk, 1980a; Kruk and Milisauskas, 1999), of a change in cultivation strategy from an intensive, garden-like type in the Early Neolithic to a more extensive type postulated for the Middle Neolithic. We expect that this would be associated with decreasing levels of manuring and labour input, reflected especially in a shift to lower cereal grain $\delta^{15}N$ values; and

2) to assess how cereal grain $\delta^{13}C$ values reflect crop water conditions and landscape openness regionally and through time.

2. Archaeological background

In this paper we compare data from two large geographical areas: north central Poland (mostly Kuyavia, *Kujawy* in Polish) and southeast Poland (Lesser Poland, *Małopolska* in Polish) (Fig. 1). The samples date to the Neolithic: the Linear Band Pottery culture (LBK), the Lengyel-Polgár complex (L-PC), the Funnel Beaker culture (TRB), the Baden culture, the Bronze Age: the Trzciniec culture, the Otomani-Füzesabony culture, and the Bronze/Early Iron Age: the Lusatian culture (LC), which in the routine research practice of northeast Central Europe is considered to be one cultural phenomenon spanning these two ages (Table 1).

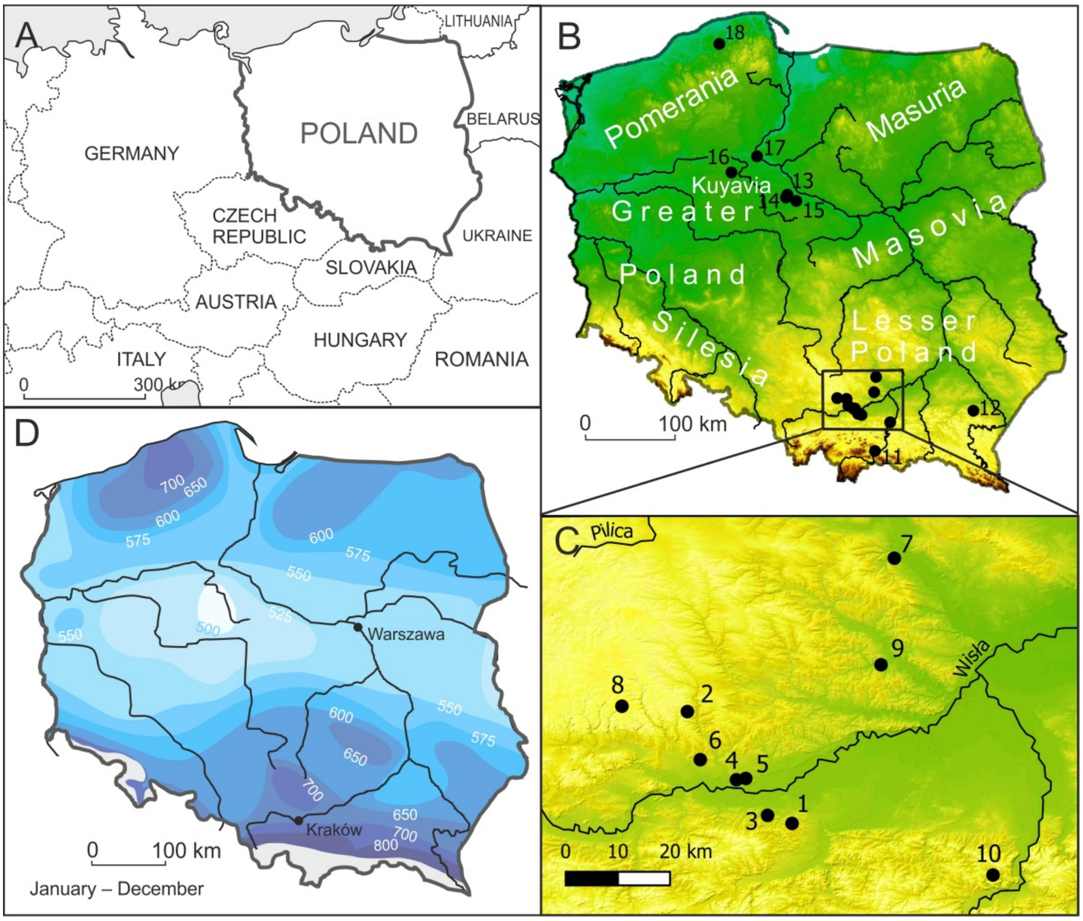

Fig. 1. Location of the studied sites (**A-C**); numbering of sites as in Table 2; **D** annual precipitation, mean in period of 1961-1995 (after Koźmiński, 2001).

The sites are listed in Table 2 and description of the sites and every studied feature context are given in Tables S1 and S2. Simplified archaeobotanical information is given in Table S3 and detailed archaeobotanical data in Tables S4-S7. Descriptive characteristics of the studied sites listed according to the side codes are given in Supplementary Text 1.

2.1. Southern Poland

The oldest Neolithic sites in southern Poland are located in Lower Silesia (*Dolny Śląsk* in Polish) and Lesser Poland (Lityńska-Zając, 2007), but in our study we have focused on data derived from the latter region. In Lesser Poland crop cultivation is known from the beginning of the Neolithic (the LBK), with several sites yielding numerous, well preserved emmer (*Triticum dicoccum*) and einkorn (*T. monococcum*) grains and their chaff remains (Lityńska-Zając et al., 2017a). These hulled wheats were most probably cultivated as a mixture (Lityńska-Zając, 2018). Barley (*Hordeum vulgare*) was less common, probably playing a marginal role in the diet. This oldest horizon was represented by a few archaeobotanical assemblages (Table 2, Tables S1-S2). The most spectacular find dated to the L-PC was pit 416 from Kraków Nowa Huta-Mogiła site 62, where whole charred spikelets of emmer, einkorn and naked barley (*Hordeum vulgare* var *nudum*), accompanied by several wild plants, including both annual weeds and perennials (*Centaurea jacea, Plantago media* and *Potentilla reptans*), were noted (Gluza, 1984). Unfortunately the material was not accessible for our isotopic studies. Despite the L-PC being archaeologically rather well represented in Lesser Poland, for our study we were able to get access to only two samples of emmer grains dated to that period. One sample came from the site of Zakrzowiec, spanning multiple cultures, and the second from Jerzmanowice (Nietoperzowa Cave, located in the karst valley of Dolina Będkowska, carved from Jurassic limestone).

Archaeological units	approximate dating (cal. BC)	
	southern Poland	northern Poland
Early Neolithic	5400-3700	5350-4000
Linear Pottery culture (LBK)	5400-4800	5350-4800
Lengyel Polgar complex (L-PC)	4800-3700	4800-4000
Middle Neolithic	3800-2800	4000-2600
Funnel Beaker culture (TRB)	3800-3000	4000-2500
Baden culture	3200-2900	
Bronze Age	2300-800	2300-800
Trzciniec culture	1800-1100	1800-1100
Otomani-Füzesabony culture	1900-1500	
Lusatian culture (LC)	1300-800	1200-800
Early Iron Age	800-400	800-400
Lusatian culture (LC)	800-400	800-400

Table 1. Simplified periodisation of Neolithic and Bronze/Early Iron Age archaeological units mentioned in the paper

The next, Middle Neolithic, horizon produced several grain samples comprising both pure emmer and einkorn grain storage deposits excavated decades ago in Kraków and in the zone of the upper Vistula valley (Kraków Prądnik Czerwony, Kraków Mogiła, Kraków Pleszów), as well as some 'pilot' samples obtained from the recently studied site of Mozgawa 1-3, located next to the Nida valley (Moskal-del Hoyo et al., 2018), which gave a lot of scattered grains of emmer.

Site code	Site	Region	Archaeological categorisation[1]	General time-frames (cal. BC)[2]	References
1	Brzezie 17	western Lesser Poland	Early Neolithic, LBK	5400-4900	Czekaj-Zastawny 2014; Lityńska-Zając et al. 2014
2	Iwanowice-Klin	western Lesser Poland	Early Neolithic, LBK	5200-4900	Czekaj-Zastawny 2008; Lityńska 1990,; Lityńska-Zając 2005; 2007; Machnikowie, Kaczanowski 1987
3	Zakrzowiec 6/8	western Lesser Poland	Early Neolithic, L-PC (Pleszów-Modlnica group)	*4600-4300*	Jarosz et al. 2012
4	Kraków-Mogiła 62	western Lesser Poland	Middle Neolithic, TRB	3600-3300	Gluza i in. 1988; Godłowska, Gluza 1989; Kluzik 2010; Kapcia and Mueller-Bieniek 2018
5	Kraków-Pleszów 17-20	western Lesser Poland	Middle Neolithic, Baden	*3200-2900*	Bielenin 1959; Gluza et al. 1988; Godłowska 1976; Rook 1971
6	Kraków-Prądnik Czerwony	western Lesser Poland	Middle Neolithic, TRB	3600-3100	Lityńska-Zając 2005; 2007; Rook, Nowak 1993
7	Mozgawa 1-3	western Lesser Poland	Middle Neolithic, TRB	3600-3000	Moskal-del Hoyo et al. 2018; Kotynia 2016; Mueller-Bieniek and Kapcia unpubl.
8	Jerzmanowice	western Lesser Poland	Early Neolithic, L-PC (Pleszów-Modlnica group)	4500-4300	Rook 1980; Wasylikowa unpubl.
9	Słonowice G	western Lesser Poland	Bronze Age, Trzciniec culture	1700-1200	Calderoni et al. 2000; Tunia 1985; Lityńska-Zając unpubl.
10	Gwoździec 2	southern Lesser Poland (Carpathians)	Early Neolithic, LBK	5400-5100	Bieniek, Lityńska-Zając 2001; Kukułka 1997; 2000; 2001; Lityńska-Zając 2007; Lityńska-Zając et al. 2017
11	Maszkowice 1	southern Lesser Poland (Carpathians)	Bronze Age, Otomani-Füzesabony culture	1800-1600	Cabalska 1974; 1975; 1977; Przybyła 2016; Przybyła, Skoneczna 2014

12	Lipnik 5	south-eastern Lesser Poland	Bronze Age, Trzciniec culture	1400-1200	Blajer, Przybyła 2006; Bieniek 2008; Blajer 2009; Przybyła, Blajer 2008; Kapcia and Mueller-Bieniek 2018
13	Miechowice 4	Kuyavia	Early Neolithic, L-PC (Brześć Kujawski group)	4500-4000	Bieniek 2002; 2003; 2007; Grygiel 2008; Mueller-Bieniek et al. 2016; Mueller-Bieniek et al. 2018
14	Osłonki 1	Kuyavia	Early Neolithic, L-PC (Brześć Kujawski group)	4500-4000	Bieniek 2002; 2003; 2007; Grygiel 2008
15	Ludwinowo 7	Kuyavia	Bronze/Early Iron Age, LC	*1300-400*	Pyzel 2012; Sobkowiak-Tabaka, Kabaciński 2012; Mueller-Bieniek unpubl.
16	Sobiejuchy	Pałuki	Early Iron Age, LC	800-450	Harding et al. 2004; Harding, Rączkowski 2010; Palmer 2004
17	Kamieniec	Chełmno Land	Early Iron Age, LC	700-400	Delekta 1937; 1938; Gackowski 2012; Tomczyńska, Wasylikowa 1988; Zielonka 1955
18	Poganice 4	eastern Pomerania	Middle Neolithic, TRB	3900-2500	Jankowska 1980; Luijten 1995; Wierzbicki 1995; 1999; Wasylikowa unpubl.

Table 2. Archaeological sites. More detailed data, including archaeobotanical context, are given in ESM (S1 and S7). [1] These data refer to the context of the sample from which isotope values were obtained (i.e. some of the sites were occupied in different prehistoric and early historic periods); [2] dates are based on absolute dating and other evidence from the site itself, i.e. they present the most probable timeframes of site occupation. Dates in *italic* are based on data external to the site, i.e. they rather present possible dates between which occupation of the site could have taken place

Despite the fact that barley (*Hordeum vulgare*) was noted from the beginning of the Neolithic in the Lesser Poland region, the only samples accessible for our study are dated to the Bronze Age (from Słonowice G and Maszkowice). At that time millet (*Panicum miliaceum*) also began to be cultivated and one sample of this summer crop was selected from the site of Lipnik (Kapcia and Mueller-Bieniek, 2019). Spelt (*Triticum spelta*) was also found at Lipnik dating to this time period, in numbers allowing its selection for isotopic studies. The sites of Lipnik and Maszkowice are located in the Carpathian mountains or their foothills (Lityńska-Zając et al., 2017b). In the Lesser Poland region no samples dated to the Lusatian culture were selected.

2.2. Northern Poland

In northern Poland archaeobotanical data from several Neolithic sites from the Kuyavia region are available. However, here there is very little evidence of crop cultivation during the LBK, in contrast to later evidence from the Brześć-Kujawski group of the L-PC. All of the studied Neolithic grain samples from Kuyavia therefore come from features dated to the Brześć-Kujawski group of the L-PC as only very few badly preserved crop grains were found in features dated to the LBK (Bieniek, 2007; Mueller-Bieniek, 2016; Mueller-Bieniek et al., 2018a, 2016). It is worth mentioning that this region, situated in the North European Plain and relatively densely settled by LBK and L-PC communities, is located on the northern margins of the Early Neolithic occupation of East-Central Europe. In fact it constitutes a geographically isolated enclave, away from more southern 'loess' ecological zones. Archaeobotanical data coming from LBK features are dominated by seeds of fat hen (*Chenopodium album* type) but some remains of hulled wheats were also noted, including the new type of glume wheat (NGW) (Mueller-Bieniek et al., 2018a).

According to some views (Grygiel, 2008), which oppose those of e.g. Nalepka (2005), the L-PC developed after a ca. 300 hundred year regional depopulation and wheat cultivation was then successful, evidenced by several finds of grains and chaff of emmer, einkorn and NGW. No remains of Neolithic barley (*Hordeum vulgare*) have been noted; the grains obtained from the site of Osłonki appeared to be much younger according to radiocarbon dating (2200 ± 30 BP, Poz-72390, 6 grain fragments from pit 116). The L-PC horizon was distinctive in terms of the abundance of feather grass remains (*Stipa* sp.), a plant typical of xerothermic grassland, and probably also a very useful plant (Bieniek, 2002; Bieniek and Pokorny, 2005), sometimes used as an indicator of open landscape even when not numerous (Moskal-del Hoyo et al., 2018, 2017). *Stipa* was very rare in the earlier, LBK, period in Kuyavia and absent in younger samples (Mueller-Bieniek et al., 2018b). During the L-PC, numerous remains of NGW were also found, dominating the wheat chaff remains. *Stipa* sp. indicate dry environmental conditions, at least locally.

The Middle Neolithic archaeobotanical remains of the TRB from this area are represented by much fewer data (Bieniek, 2007, 2002; Mueller-Bieniek, 2016; Mueller-Bieniek et al., 2016). In more northern Poland (Pomerania, *Pomorze* in Polish) a separate sample of emmer from a TRB site in Poganice was also studied; the site is located ca. 20 km from the shore of the Baltic Sea.

Recently studied sites dated to the Bronze Age, from which material would be easily accessible for our research, usually did not give sufficient, well-preserved crop grains (Mueller-Bieniek, 2011; Mueller-Bieniek et al., 2016, 2015). However, in the studied region of Kuyavia and western Greater Poland (*Wielkopolska* in Polish), storage deposits of charred cultivated plants from fortified sites of the Lusatian culture were noted (Kamieniec, Sobiejuchy and probably not fortified Ludwinowo). At that time emmer and spelt were common as well as barley and pulses (*Pisum sativum, Lens culinaris, Vicia faba*) (Palmer, 2004; Tomczyńska and Wasylikowa, 1988). We only carried out a pilot study of cereals found at those sites to compare with older, Neolithic samples from the area.

3. Environmental characteristics of regions

3.1. Climate

The studied sites experience relatively similar temperatures. The greatest differences in temperature are between southwest Poland (Wrocław) and northeast Poland (Suwałki), but our data originate from sites located in a belt between these areas that is characterized by relatively consistent conditions (Koźmiński and Michalska, 2001a). Between 1961 and 1995, the monthly mean temperature for January-December was 7.5-8 °C with an annual amplitude of 20-21 °C (Michalska, 2001). The number of days with snow cover during November-March depends on the thickness of the snow layer. In southern Poland there are more days with a thin snow layer (up to 5 cm) but the number of days when at least 10 cm of snow covers the ground is similar across the whole study area (Czarnecka, 2011; Koźmiński and Michalska, 2001a). The exception is the sub-mountainous area (sites of Maszkowice and Gwoździec) and Pomerania (site of Poganice), where more days with snow cover are noted in general. However the site of Maszkowice has a specific local microclimate, generally milder than the surrounding mountains and river valley (Przybyła et al., 2012). The farming season (ca. 245 days per year with temp. > 3 °C), as well as the growing season (ca. 220 days with temp. > 5 °C), are also similar for the whole studied area.

The more notable differences between the southern and northern regions are the amount of insolation and precipitation. Actual insolation is higher in the northern area by about 100 hours: 1600-1650 hours in Kuyavia compared to 1450-1550 hours in southern Poland (January-December between 1966 and 1995)(Koźmiński and Michalska, 2001b). Similar differences are also visible in the summer months global radiation (April-September 1976-1995) (Podogrocki, 2001). Summer precipitation is generally higher in the southern regions (>400 mm in April-September), especially in the sub-mountainous area (450-550 mm), than in Kuyavia (<350 mm). The differences are higher when annual rainfall is taken into account (Fig. 1D). In Pomerania, water availability is similar to the southern uplands. Annual precipitation (1961-1995) is also notably lower in the belt of lowlands in central Poland. Kuyavia is the driest part of Poland where annual precipitation does not exceed 525 mm, while in Lesser Poland it is greater than 650 mm per year, similar to the Pomerania region around the site of Poganice (Koźmiński, 2001).

3.2. Soils

In Poland a patchwork of diverse soil types is noted (Bednarek and Prusinkiewicz, 1999; Kondracki, 2000; "Soil Atlas of Europe - ESDAC - European Commission," 2005). In general the first farmers chose the most fertile soils, which comprise Haplic Phaeozem (Chernozems) and Cambisols (brown earths) developed on loess in southern Poland and Stagnic Phaeozem (black soils) in Kuyavia. In southern Poland Rendzic Leptosols (rendzinas), as well as relatively fertile Eutric Cambisols, were also targeted and used from the beginning of the Neolithic. In the whole study area less fertile soils (Podsols, Arenosols, Luvisols) are also noted, covering large areas. Additionally in the mountains Umbrisols are present, while river beds (valleys) in the whole area are covered by fertile Calcaric Fluvisols and Eutric Histosols. While most of the studied Neolithic sites are located on fertile soils, the Bronze Age sites and the Early Iron Age sites are located both in areas with mainly fertile (Słonowice, Ludwinowo) or mainly poor soils (Lipnik, Maszkowice, Sobiejuchy, Kamieniec). Nonetheless, patches of fertile soils, usually Fluvisols, are noted in the vicinity of most of the studied sites (e.g. Przybyła and Skoneczna, 2014).

3.3. Potential vegetation

The archaeological sites are located in diverse regions of lowlands, uplands and mountains that belong to the region of European woodlands (broad-leaved and mixed forests) (Matuszkiewicz, 1993). They represent five different basic units of the geobotanical division of Poland, which are described and characterized in terms of the potential natural vegetation, mostly as plant associations (Table S1; after Matuszkiewicz, 2008). The type of potential natural vegetation reflects the recent environmental conditions of the described areas, not a primeval vegetation or vegetation that was present in prehistoric times, but vegetation which would have developed in the absence of human activity, based on the taxa currently present in the flora (Milisauskas et al., 2012).

The majority of sites (no. 1-9) are located in the Divide of South Polish Uplands, where various forms of subcontinental oak-hornbeam forests (Tilio-Carpinetum) dominate. Thermophilous oak forests (Potentillo albae-Quercetum) and mesic acidophilous oak-forests (Luzulo luzuloides-Quercetum) are also present, as well as oak-pine forests (Querco-Pinetum) and pine forests (Leucobryo-Pinetum). In some areas (no. 7-8), patches of xerophilous vegetation of the order Festucetalia valesiacae may be found. Other types of woodlands play a lesser role, such as beech forest (Dentario glandulosae-Fagetum). Three sites are located in the Carpathian Geobotanical Divide (no. 10-12). In the foothills zone, mesic acidophilous oak-forests (Luzulo luzuloides-Quercetum) and rich submontane oak-hornbeam forests (Tilio-Carpinetum) could develop. The latter is also typical for the area of the Łącko valley (no. 11, Maszkowice), but in surrounding areas montane beech forests (Dentario glandulosae-Fagetum) and fir-spruce forests (Abieti-Piceetum) predominate.

Four sites (no. 13-16) are located in the Brandenburg-Wielkopolski Divide of the Middle European lowlands. The dominant woodlands include oak-hornbeam forests (Galio-Carpinetum and Tilio-Carpinetum), subcontinental fresh pine forests (Peucedano-Pinetum) and oak-pine forests (Pino-Quercetum), while other types have a lower contribution (i.e. Potentillo albae-Quercetum). Rich subcontinental oak-hornbeam forests (Tilio-Carpinetum) would be the most widespread near Poganice, located in the Pomeranian Geobotanical Divide (no. 18), while forests dominated by pine and oak (Peucedano-Pinetum and Pino-Quercetum) developed near Kamieniec in the Masovio-Polesian Geobotanical Divide (no. 17). Close to the all sites, various types of riparian azonal vegetation are encountered, representing elm-ash forests, willow-poplar forests and alder carrs (i.e. Fraxino-Ulmetum, Salici-Populetum and Carici elongatae-Alnetum) (Matuszkiewicz, 2008).

3.4. Palaeogeographical background

The geographical and environmental differences between southern and northern Poland could have been even more pronounced in the Mid-Holocene. The northern area (including Kuyavia) was covered by ice during the last glaciation. The southern part of Poland is placed in the European belt between 43° and 50° of northern latitude, where Holocene climatic fluctuations probably differed the most between northern and southern regions. It is stated that the jet stream route with humid air masses was blocked before the northern ice sheet melted in the Early Holocene (Magny et al., 2003; Starkel et al., 2013). The spatial and temporal diversity of European Holocene climate fluctuations is clear despite fragmentary data (i.e. Mauri et al., 2015; Zhang et al., 2017).

A detailed study of the whole territory of Poland, focused on several types of sediments, environmental data and radiocarbon dating led to climatostratigraphic division of the Holocene, with particularly well-expressed changes in hydrological regime (Starkel et al., 2013). In general the Mid-

Holocene rise in temperature was observed in ca. 8600 cal. BP (ca. 6600 BC) and it was relatively warm until ca. 5600 cal. BP (3600 BC), when a decline in temperature and a sharp rise in precipitation was noted. A further decline in temperature, again connected with a rise in precipitation, was noted in ca. 5000-4800 cal. BP. (ca. 3000-2800 BC). This was also a boundary between the Mid- and Late Holocene (4850 cal. BP, 2900 BC). During the warm period of the Mid-Holocene at least two periods with a high frequency of extremes (fluvial activity) were noted between ca. 7600-7400 cal. BP and 6400 – 6000 cal. BP, which coincides with the beginning of the Neolithic (the LBK) and the development of the later L-PC (including i.a. Brześć Kujawski group). The next warmer phase began in ca. 3700 cal. BP and lasted until ca. 2850 cal. BP (ca. 900 BC), when a cooler and more humid period started followed by the beginning of the Iron Age.

Summing up the most distinct geographical differences between the studied regions, the Kuyavia region and northwestern part of central Poland are much drier and receive more insolation than the southern part. Additionally the fertile soils, chosen by the first farmers, in southern Poland are frequently developed on loess substrate and their genesis must be older than the fertile soils developed after the last glaciation in northern Poland, especially in Kuyavia, a territory where retreating ice left a differentiated landscape of moraines, dunes, and several hydrological features left by meltwater and buried ice blocks (Bogucki et al., 2012). The availability of water also differed in those two areas in prehistory (Starkel et al., 2013).

4. Material and Methods

4.1. Selection of archaeobotanical remains

The requirement of at least five (ideally 10) well-preserved charred grains of wheat or barley for studying the isotopic composition of archaeological crop remains is a limiting factor. However, it is necessary in order to ensure that the crop isotope values obtained are representative of a growing condition (Nitsch et al., 2015). Such samples are usually not accessible from the sites dated to the initial phases of the Neolithic in northern Europe. Most of the studied samples come from storage deposits of pure grain (fine sieve products according to Jones, 1987, 1984), thus any information about the local agriculture derived from weed ecology of the selected samples is not very accessible (i.e. Bogaard, 2004; Bogaard et al., 2016; Kreuz and Schäfer, 2011). However, archaeological and botanical descriptions of the studied material allow descriptive interpretation of the obtained isotopic data by taking into account the complexity of agricultural development in the territory of Poland, where at least two 'Neolithic frontier zones' can be located (Fernández et al., 2014; Silva and Linden, 2017). Bronze Age/Early Iron Age samples from these regions show large internal variability in crop composition, especially those derived from Early Iron Age fortified settlements (proto cities) like Sobiejuchy and Kamieniec in northern Poland (Fig. 1, Tables 2, 3, S1).

The crop samples have been selected from the materials studied and stored at the W. Szafer Institute of Botany PAS (IB PAS), the Institute of Archaeology and Ethnology PAS (IAE PAS), the Institute of Archaeology of the Jagiellonian University (IA UJ) and the Archaeological Museum in Kraków (MAK) (Table S1). A summary of the archaeological and archaeobotanical information relating to the studied material is given in Table 2 and Tables S1 and S2. Samples and their archaeobotanical context are listed in Table S3. All wheat grains selected for the isotopic analyses were documented by drawing in three projections. Only well-preserved grains, charred in optimal conditions, were selected (Charles et al., 2015; Nitsch et al., 2015).

4.2. Sampling of archaeobotanical remains

Between three and 30 grains were selected from each archaeobotanical sample for isotopic analysis. Eleven of the samples, from Osłonki 1 and Miechowice 4, were scraped clean with a scalpel, crushed and analysed using fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) to look for the presence of carbonate, nitrate and/or humic contamination (Vaiglova et al., 2014). Peaks characteristic of carbonate contamination (870 and 720 cm^{-1}) were observed in all of the FTIR spectra. It was therefore decided to acid pre-treat all of the crop samples to dissolve any carbonate (Ramsey, 2008). This procedure consists of treatment with 10 ml of 0.5 M hydrochloric acid at 70 °C for 30–60 minutes, then rinsing in distilled water three times before freeze-drying. This acid pre-treatment does not affect the isotope values of charred grains in the absence of contamination (Vaiglova et al., 2014). The samples were crushed using an agate mortar and pestle.

4.3. Laboratory analysis

The homogenised powders of the archaeological grains were weighed into tin capsules for isotopic analysis on a Sercon 20-22 isotope ratio mass spectrometer coupled to a Sercon GSL elemental analyser at the Research Laboratory for Archaeology and the History of Art, University of Oxford, UK. Isotopic data are provided in Table 3. The $\delta^{13}C$ and $\delta^{15}N$ values of charred cereal grains were measured in separate runs due to their low nitrogen content. Their $\delta^{13}C$ and $\delta^{15}N$ values were calibrated relative to the VPDB and AIR scales using two bracketing reference materials: IAEA-C6 ($\delta^{13}C$ -10.45±0.03‰) and IAEA-C7 ($\delta^{13}C$ -32.15±0.05‰) for $\delta^{13}C$ and Caffeine-2* ($\delta^{15}N$ -2.90±0.03‰; University of Indiana) and IAEA-N2 ($\delta^{15}N$ 20.3±0.2‰) for $\delta^{15}N$ (Tables S8-S10). Measurement uncertainty was monitored using one in-house standard: Alanine (DL alanine, $\delta^{15}N$ -1.56 ± 0.03‰ and $\delta^{13}C$ -27.11±0.05‰). Precision of $\delta^{13}C$ values ($u(R_w)$) was determined to be ±0.07‰, accuracy or systematic error (u(*bias*)) was ±0.13‰ and the total analytical uncertainty was estimated to be ±0.15‰ using the equation presented in Tables S11 and S12. Precision of δ^{15}N values ($u(R_w)$) was determined to be ±0.16‰, accuracy or systematic error (u(*bias*)) was ±0.40‰ and the total analytical uncertainty was estimated to be ±0.43‰ using the equation presented in Tables S11 and S12.

The δ^{13}C and δ^{15}N values of the carbonised crop remains were corrected for the effect of charring by subtracting 0.11‰ and 0.31‰, respectively, from the determined δ^{13}C and δ^{15}N values, which are the average offsets between uncarbonised crop seeds and those heated for 4, 8 or 24 h at 215, 230, 245 or 260°C (Nitsch et al., 2015). Statistical analyses were performed in R v.3.4.3.

5. Results

The samples were divided into groups: taxonomic, chronological (Early Neolithic, Middle Neolithic, Bronze/Iron Age) and geographical (southern Poland, northern Poland) (Table 3). It is worth remembering that both millet and barley samples were selected only from the Bronze Age or Early Iron Age sites. Wheat samples (einkorn, emmer and spelt) were the most numerous and selected from all periods.

Fig. 2 shows the δ^{13}C and δ^{15}N values of all of the samples, colour-coded by taxa. The δ^{15}N values of wheat range from 2.6 to 7.3‰, the values of barley from 4.5 to 6.5‰ and the values of millet from 4.5 to 5.5‰. The δ^{13}C values of wheat range from -25.6 to -22.4‰, the values of barley from -26.1 to -24.2‰ and the values of millet from -10.7 to -9.9‰. The δ^{15}N and δ^{13}C values of wheat grains, the most numerous of the samples, are normally distributed (W = 0.96, p = 0.22 and W = 0.96, p = 0.21 respectively) and variances in the δ^{15}N and δ^{13}C values are equal across the regions and time periods (assessed with Levene's test). The most visible difference in Fig. 2 is between the δ^{13}C values of C_3 (wheat, *Triticum* and barley, *Hordeum*) and C_4 cereals (millet, *Panicum*). The samples of barley generally have lower δ^{13}C values than the wheats, which reflects the difference in δ^{13}C values of modern wheat and barley growing in the same watering conditions (Wallace et al., 2013). Their δ^{15}N values are also generally high, although they only derive from Bronze/Iron Age contexts and are not numerous.

Site code	Site	Feature	Evaluated absolute chronology (cal BC)	Species	N.Grains	Sample ID	%C	$\delta^{13}C_{raw}$	$\delta^{13}C_{VPDB}$	$\delta^{13}C_{air}$ mean	$\Delta^{13}C$	%N	$\delta^{15}N_{raw}$	$\delta^{15}N_{AIR}$	C:N atomic ratio	Part of Poland	Chronology
1	Brzezie 17	1357	5200-5060	*Triticum dicoccum*	6	AMB02	48,0	-25,3	-25,4	-6,4	19,5	3,0	6,9	6,8	18,8	S	EN
2	Iwanowice-Klin	8	5200-5000	*Triticum dicoccum*	8	AMB03	42,2	-24,8	-24,9	-6,39	19,0	2,8	7,0	6,9	17,4		
3	Zakrzowiec 6/8	715	4600-4300	*Triticum dicoccum*	6	AMB11	52,4	-24,8	-24,9	-6,3	19,1	2,8	5,5	5,4	21,6		
				Triticum dicoccum	6	AMB12	43,5	-24,4	-24,5	-6,3	18,6	2,5	6,6	6,6	20,2		
4	Kraków-Mogiła 62	395	3500-3300	*Triticum dicoccum*	6	AMB17	60,3	-23,6	-23,6	-6,36	17,7	4,0	7,6	7,6	17,6		MN
				Triticum monococcum	6	AMB18	64,1	-24,2	-24,3	-6,36	18,4	4,5	6,1	6,1	16,7		
5	Kraków-Pleszów 17-20	440	3200-2900	*Triticum dicoccum*	5	AMB30	63,4	-23,0	-23,0	-6,35	17,1	4,1	7,6	7,5	17,8		
6	Kraków-Prądnik Czerwony	32	3500-3100	*Triticum monococcum*	6	AMB08	61,4	-24,3	-24,4	-6,36	18,5	4,5	5,9	5,8	15,9		
				Triticum dicoccum	10	AMB13	67,0	-22,9	-23,0	-6,36	17,0	4,2	5,8	5,7	18,4		
				Triticum dicoccum	10	AMB14	60,0	-24,0	-24,0	-6,36	18,1	4,4	5,8	5,8	15,8		
				Triticum dicoccum	10	AMB15	61,0	-23,8	-23,8	-6,36	17,9	4,7	5,9	5,8	15,2		
				Triticum dicoccum	10	AMB16	63,3	-23,6	-23,7	-6,36	17,8	4,4	6,8	6,8	16,6		
7	Mozgawa 1-3	6	3350-3050	*Triticum dicoccum*	6	AMB19	60,9	-24,6	-24,7	-6,36	18,8	3,7	6,1	6,0	19,1		
		7	3500-3350	*Triticum dicoccum*	9	AMB20	64,6	-23,4	-23,5	-6,36	17,5	3,8	6,9	6,9	20,1		
		8	3530-3360	*Triticum dicoccum*	5	AMB21	62,0	-24,1	-24,2	-6,37	18,3	3,3	7,0	7,0	22,2		
		10	3600-3350	*Triticum dicoccum*	10	AMB22	60,7	-23,4	-23,5	-6,37	17,5	3,4	6,5	6,4	20,5		
8	Jerzmanowice	cave	4500-4360	*Triticum dicoccum*	10	AMB31	64,1	-24,8	-24,9	-6,31	19,1	2,8	4,4	4,3	26,3		EN
9	Słonowice G	28	1570-1300	*Hordeum vulgare*	10	AMB26	65,2	-24,8	-24,9	-6,47	18,9	3,7	5,0	4,8	20,7		B
10	Gwoździec 2	1	5370-5210	*Triticum dicoccum*	5	AMB01	33,6	-24,4	-24,4	-6,51	18,4	2,1	5,9	5,8	19,1		EN
				Triticum sp. (NGW)	4	AMB54	46,5	-24,1	-24,2	-6,51	18,1	2,9	5,6	5,5	19,0		
11	Maszkowice 1	59	1730-1620	*Hordeum vulgare*	10	AMB27	61,7	-24,2	-24,3	-6,42	18,3	4,8	6,8	6,8	14,9		B
12	Lipnik 5	302	1400-1180	*Triticum dicoccum*	5	AMB23	48,9	-23,2	-23,2	-6,49	17,2	3,3	6,4	6,4	17,3		
				Triticum spelta	5	AMB24	45,5	-22,3	-22,3	-6,49	16,2	2,8	6,4	6,3	18,8		
				Panicum miliaceum	20	AMB25	59,1	-9,9	-9,8	-6,49	3,3	3,2	5,7	5,6	21,8		
13	Miechowice 4	30	4400-4300	*Triticum dicoccum*	7	AMB10	57,3	-23,3	-23,4	-6,32	17,4	3,7	4,4	4,3	18,1	N	EN
				Triticum monococcum	5	AMB53	57,7	-23,4	-23,4	-6,32	17,5	3,3	4,8	4,7	20,5		

14	Osłonki 1	81	4240-4030	*Triticum dicoccum*	5	AMB06	62,4	-23,2	-23,3	-6,36	17,3	3,4	4,7	4,5	21,1		
		149	4350-4175	*Triticum dicoccum*	6	AMB04	62,6	-23,0	-23,0	-6,34	17,1	3,8	4,5	4,4	19,0		
				Triticum monococcum	6	AMB05	64,8	-22,3	-22,3	-6,34	16,4	3,4	3,5	3,4	22,2		
				Triticum monococcum	4	AMB09	61,9	-23,0	-23,1	-6,34	17,1	3,0	4,4	4,2	24,0		
				Triticum dicoccum	4	AMB49	59,5	-22,6	-22,7	-6,34	16,7	4,1	4,6	4,5	17,1		
				Triticum dicoccum	3	AMB50	62,2	-22,5	-22,6	-6,34	16,6	3,4	5,7	5,6	21,1		
				Triticum dicoccum	5	AMB52	64,1	-22,6	-22,6	-6,34	16,7	4,2	3,9	3,7	17,8		
		2 (114)	4450-4300	*Triticum dicoccum*	6	AMB07	61,0	-23,0	-23,0	-6,32	17,1	3,8	3,9	3,8	18,7		
			4450-4300	*Triticum dicoccum*	7	AMB51	60,3	-23,2	-23,3	-6,32	17,4	4,0	4,5	4,4	17,7		
15	Ludwinowo 7	B32	900-800	*Triticum dicoccum*	10	AMB28	56,3	-24,2	-24,3	-6,52	18,2	2,5	5,7	5,6	26,4		B/I
				Triticum spelta	5	AMB29	54,1	-23,0	-23,1	-6,52	17,0	3,0	5,7	5,6	20,8		
16	Sobiejuchy	D88/106	800-450	*Hordeum vulgare*	10	AMB35	63,6	-25,5	-25,6	-6,5	19,6	2,7	6,1	6,1	27,2		
				Hordeum vulgare	10	AMB36	63,6	-25,2	-25,3	-6,5	19,3	2,8	6,7	6,7	26,8		
				Hordeum vulgare	10	AMB37	62,6	-25,9	-26,0	-6,5	20,0	2,7	6,9	6,8	27,1		
				Hordeum vulgare	10	AMB38	62,2	-25,5	-25,6	-6,5	19,6	3,0	6,6	6,5	24,2		
				Hordeum vulgare	10	AMB39	64,1	-24,6	-24,7	-6,5	18,7	2,9	6,2	6,1	25,4		
		C87/37		*Hordeum vulgare*	7	AMB40	63,8	-24,0	-24,1	-6,5	18,0	3,6	6,6	6,5	20,7		
		D88/106		*Triticum dicoccum*	5	AMB41	64,3	-24,0	-24,1	-6,5	18,0	3,3	5,7	5,7	23,0		
		C87/73		*Panicum miliaceum*	30	AMB42	66,2	-10,4	-10,3	-6,5	3,9	3,4	5,5	5,4	22,5		
					30	AMB43	65,3	-10,5	-10,4	-6,5	4,0	3,6	5,5	5,4	21,4		
					30	AMB44	64,8	-10,4	-10,4	-6,5	3,9	3,8	5,9	5,8	19,9		
					30	AMB45	64,4	-10,4	-10,3	-6,5	3,9	3,6	5,6	5,5	20,7		
					30	AMB46	61,1	-10,4	-10,4	-6,5	3,9	3,6	5,8	5,7	19,8		
					30	AMB47	66,0	-10,4	-10,3	-6,5	3,9	3,6	5,7	5,6	21,2		
					30	AMB48	73,4	-10,7	-10,6	-6,5	4,1	3,1	5,0	4,9	27,5		
17	Kamieniec		700-400	*Triticum dicoccum*	5	AMB33	57,3	-22,7	-22,8	-6,5	16,7	3,5	4,4	4,3	19,1		
			700-400	*Triticum spelta*	5	AMB34	61,7	-23,0	-23,0	-6,5	16,9	3,3	3,5	3,4	22,1		
18	Poganice		3600-3400	*Triticum dicoccum*	8	AMB32	63,4	-25,4	-25,5	-6,37	19,6	3,1	3,1	2,9	23,6		MN

Table 3. Stable isotope results of the Neolithic and Bronze Age/Early Iron Age sites from Poland

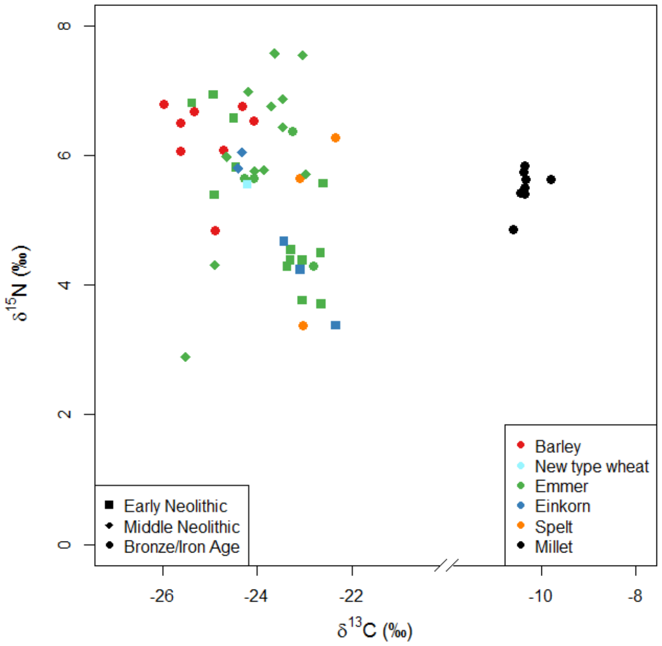

Fig. 2. $\delta^{13}C$ and $\delta^{15}N$ values of all cereal grains included in this study, colour-coded by taxa. The shape of the symbols corresponds to the archaeological period.

When we compare $\delta^{15}N$ values separately for each time period and geographic region (northern or southern Poland) (Fig. 3), wheat samples dated to the Early Neolithic from northern Poland tend to have lower $\delta^{15}N$ values than those from southern Poland ($t(9.10) = -5.74$, $p < 0.001$, mean $\delta^{15}N$ in north = 4.00‰, mean $\delta^{15}N$ in south = 5.87‰). However, it should be noted here that in northern Poland only samples from the L-PC and not the LBK were available, whereas most of the Early Neolithic samples from southern Poland dated to the LBK. Subsamples from a large cereal storage deposit (pit 149) from the Osłonki site have very varied $\delta^{15}N$ values and the same samples also have the highest $\delta^{13}C$ values. Wheat grain $\delta^{15}N$ values may also have been lower in northern Poland than southern Poland during the Middle Neolithic, but there is only one sample from northern Poland, which may not be representative of this period.

In southern Poland there is some variability in $\delta^{15}N$ values from wheat dated to the Middle Neolithic. The lowest $\delta^{15}N$ value is observed in the sample from Jerzmanowice Cave site (no. 8 in Fig. 1), whereas the two highest $\delta^{15}N$ values derive from the sites of Kraków Mogiła and Kraków Pleszów, which are in fact located very close to each other (nos. 4-5 in Fig. 1) in the upper Vistula valley. The wheat samples from northern Poland generally have similar $\delta^{15}N$ and $\delta^{13}C$ values in the Early Iron Age (the late Lusatian Culture) to those dated to the Early Neolithic (the Brześć Kujawski Group of the L-PC).

The two Bronze Age wheat samples from southern Poland also have similar $\delta^{15}N$ values to those of wheat from the previous periods. A comparison of linear models found that the best fit was for a model including an effect of region (northern or southern Poland) but not time period on wheat $\delta^{15}N$ values (*Beta* = 1.84, SE = 0.26, $t = 7.05$, $p < 0.001$). Barley, which is only available in northern Poland in the Bronze/Early Iron Age and derives from one archaeological context, has higher $\delta^{15}N$ values than wheats at this time. Millet grains from the same context as the barley have slightly lower $\delta^{15}N$ values.

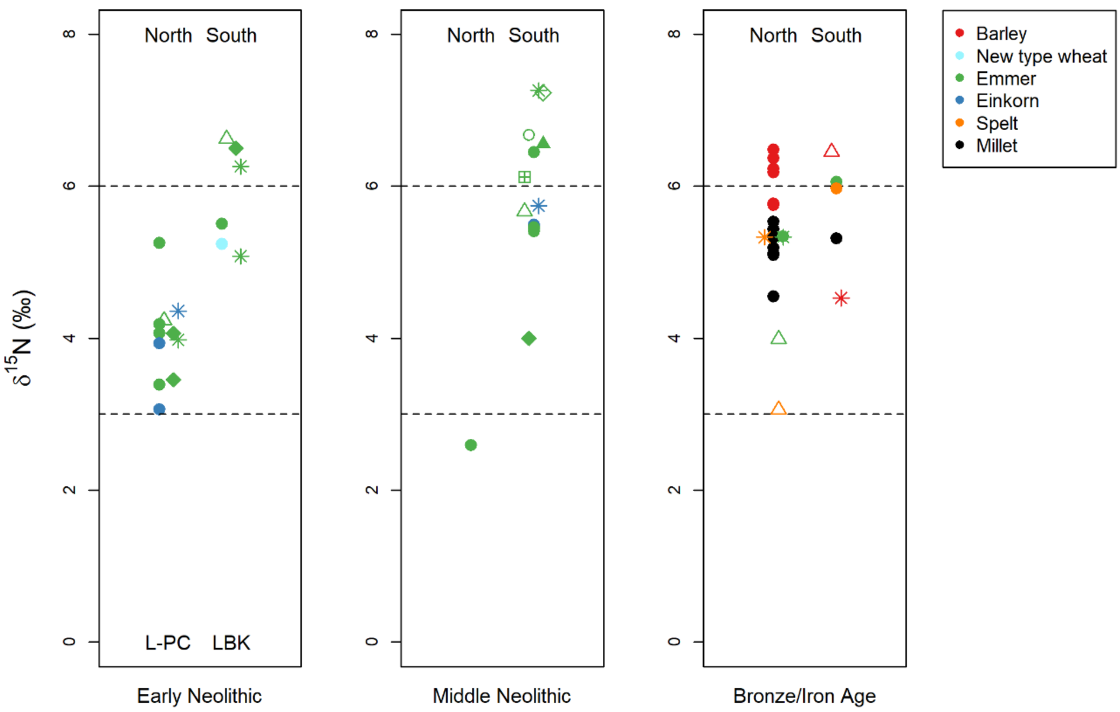

Fig. 3. $\delta^{15}N$ values of carbonized cereal grains from Poland dating to between the Early Neolithic and Iron Age. The shapes of the symbols represent different archaeological contexts within each time period and region, i.e. all barley and millet grains from northern Poland dating to the Bronze/Early Iron Age derive from a single archaeological context.

When we compare $\delta^{13}C$ values separately for each time period and geographic region (excluding millet because of its extreme $\delta^{13}C$ values) (Fig. 4), wheat samples dated to the Early Neolithic again show a clear difference in their isotopic composition between northern and southern Poland, with wheat grains from northern Poland exhibiting higher $\delta^{13}C$ values than those from the south ($t(9.16) = 8.47$, $p < 0.001$, mean $\delta^{13}C$ in north = -23.1‰, mean $\delta^{13}C$ in south = -24.8‰). The only Middle Neolithic (TRB) sample from Poganice in northern Poland is geographically distant from the other sites and has a distinctively low $\delta^{13}C$ value, which correlates with its low $\delta^{15}N$ value. As the only sample from this period in the region, however, its informative value is low.

The $\delta^{13}C$ values of wheat grains from the Middle Neolithic in southern Poland are more varied than in the Early Neolithic. The highest $\delta^{13}C$ values are associated with samples from Kraków Pleszów (5) and Kraków Prądnik Czerwony (6), and the lowest $\delta^{13}C$ values come from Jerzmanowice (8) and Mozgawa (7). By the Bronze/Iron Age the $\delta^{13}C$ values of wheat grains from northern and southern Poland (albeit few in number) are relatively similar to one another. The $\delta^{13}C$ values of barley from the Bronze/Iron Age, as mentioned previously, are lower than those of the wheat, due to physiological differences (Wallace et al., 2013).

When we compare data derived from the Neolithic wheat grains solely from southern Poland, there is a strong, positive correlation between $\delta^{13}C$ values and archaeological period (Spearman's correlation r_s = .71, n = 21, $p < .001$), with relatively higher $\delta^{13}C$ values of the Bronze/Iron Age and Middle Neolithic samples compared to the Early Neolithic. In the Middle Neolithic material, seeds of corncockle (*Agrostemma githago*) are also common whereas they are absent (or sporadic) in the Early Neolithic samples.

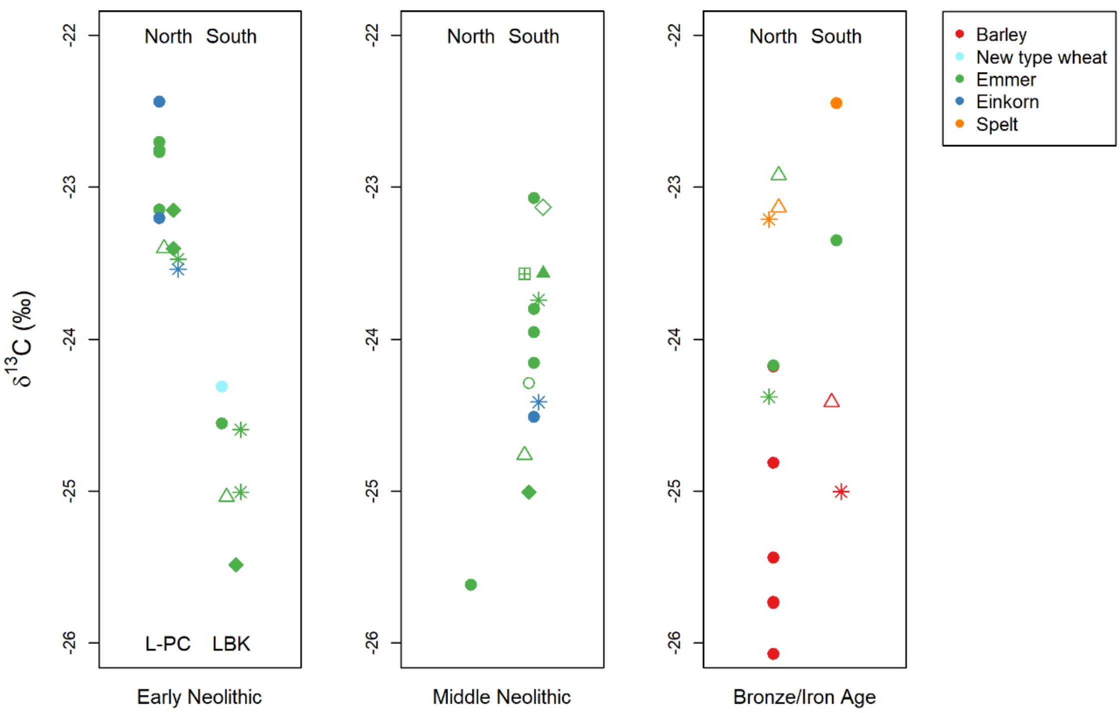

Fig. 4. $\delta^{13}C$ values of carbonized cereal grains from Poland dating to between the Early Neolithic and Iron Age. The shapes of the symbols represent different archaeological contexts within each time period and region.

6. Discussion

If we refer to the indicative $\delta^{15}N$ values intended to reflect specific rates of manuring established by Bogaard et al. (2013, 2016), it is possible that virtually all analysed samples (except the one from Poganice) could have come from fertilized fields. Cereal grain $\delta^{15}N$ values range from ca. 3 to 7‰ and 3‰ is taken to be the general threshold between low and medium levels of manuring (Bogaard et al., 2016, 2013). Almost all grains from southern (Lesser) Poland and a significant number of the samples dated to the Bronze/Early Iron Age in northern Poland (Kuyavia) are characterized by relatively high values, from 5 to 7‰, which may be associated with a high level of manuring (> 6‰; Bogaard et al., 2013).

Based on archaeological data and models (Kruk, 1980a; Kruk and Milisauskas, 1999), a clear decrease in cereal grain $\delta^{15}N$ values between the Early Neolithic and later periods was expected, reflecting a decrease in the intensity of manuring associated with the transition from intensive garden-type cultivation to extensive cultivation over large areas. However, the $\delta^{15}N$ values obtained indicate a stronger territorial relationship than a chronological one. Grains of prehistoric cereals from northern Poland, especially those of Neolithic wheats, generally have lower $\delta^{15}N$ values than grains from southern Poland. This may indicate either a lower level of manuring and intensity of cultivation in Kuyavia (northern Poland) and/or different properties of soils compared to southern Poland.

It seems unlikely that inherent differences in the characteristics of soils could have caused the difference in cereal grain $\delta^{15}N$ values between northern and southern Poland in the Early Neolithic, because millet and barley grains dated to the Bronze/Early Iron Age have similar $\delta^{15}N$ values in both regions. Therefore, it seems more probable that in southern Poland in the Neolithic, the cultivated fields were more intensively fertilized than in northern Poland. In northern Poland during the Early Neolithic period, manuring may have been practiced, but with lower intensity.

Answering the question of whether this fertilization involved manure or household waste, or whether the high crop $\delta^{15}N$ values resulted from burning the vegetation to clear the land for agriculture, is more difficult. All of the $\delta^{15}N$ values are much higher than the values from wheat grown on experimental fields cleared by fire (-1.1 ‰; Styring et al., 2017), but it must be underlined that the experimental fields were on acidic, poor soils, which could have inherently lower $\delta^{15}N$ values. On the other hand, it is *precisely* on such relatively poor soils that slash-and-burn can be an advantage over more intensive forms of cultivation (Ehrmann et al., 2014; Halstead, 2018).

In terms of cereal grain $\delta^{13}C$ values, clear differences between the Early Neolithic samples from northern and southern Poland can be interpreted in two ways. The lower $\delta^{13}C$ values of wheat from southern Poland could be explained by the wetter and less sunny climatic conditions in the south compared to the north, but the fact that these differences do not persist in the later periods suggests that factors other than generic climatic differences are at play. Most of the samples from southern Poland date to the Linear Band Pottery Culture (LBK, ca. 5400 - 4800 cal. BC), whereas the samples from northern Poland come from the Brześć Kujawski Group of L-PC (ca. 4500 – 4000 cal. BC). Thus, they are separated from each other by at least 300/400 years. It could therefore be supposed that climatic conditions in the second half of the 5th millennium BC in northern Poland were slightly drier than those in the second half of the 6th millennium BC and the beginning of the 5th millennium BC in southern Poland. However, detailed chronostratigraphy based on dating of various facies of continental sediments, including organic remains, supported by environmental data derived from pollen profiles from Poland (Starkel et al., 2013), indicates a rise in precipitation about 6400 cal yr BP and a humid phase between 6400 and 5600 cal yr BP (ca. 4400 – 3600 BC). Therefore during the second half of the 5th millennium BC (L-PC) it was probably more humid than in the 6th millennium BC, which does not correspond to the higher $\delta^{13}C$ values.

An alternative explanation for the lower $\delta^{13}C$ values in southern Poland in the Early Neolithic, which could also account for the shift to higher and more varied $\delta^{13}C$ values in the Middle Neolithic, could be that there was denser vegetation surrounding fields in the south at the beginning of the Neolithic, which shaded the crops and thus reduced the amount of light reaching them. Similar cereal grain $\delta^{13}C$ values of around -25‰ were determined at the Early Neolithic site of Stensborg in Sweden, where farming has been interpreted to have been carried out on a small-scale in forest clearings (Gron et al., 2017). The increase in variation of $\delta^{13}C$ values of wheat between the Early and Middle Neolithic in the south could thus reflect a clearing of the vegetation and more variable use of both small-scale forest clearings and open fields. It is also worth noting here that in archaeological literature fundamental changes in the Neolithic settlement model related to the emergence and spread of the Middle Neolithic TRB culture, especially in southern Poland, have been postulated for a long time (Burchard and Lityńska-Zając, 2002; Kruk, 1980a; Nowak, 2006). They consisted of the settling and exploitation of topographically higher zones of the landscape, mainly rims of river valleys and some parts of the uplands (watersheds). Geomorphological, and to some extent palynological, data point to - at least locally – significant deforestation and the start of intensive slope processes (erosion) in the 4th millennium BC (Nowak, 2009). However, what is also significant is that the "traditional", low-lying, moist habitats, inhabited and exploited since the beginning of the Early Neolithic, were inhabited and used by the TRB groups as well. This could correlate with the variable $\delta^{13}C$ values observed in the Middle Neolithic of southern Poland. In other words, the conditions for growing cereals (mainly wheat) in some fields remained the same as in the Early Neolithic period, i.e. the change described above was not a radical, all-encompassing process.

7. Conclusions

The stable carbon and nitrogen isotopic values of wheat, barley and millet grain samples from the territory of present-day Poland, dated to archaeological contexts spanning the Early Neolithic, Middle Neolithic and Bronze/Early Iron Age, provide an insight into regional and temporal changes in cultivation practices. In general, all cereal plots could have received some inputs of fertilizer, including manure and household waste, but there seems to be a regional difference in the intensity of that practice in the Neolithic, with generally greater accessibility of heavy isotope of nitrogen on plots in southern Poland than in northern Poland which can be connected with greater application of manure (and household waste) in southern Poland. Moreover, cereal plots in southern Poland in the Early Neolithic seem to have been located on soils with higher water retention and/or within denser vegetation than plots in northern Poland. In the Middle Neolithic, however, plots in southern Poland seemed to have expanded into areas with lower water availability or that were more open, supporting the ideas expressed already in the early 1970's by Janusz Kruk, based mainly on settlement data (Kruk, 1973; English translation: 1980b), that agriculture spread into new, more elevated areas at this time.

Declaration of interests

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

Acknowledgements

We wish to thank the Cracow Team for Archaeological Supervision of Motorway Construction (*Krakowski Zespół do Badań Autostrad* in Polish), especially Jan Chochorowski, Janusz Kruk, and Jacek Górski for allowing us the use of the plant remains obtained from the excavations financed by the Team. We are also very grateful to Jacek Górski, Janusz Bober and Justyna Rodak from the Archaeological Museum in Kraków for making the plant remains stored in the Museum accessible for our studies. Most of the plant remains from Kuyavia were found thanks to long term collaboration with Ryszard Grygiel from the Archaeological and Ethnographic Museum in Łódź and Peter Bogucki from Princeton University. Archaeobotanical studies of the Lusatian sample from Ludwinowo site 7 were possible thanks to Lech Czerniak and Joanna Pyzel, who used a special sampling program in part of the site. Carol Palmer allowed us to use samples from Sobiejuchy. The plant remains from Mozgawa site were collected thanks to the National Science Centre Grant (UMO-2013/11/B/HS3/03822) and statutory funds of the Institute of Archaeology, Jagiellonian University. Krzysztof Kotynia identified most of the samples from Mozgawa site mentioned in the study, as part of his MA dissertation. Sławomir Kadrow allowed us to use plant remains from Iwanowice site. We are especially grateful to Krystyna Wasylikowa and Zofia Tomczyńska for their long term, fruitful work in the field of archaeobotany which makes such isotopic research of several sites possible. We are also grateful to Edward Wilman for processing the archaeobotanical samples for isotope analysis. Special thanks are also addressed to two anonymous reviewers.

This work was supported by the National Science Centre under Grant UMO-2013/10/M/HS3/00537 (PI Aldona Mueller-Bieniek) and the statutory funds of the W. Szafer Institute of Botany, Polish Academy of Sciences but most of the plant materials used here were discovered thanks to several decades of archaeological and archaeobotanical work, followed by loving care of the fragile plant macroremains in the collections of museums and institutes.

Appendix A. Supplementary data

Supplementary data to this article can be found online …..

References

Bednarek, R., Prusinkiewicz, Z., 1999. Geografia gleb. Wydawnictwo Naukowe PWN, Warszawa.

Bielenin, K., 1959. Zabytki kultury ceramiki promienistej z Pleszowa (Nowa Huta) z badań w roku 1953. Materiały Archeologiczne 1, 63–76.

Bieniek, A., 2002. Archaeobotanical analysis of some early Neolithic settlements in the Kujawy region, central Poland, with potential plant gathering activities emphasised. Veg. Hist. Archaeobotany 11, 33–40. https://doi.org/10.1007/s003340200004

Bieniek, A., 2007. Neolithic plant husbandry in the Kujawy region of central Poland, in: Colledge, S., Conolly, J. (Eds.), The Origins and Spread of Domestic Plants in Southwest Asia and Europe. Routledge, pp. 327–342.

Bieniek, A., 2008. Pozostałości paszy zwierzęcej? Archeobotaniczne badania jamy 302 ze stanowiska 5 w Lipniku, pow. Przeworsk, in: Przybyła, M.S., Blajer, W. (Eds.), Struktury osadnicze w epoce brązu i wczesnej epoce żelaza na obszarze podkarpackiej wysoczyzny lessowej między Wisłokiem i Sanem, 319–327. Kraków, Wydawnictwo Uniwersytetu Jagiellońskiego.

Bieniek, A., Lityńska-Zając M., 2001. New finds of wild apple Malus sylvestris Mill. from the Neolithic sites in Poland. Veg. Hist. Archaeobotany 10, 105–106.

Bieniek, A., Pokorny, P., 2005. A new find of macrofossils of feather grass (Stipa) in an Early Bronze Age storage pit at Vlineves, Czech Republic: local implications and possible interpretation in a Central European context. Veg. Hist. Archaeobotany 14, 295–302. https://doi.org/10.1007/s00334-005-0076-9

Blajer, W., 2009. Die Ausgrabungen an der Fundstelle 5 in Lipnik, Kr. Przeworsk (Siedlung der Trzciniec-Kultur, Gräberfeld der Tarnobrzeg-Gruppe), in den Jahren 2004–2006 (7.-9. Grabungssaison). Recherches Archéologiques NS 1, 73–82.

Blajer, W., Przybyła, M., 2006. Die Notgrabungen an der Fundstelle 5 in Lipnik, Kr. Przeworsk in den Jahren 1999-2003 (2.-6. Grabungssaison), Recherches Archéologiques de 1999-2003, 65–79.

Cabalska, M., 1974. Z badań nad problematyką najstarszej ceramiki zdobionej ornamentem guzowym z terenu polski południowej w świetle materiałów z Maszkowic, pow. Nowy Sącz. Slovenská archeologia 22, 39–71.

Cabalska, M., 1975. Osadnictwo kultury łużyckiej w Maszkowicach w świetle dotychczasowych badań archeologicznych. Materiały Starożytne i Wczesnośredniowieczne 3, 159–184.

Cabalska, M., 1977. Hillfort and fortified settlement of Lusatian Culture in Maszkowice, voivodship of Nowy Sącz. Archaeologia Polona 18, 107–136.

Bogaard, A., 2004. Neolithic Farming in Central Europe: an Archaeobotanical Study of Crop Husbandry Practices. Routledge, London.

Bogaard, A., Fraser, R., Heaton, T.H.E., Wallace, M., Vaiglova, P., Charles, M., Jones, G., Evershed, R.P., Styring, A.K., Andersen, N.H., Arbogast, R.-M., Bartosiewicz, L., Gardeisen, A., Kanstrup, M., Maier, U., Marinova, E., Ninov, L., Schäfer, M., Stephan, E., 2013. Crop manuring and intensive land management by Europe's first farmers. Proc. Natl. Acad. Sci. 110, 12589–12594. https://doi.org/10.1073/pnas.1305918110

Bogaard, A., Heaton, T.H.E., Poulton, P., Merbach, I., 2007. The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. J. Archaeol. Sci. 34, 335–343. https://doi.org/10.1016/j.jas.2006.04.009

Bogaard, A., Hodgson, J., Nitsch, E., Jones, G., Styring, A., Diffey, C., Pouncett, J., Herbig, C., Charles, M., Ertuğ, F., Tugay, O., Filipovic, D., Fraser, R., 2016. Combining functional weed ecology and crop stable isotope ratios to identify cultivation intensity: a comparison of cereal production regimes in Haute Provence, France and Asturias, Spain. Veg. Hist. Archaeobotany 25, 57–73. https://doi.org/10.1007/s00334-015-0524-0

Bogucki, P., Nalepka, D., Grygiel, R., Nowaczyk, B., 2012. Multiproxy environmental archaeology of Neolithic settlements at Osłonki, Poland, 5500–4000 BC. Environ. Archaeol. 17, 45–65. https://doi.org/10.1179/1461410312Z.0000000004

Bonafini, M., Pellegrini, M., Ditchfield, P., Pollard, A.M., 2013. Investigation of the 'canopy effect' in the isotope ecology of temperate woodlands. J. Archaeol. Sci. 40, 3926–3935. https://doi.org/10.1016/j.jas.2013.03.028

Broadmeadow, M.S.J., Griffiths, H., 1993. Carbon Isotope Discrimination and the Coupling of CO2 Fluxes within Forest Canopies, in: Ehleringer, J.R., Hall, A.E., Farquhar, G.D. (Eds.), Stable Isotopes and Plant Carbon-Water Relations. Academic Press, San Diego, pp. 109–129. https://doi.org/10.1016/B978-0-08-091801-3.50015-5

Burchard, B., Lityńska-Zając, M., 2002. Plant remains from the Funnel Beaker Culture site at Niedźwiedź, Słomniki commune, Małopolska province. Acta Palaeobot. 41, 171–176.

Calderoni, G., Gancarski, J., Lityńska-Zając, M., Tunia, K., 2000. Radiocarbon dating and palaeobotanical data for the Bronze Age assemblages of Słonowice and Trzcinica sites (Kielce and Krosno provinces, southern Poland). Origini 22, 267–298.

Charles, M., Forster, E., Wallace, M., Jones, G., 2015. "Nor ever lightning char thy grain"1: establishing archaeologically relevant charring conditions and their effect on glume wheat grain morphology. STAR Sci. Technol. Archaeol. Res. 1, 1–6. https://doi.org/10.1179/2054892315Y.0000000008

Czarnecka, M., 2011. Zmienność terminów początku i końca pokrywy śnieżnej o różnym czasie zalegania i ich uwarunkowania cyrkulacyjne. Pr. Stud. Geogr. 47, 109–118.

Czekaj-Zastawny, A., 2008. Osadnictwo społeczności kultury ceramiki wstęgowej rytej w dorzeczu górnej Wisły. Kraków, Instytut Archeologii i Etnologii PAN.

Czekaj-Zastawny, A., 2014. Brzezie 17. Osada kultury ceramiki wstęgowej rytej. Kraków, Krakowski Zespół do Badań Autostrad (Via Archaeologica. Źródła z badań wykopaliskowych na trasie autostrady A4 w Małopolsce).

Delekta, J., 1937. Badania na grodzisku „łużyckim" z wczesnej epoki żelaznej Kamieńcu nad Wisłą w pow. Toruńskim. Z Otchłani Wieków 12(9–10), 123–126.

Delekta, J., 1938. Nowe odkrycia w grodzie prasłowiańskim kultury „łużyckiej" w Kamieńcu w pow. toruńskim, ZOW 13(5-6), 73–74.

Dietze, E., Theuerkauf, M., Bloom, K., Brauer, A., Dörfler, W., Feeser, I., Feurdean, A., Gedminienė, L., Giesecke, T., Jahns, S., Karpińska-Kołaczek, M., Kołaczek, P., Lamentowicz, M., Latałowa, M., Marcisz, K., Obremska, M., Pędziszewska, A., Poska, A., Rehfeld, K., Stančikaitė, M., Stivrins, N., Święta-Musznicka, J., Szal, M., Vassiljev, J., Veski, S., Wacnik, A., Weisbrodt, D., Wiethold, J., Vannière, B., Słowiński, M., 2018. Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe. Quat. Sci. Rev. 201, 44–56. https://doi.org/10.1016/j.quascirev.2018.10.005

Ehrmann, O., Biester, H., Bogenrieder, A., Rösch, M., 2014. Fifteen years of the Forchtenberg experiment—results and implications for the understanding of Neolithic land use. Veg. Hist. Archaeobotany 23, 5–18. https://doi.org/10.1007/s00334-014-0452-4

Farquhar, G.D., Richards, R.A., 1984. Isotopic Composition of Plant Carbon Correlates With Water-Use Efficiency of Wheat Genotypes. Funct. Plant Biol. 11, 539–552. https://doi.org/10.1071/pp9840539

Fernández, E., Pérez-Pérez, A., Gamba, C., Prats, E., Cuesta, P., Anfruns, J., Molist, M., Arroyo-Pardo, E., Turbón, D., 2014. Ancient DNA Analysis of 8000 B.C. Near Eastern Farmers Supports an Early Neolithic Pioneer Maritime Colonization of Mainland Europe through Cyprus and the Aegean Islands. PLOS Genet. 10, e1004401. https://doi.org/10.1371/journal.pgen.1004401

Fraser, R.A., Bogaard, A., Heaton, T., Charles, M., Jones, G., Christensen, B.T., Halstead, P., Merbach, I., Poulton, P.R., Sparkes, D., Styring, A.K., 2011. Manuring and stable nitrogen isotope ratios in cereals and pulses: towards a new archaeobotanical approach to the inference of land use and dietary practices. J. Archaeol. Sci. 38, 2790–2804. https://doi.org/10.1016/j.jas.2011.06.024

Fraser, R.A., Bogaard, A., Schäfer, M., Arbogast, R., Heaton, T.H.E., 2013. Integrating botanical, faunal and human stable carbon and nitrogen isotope values to reconstruct land use and palaeodiet at LBK Vaihingen an der Enz, Baden-Württemberg. World Archaeol. 45, 492–517. https://doi.org/10.1080/00438243.2013.820649

Gackowski, J., 2012. Przestrzeń osadnicza Pojezierza Chełmińskiego i przyległych dolin Wisły, Drwęcy i Osy w młodszej epoce brązu i na początku epoki żelaza. Toruń, Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika.

Gluza, I., 1984. Neolithic cereals and weeds from the locality of the Lengyel Culture at Nowa Huta-Mogiła near Cracow. Acta Palaeobot. 23, 12–184.

Gluza, I., Tomczyńska, Z., Wasylikowa, K., 1988. Uwagi o użytkowaniu drewna w neolicie na podstawie analizy węgli drzewnych ze stanowisk archeologicznych w Krakowie-Nowej Hucie. Mater. Archeol. Nowej Huty 12, 7–26.

Godłowska, M., 1976. Próba rekonstrukcji rozwoju osadnictwa neolitycznego w rejonie Nowej Huty. Materiały Archeologiczne Nowej Huty 5, 7–180.

Godłowska M., Gluza I., 1989. Lengyel Culture. Cracow-Nowa Huta-Mogiła. Przegląd Archeologiczny 36, 225–227.

Gron, K.J., Gröcke, D.R., Larsson, M., Sørensen, L., Larsson, L., Rowley-Conwy, P., Church, M.J., 2017. Nitrogen isotope evidence for manuring of early Neolithic Funnel Beaker Culture cereals from Stensborg, Sweden. J. Archaeol. Sci. Rep. 14, 575–579. https://doi.org/10.1016/j.jasrep.2017.06.042

Grygiel, R., 2004. Neolit i początki epoki brązu w rejonie Brześcia Kujawskiego i Osłonek. Tom I: wczesny neolit, kultura ceramiki wstęgowej rytej. Łódź, Fundacja Badań Archeologicznych im. K. Jażdżewskiego, MAiE w Łodzi.

Grygiel, R., 2008. Neolit i początki epoki brązu w rejonie Brześcia Kujawskiego i Osłonek, tom II: Środkowy neolit. Grupa brzesko-kujawska kultury lendzielskiej. Fundacja Badań Archeologicznych Imienia Profesora Konrada Jażdżewskiego, Łódź.

Halstead, P., 2018. Forest clearance and land use by early farmers in Europe: Insights from north Greek oral history. Quat. Int., The Neolithic of Northern Greece and the Balkans – the environmental context of cultural transformation 496, 42–50. https://doi.org/10.1016/j.quaint.2017.04.010

Harding, A., Ostoja-Zagórski, J., Palmer, C. & Rackham, J., 2004. Sobiejuchy, a fortified site of the Early Iron Age in Poland. Warsaw, Institute of Archaeology and Ethnology.

Harding, A., Rączkowski, Z., 2010. Living on the lake in the Iron Age: new results from aerial photographs, geophysical survey and dendrochronology on sites of Biskupin type. Antiquity 84, 386–404.

Hellmund, M., 2008. The Neolithic records of Onopordum acanthium, Agrostemma githago, Adonis cf. aestivalis and Claviceps purpurea in Sachsen-Anhalt, Germany. Veg. Hist. Archaeobotany 17, 123–130. https://doi.org/10.1007/s00334-008-0180-8

Jacomet, S., Ebersbach, R., Akeret, Ö., Antolín, F., Baum, T., Bogaard, A., Brombacher, C., Bleicher, N.K., Heitz-Weniger, A., Hüster-Plogmann, H., Gross, E., Kühn, M., Rentzel, P., Steiner, B.L., Wick, L., Schibler, J.M., 2016. On-site data cast doubts on the hypothesis of shifting cultivation in the late Neolithic (c. 4300–2400 cal. BC): Landscape management as an alternative paradigm. The Holocene 26, 1858–1874. https://doi.org/10.1177/0959683616645941

Jankowska, D., 1980. Kultura pucharów lejkowatych na Pomorzu środkowym. Grupa Łupawska. Poznań: UAM

Jarosz, P., Szczepanek, A., Wołoszyn, M., 2012. Ratownicze badania wykopaliskowe na stanowiskach 6 i 8 w Zakrzowcu, gm. Niepołomice,woj. małopolskie, w 2007 roku, in: Kadrow, S. (ed.), Raport 2007–2008, vol. 1. Narodowy Instytut Dziedzictwa, Warszawa, pp. 303–320.

Jones, G., 1984. Interpretation of archaeological plant remains: ethnographic models from Greece, in: van Zeist, W., Casparie, W. (Eds.), Plants and Ancient Man. Balkema, Rotterdam, pp. 43–61.

Jones, G., 1987. A statistical approach to the archaeological identification of crop processing. J. Archaeol. Sci. 14, 311–323. https://doi.org/10.1016/0305-4403(87)90019-7

Jones, G., Bogaard, A., Charles, M., Hodgson, J.G., 2000. Distinguishing the Effects of Agricultural Practices Relating to Fertility and Disturbance: a Functional Ecological Approach in Archaeobotany. J. Archaeol. Sci. 27, 1073–1084. https://doi.org/10.1006/jasc.1999.0543

Jones, G., Charles, M., Bogaard, A., Hodgson, J., 2010. Crops and weeds: the role of weed functional ecology in the identification of crop husbandry methods. J. Archaeol. Sci. 37, 70–77. https://doi.org/10.1016/j.jas.2009.08.017

Kapcia, M., Mueller-Bieniek, A., 2017. Żołędzie (Quercus sp.) jako źródło pożywienia i paszy w pradziejowej gospodarce. Fragm Flor Geobot Pol. 24, 133–155.

Kapcia, M., Mueller-Bieniek, A., 2018. Archaeobotanical analysis of abundant cereal finds from Kraków Nowa-Huta Mogiła 62 – getting back to the old story. Folia Quat. 2018, 217–231. https://doi.org/10.4467/21995923FQ.18.004.9822

Kapcia, M., Mueller-Bieniek, A., 2019. An insight into Bronze Age subsistence strategy in forested Carpathian foothills, based on plant macro-remains. Archaeol. Anthropol. Sci. 11, 2879–2895. https://doi.org/10.1007/s12520-018-0720-9

Kluzik, A., 2010. Osada kultury pucharów lejkowatych w Krakowie Nowej Hucie-Mogile, stan. 62. Materiały Archeologiczne Nowej Huty 25, 7–66.

Kondracki, J., 2000. Geografia regionalna Polski, 2nd ed. Wydawnictwo Naukowe PWN, Warszawa.

Kotynia, K., 2016. Gospodarka roślinna na osadzie KPL w Mozgawie (stanowiska 1–3) na tle danych z południowo-wschodniej grupy kultury pucharów lejkowatych (Praca Magisterska). Jagiellonian University, Kraków.

Kowalska-Lewicka, A., 1961. Gospodarka i trzebież żarowa w Karpatach polskich w XIX i XX wieku. Uprawa krzycy. Etnografia Pol. 5, 101–116.

Koźmiński, C., 2001. Opady atmosferyczne. Precipitation. Okres - Period 1961-1995, in: Koźmiński, C., Michalska, B. (Eds.), Atlas... p. 21.

Koźmiński, C., Michalska, B. (Eds.), 2001a. Atlas klimatycznego ryzyka uprawy roślin w Polsce. Akademia Rolnicza, Szczecin.

Koźmiński, C., Michalska, B., 2001b. Usłonecznienie rzeczywiste. Actual insolation. Okres - Period 1966-1995, in: Koźmiński, C., Michalska, B. (Eds.), Atlas... p. 11.

Kreuz, A., Schäfer, E., 2011. Weed finds as indicators for the cultivation regime of the early Neolithic Bandkeramik culture? Veg. Hist. Archaeobotany 20, 333. https://doi.org/10.1007/s00334-011-0294-2

Kukułka, A., 2001. Wczesnoneolityczna osada w Gwoźdźcu, gm. Zakliczyn, stan. 2 na Pogórzu Wiśnickim, in: Gancarski, J. (red.), Neolit i początki epoki brązu w Karpatach polskich. Krosno, pp. 11–40.

Kruk, J., 1973. Studia osadnicze nad neolitem wyżyn lessowych. Zakład Narodowy im. Ossolińskich, Wrocław.

Kruk, J., 1980a. Gospodarka w Polsce południowo-wschodniej w V-III tysiącleciu p.n.e. Zakład Narodowy im. Ossolińskich, Wrocław.

Kruk, J., 1980b. The Neolithic Settlement of Southern Poland. Oxford, British Archaeological Reports (Int. Series 93).

Kruk, J., Milisauskas, S., 1999. Rozkwit i upadek społeczeństw rolniczych neolitu. Instytut Archeologii i Etnologii Polskiej Akademii Nauk, Kraków.

Lityńska, M., 1990. Zboża i chwasty z neolitycznego stanowiska Iwanowice-Klin, woj. Kraków. Spraw. Archeol. 42, 105–108.

Lityńska-Zając, M., 2005. Chwasty w uprawach roślinnych w pradziejach i wczesnym średniowieczu. Instytut Archeologii i Etnologii Polskiej Akademii Nauk, Kraków.

Lityńska-Zając, M., 2007. Early Neolithic agriculture in south Poland as reconstructed from archaeobotanical plant remains, in: Colledge, S., Conolly, J. (Eds.), The Origins and Spread of Domestic Plants in Southwest Asia and Europe. Left Coast Press, Walnut Creek, pp. 315–326.

Lityńska-Zając, M., 2018. A Man and a Plant: Archaeobotany, in: Pişkin, E., Marciniak, A., Bartkowiak, M. (Eds.), Environmental Archaeology, Interdisciplinary Contributions to Archaeology. Springer, Cham, pp. 75–110. https://doi.org/10.1007/978-3-319-75082-8_5

Lityńska-Zając, M., Czekaj-Zastawny, A., Rauba-Bukowska, A., 2017a. Utilisation of cultivated and wild plants in the economy of the Linear Pottery culture in the Upper Vistula Basin. Spraw. Archeol. 69, 271–296. https://doi.org/10.23858/SA69.2017.011

Lityńska-Zając, M., Moskal-del Hoyo, M., Mueller-Bieniek, A., Wacnik, A., 2017b. Stan i problematyka badań archeobotanicznych w polskiej części Karpat, in: Gancarski, J. (Ed.), Stan i potrzeby badań archeologicznych w Karpatach. Muzeum Podkarpackie w Krośnie, Krosno, pp. 719–750.

Lityńska-Zając, M., Tomczyńska, Z., Cywa, K., Wasylikowa, K., Madeyska, E., 2015. Badania archeobotaniczne materiałów roślinnych kultury mierzanowickiej ze stanowiska 6/8 w Zakrzowcu, gm. Niepołomice, woj. małopolskie, in: Górski, J., Jarosz, P. (Eds.), Wielofazowe osady kultury mierzanowickiej w Targowisku i Zakrzowcu na Podgórzu Bocheńskim, Via Archaeologica, Źródła z badań wykopaliskowych na trasie autostrady A4 w Małopolsce. Krakowski Zespół do Badań Autostrad, Kraków, pp. 233–238.

Lityńska-Zając, M., Wasylikowa, K., Cywa, K., Tomczyńska, Z., Madeyska, E., Koziarska, A., Skawińska-Wieser, K., 2014. Brzezie, stan. 17, gm. Kłaj. Materiały archeobotaniczne z obiektów kultury ceramiki wstęgowej rytej, in: Czekaj-Zastawny, A. (Ed.), Materiały archeobotaniczne z obiektów kultury ceramiki wstęgowej rytej, in: A. Czekaj-Zastawny, Brzezie 17. Osada kultury ceramiki wstęgowej rytej, Via Archaeologica. Źródła z badań wykopaliskowych na trasie autostrady A4 w Małopolsce. Krakowski Zespół do Badań Autostrad, Kraków, pp. 405–436.

Luijten, H., 1995. Macro-botanical analysis of two Funnel Beaker Culture settlement sites Poganice 4 (zones 2 and 5), Potęgowo commune, Słupsk voivodeship (Pomerania, Poland). Folia Praehist. Posnaniensia 7, 81–99.

Machnikowie, A., & J., Kaczanowski, K., 1987. Osada i cmentarzysko z wczesnego okresu epoki brązu na „Górze Klin" w Iwanowicach. Wrocław.

Magny, M., Bégeot, C., Guiot, J., Peyron, O., 2003. Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. Quat. Sci. Rev. 22, 1589–1596. https://doi.org/10.1016/S0277-3791(03)00131-8

Matuszkiewicz, J.M., 1993. Krajobrazy roślinne i regiony geobotaniczne Polski, Prace Geograficzne. Zakład Narodowy im. Ossolińskich, Wrocław.

Matuszkiewicz, J.M., 2008. Potencjalna roślinność naturalna Polski. Instytut Geografii i Przestrzennego Zagospodarowania Polskiej Akademii Nauk, Warszawa

Mauri, A., Davis, B.A.S., Collins, P.M., Kaplan, J.O., 2015. The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation. Quat. Sci. Rev. 112, 109–127. https://doi.org/10.1016/j.quascirev.2015.01.013

McClatchie, M., 2014. Archaeobotany of Agricultural Intensification, in: Smith, C. (Ed.), Encyclopedia of Global Archaeology. Springer New York, New York, NY, pp. 310–318. https://doi.org/10.1007/978-1-4419-0465-2_2262

Michalska, B., 2001. Temperatura powietrza. Air temperature. Srednie miesięczne i roczne. Monthly and annual means. Okres-Period 1961-1995, in: Koźmiński, C., Michalska, B. (Eds.), Atlas... pp. 13–14.

Milisauskas, S., Kruk, J., Ford, R., Lityńska-Zając, M., 2012. Neolithic plant exploitation at Bronocice. Spraw. Archeol. 64, 77–112.

Moskal-del Hoyo, M., Mueller-Bieniek, A., Alexandrowicz, W.P., Wilczyński, J., Wędzicha, S., Kapcia, M., Przybyła, M.M., 2017. The continuous persistence of open oak forests in the Miechów Upland (Poland) in the second half of the Holocene. Quat. Int., Anthracology: Local to Global Significance of Charcoal Science Part II 458, 14–27. https://doi.org/10.1016/j.quaint.2016.11.017

Moskal-del Hoyo, M., Wacnik, A., Alexandrowicz, W.P., Stachowicz-Rybka, R., Wilczyński, J., Pospuła-Wędzicha, S., Szwarczewski, P., Korczyńska, M., Cappenberg, K., Nowak, M., 2018. Open country species persisted in loess regions during the Atlantic and early Subboreal phases: New multidisciplinary data from southern Poland. Rev. Palaeobot. Palynol. 253, 49–69. https://doi.org/10.1016/j.revpalbo.2018.03.005

Mueller-Bieniek, A., 2011. Makroszczątki roślinne z wielokulturowego stanowiska Pęcławice 5, gmina Piątek, powiat Łęczyca, województwo łódzkie, in: Dziubek, E., Marchelak, I., Tyszler, L. (Eds.), Ratownicze badania archeologiczne na stanowisku 5 w Pęcławicach, pow. Łęczyca, woj. łódzkie (trasa autostrady A-1), Via Archaeologica Lodziensis. Fundacja Badań Archeologicznych im. Profesora Konrada Jażdżewskiego and Muzeum Archeologiczne w Łodzi, Łódź, pp. 353–376.

Mueller-Bieniek, A., 2016. Badania materiałów roślinnych związanych z kulturą pucharów lejkowatych w rejonie Brześcia Kujawskiego i Osłonek, in: In: R. Grygiel. Neolit i początki epoki brązu w rejonie Brześcia Kujawskiego i Osłonek. Tom III. Środkowy i późny neolit, kultura pucharów lejkowatych. Fundacja Badań Archeologicznych Imienia Profesora Konrada Jażdżewskiego, Łódź, pp. 753–769.

Mueller-Bieniek, A., Kittel, P., Muzolf, B., Cywa, K., Muzolf, P., 2016. Plant macroremains from an early Neolithic site in eastern Kuyavia, central Poland. Acta Palaeobot. 56, 79–89. https://doi.org/10.1515/acpa-2016-0006

Mueller-Bieniek, A., Kittel, P., Muzolf, B., Muzolf, P., 2015. Useful plants from the site Lutomiersk–Koziówki near Łódź (central Poland) with special reference to the earliest find of Xanthium strumarium L. seeds in Europe. J. Archaeol. Sci. Rep. 3, 275–284. https://doi.org/10.1016/j.jasrep.2015.06.025

Mueller-Bieniek, A., Pyzel, J., Kapcia, M., 2018a. Chenopodium seeds in open-air archaeological sites - how to not throw the baby out with the bathwater. Environ. Archaeol.

Mueller-Bieniek, A., Pyzel, J., Kapcia, M., 2018b. Chenopodium Seeds in Open-Air Archaeological Sites – How to Not Throw the Baby Out with the Bathwater. Environ. Archaeol. 1–13. https://doi.org/10.1080/14614103.2018.1536500

Nalepka, D., 2005. Late Glacial and Holocene palaeoecological conditions and changes of vegetation cover under early farming activity in the south Kujawy region (Central Poland), Acta Palaeobotanica Supplement. Instytut Botaniki im. W. Szafera, Polska Akademia Nauk, Kraków.

Nitsch, E.K., Charles, M., Bogaard, A., 2015. Calculating a statistically robust δ13C and δ15N offset for charred cereal and pulse seeds. STAR Sci. Technol. Archaeol. Res. 1, 1–8. https://doi.org/10.1179/2054892315Y.0000000001

Nowak, M., 2006. Transformations in East-Central Europe from 6000 to 3000 BC: local vs. foreign patterns. Doc. Praehist. 33, 143–158.

Nowak, M., 2009. Drugi etap neolityzacji ziem polskich. Księgarnia Akademicka, Kraków.

Nowak, M., Moskal-del Hoyo, M.M., Mueller-Bieniek, A., Lityńska-Zając, M., Kotynia, K., 2017. Benefits and weaknesses of radiocarbon dating of plant material as reflected by Neolithic archaeological sites from Poland, Slovakia and Hungary. Geochronometria 44, 188–201. https://doi.org/10.1515/geochr-2015-0066

Palmer, C., 2004. Palaeoeconomic and palaeoenvironmental studies: 1. The carbonized macroscopic plant remains, in: Harding, A., Ostoja-Zagórski, J., Palmer, C., Rackham, J. (Eds.), Sobiejuchy, a Fortified Site of the Early Iron Age in Poland. Institute of Archaeology and Ethnology Polish Academy of Sciences, Warsaw, pp. 66–119.

Podogrocki, J., 2001. Promieniowanie całkowite. Global radiation. Okres - Period 1976-1995, in: Koźmiński, C., Michalska, B. (Eds.), Atlas... p. 10.

Przybyła, M.S., 2016. Early Bronze Age stone architecture discovered in the Polish Carpathians. Archäologisches Korrespondenzblatt 46, 291–308.

Przybyła, M.S., Blajer, W., 2008. Struktury osadnicze w epoce brązu i wczesnej epoce żelaza na obszarze podkarpackiej wysoczyzny lessowej między Wisłokiem i Sanem. Kraków, Wydawnictwo Uniwersytetu Jagiellońskiego.

Przybyła, M.M., Skoneczna, M., Vitoš, A., 2012. Interregional Contacts or Local Adaptation? Studies on the Defensive Settlement from the Bronze and Early Iron Age in Maszkowice (Western Carpathians), in: Jaeger, M., Czebreszuk, J., Fischl, K.P. (Eds.), Enclosed Space — Open Society. Contact and Exchange in the Context of Bronze Age Fortified Settlements in Central Europe, Studien Zur Archäologie in Ostmitteleuropa. Poznań–Bonn, pp. 225–273.

Przybyła, M.S., Skoneczna, M., 2014. The Bronze Age settlement in Maszkowice (Western Carpathians) – analyses and interpretations, in: Kienlin, T.L., Valde-Nowak, P., Korczyńska, M., Cappenberg, K., Ociepka, J. (Eds.), Settlement, Communication and Exchange around the Eastern Carpathians in European Context. Archaeopress, Oxford, pp. 265–285.

Pyzel, J., 2012. Preliminary results of large scale emergency excavations in Ludwinowo 7, comm. Włocławek. New research on the Linear Pottery Culture in Kuyavia, in: Wolfram, S., Stäuble, H. (eds.), Siedlungsstruktur und Kulturwandel in der Bandkeramik. Beiträge der internationalen Tagung „Neue Fragen zur Bandkeramik oder alles beim Alten?!“ Leipzig 23. bis 24. September 2010. Dresden: Landesamt für Archäologie, Dresden ,pp. 160–166

Ramsey, C.B., 2008. Radiocarbon Dating: Revolutions in Understanding*. Archaeometry 50, 249–275. https://doi.org/10.1111/j.1475-4754.2008.00394.x

Rook, E., 1971. Materiały kultury ceramiki promienistej odkryte na stanowisku Nowa Huta-Pleszów (badania w latach 1954–1963). Materiały Archeologiczne Nowej Huty 4, 111–236.

Rook, E., 1980. Osadnictwo neolityczne w jaskiniach Wyżyny Krakowsko-Częstochowskiej. Materiały Archeologiczne XX, 5–130.

Rook, E., Nowak, M., 1993. Sprawozdanie z badań wielokulturowego stanowiska w Krakowie-Prądniku Czerwonym, w latach 1990 i 1991. Spraw. Archeol. 45, 35–73.

Rösch, M., Biester, H., Bogenrieder, A., Eckmeier, E., Ehrmann, O., Gerlach, R., Hall, M., Hartkopf-Fröder, C., Herrmann, L., Kury, B., Lechterbeck, J., Schier, W., Schulz, E., 2017. Late Neolithic Agriculture in Temperate Europe—A Long-Term Experimental Approach. Land 6, 1–17.

Rösch, M., Kleinmann, A., Lechterbeck, J., Wick, L., 2014. Botanical off-site and on-site data as indicators of different land use systems: a discussion with examples from Southwest Germany. Veg. Hist. Archaeobotany 23, 121–133. https://doi.org/10.1007/s00334-014-0437-3

Silva, F., Linden, M.V., 2017. Amplitude of travelling front as inferred from 14 C predicts levels of genetic admixture among European early farmers. Sci. Rep. 7, 11985. https://doi.org/10.1038/s41598-017-12318-2

Sobkowiak-Tabaka, I., Kabaciński, J., 2012. Ratownicze badania wykopaliskowe Zespołu Archeologicznych Badań Ratowniczych przy Ośrodku Studiów Pradziejowych i Średniowiecznych Instytutu Archeologii i Etnologii PAN w latach 2007–2008 na trasach budowy autostrad, in: Kadrow, S. (ed.), Raport 2007–2008 (1). Narodowy Instytut Dziedzictwa, Warszawa, pp. 11–41.

Soil Atlas of Europe - ESDAC - European Commission [WWW Document], 2005. URL https://esdac.jrc.ec.europa.eu/content/soil-atlas-europe (accessed 2.28.19).

Starkel, L., Michczyńska, D.J., Krąpiec, M., Margielewski, W., Nalepka, D., Pazdur, A., 2013. Progress in the holocene chrono-climatostratigraphy of Polish territory. Geochronometria 40, 1–21. https://doi.org/10.2478/s13386-012-0024-2

Styring, A., Rösch, M., Stephan, E., Stika, H.-P., Fischer, E., Sillmann, M., Bogaard, A., 2017. Centralisation and long-term change in farming regimes: Comparing agricultural practices in Neolithic and Iron Age south-west Germany. Proc. Prehist. Soc. 83, 357–381. https://doi.org/10.1017/ppr.2017.3

Styring, A.K., Ater, M., Hmimsa, Y., Fraser, R., Miller, H., Neef, R., Pearson, J.A., Bogaard, A., 2016. Disentangling the effect of farming practice from aridity on crop stable isotope values: A present-day model from Morocco and its application to early farming sites in the eastern Mediterranean. Anthr. Rev. 3, 2–22. https://doi.org/10.1177/2053019616630762

Szpak, P., 2014. Complexities of nitrogen isotope biogeochemistry in plant-soil systems: implications for the study of ancient agricultural and animal management practices. Front. Plant Sci. 5. https://doi.org/10.3389/fpls.2014.00288

Tieszen, L.L., 1991. Natural variations in the carbon isotope values of plants: Implications for archaeology, ecology, and paleoecology. J. Archaeol. Sci. 18, 227–248. https://doi.org/10.1016/0305-4403(91)90063-U

Tomczyńska, Z., Wasylikowa, K., 1988. Plant material from a Hallstatt settlement at Kamieniec near Toruń, north Poland (A reinvestigation), in: Küster, H.J. (Ed.), Der Prähistorische Mensch Und Seine Umwelt, Festschrift Für Uldegard Körber-Grohne. Konrad Theiss, Stuttgart, pp. 281–287.

Tunia, K., 1985. Aus der problematik der Fundstelle „G" in Słonowice, Woiw. Kielce. Forschungen 1979–1982. 1. Vorbericht, in: Gedl, M. (ed.), Frühbronzezeitliche befestigte Siedlungen in Mitteleuropa. Warszawa (Archaeologia Interregionalis 6), pp. 207–218.

Vaiglova, P., Bogaard, A., Collins, M., Cavanagh, W., Mee, C., Renard, J., Lamb, A., Gardeisen, A., Fraser, R., 2014. An integrated stable isotope study of plants and animals from Kouphovouno, southern Greece: a new look at Neolithic farming. J. Archaeol. Sci. 42, 201–215. https://doi.org/10.1016/j.jas.2013.10.023

Wallace, M., Jones, G., Charles, M., Fraser, R., Halstead, P., Heaton, T.H.E., Bogaard, A., 2013. Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. World Archaeol. 45, 388–409. https://doi.org/10.1080/00438243.2013.821671

Wasylikowa, K., 1989. Paleoecological characteristics of the settlement periods of the linear pottery and lengyel cultures at Cracow – Nowa Huta (on the basis of plant material). Przegląd Archeol. 36, 57–87.

Wasylikowa, K., Starkel, L., Niedziałkowska, E., Skiba, S., Stworzewicz, E., 1985. Environmental changes in the Vistula valley at Pleszów caused by Neolithic man. Przegląd Archeol. 33, 19–55.

Wierzbicki, J., 1995. Wstępne wyniki badań wykopaliskowych osiedli ludności kultury pucharów lejkowatych na stanowisku Poganice 4 (strefy 2 i 5), gm. Potęgowo, woj. Słupskie. Folia Praehistorica Posnaniensia 7, 53–81 + opr. Archeobotaniczne.

Wierzbicki, J., 1999. Łupawski mikroregion osadniczy ludności kultury pucharów lejkowatych. Wydawnictwo Naukowe UAM, Poznań.

Zhang, Y., Renssen, H., Seppä, H., Valdes, P.J., 2017. Holocene temperature evolution in the Northern Hemisphere high latitudes – Model-data comparisons. Quat. Sci. Rev. 173, 101–113. https://doi.org/10.1016/j.quascirev.2017.07.018

Zielonka, B., 1955. Materiały z osiedla obronnego kultury łużyckiej w miejscowości Kamieniec, pow. Toruń. Wiadomości Archeologiczne 22(2), 159–174.

Captions

Fig. 1. Location of the studied sites (**A-C**); numbering of sites as in Table 2; **D** annual precipitation, mean in period of 1961-1995 (after Koźmiński 2001).

Fig. 2. $\delta^{13}C$ and $\delta^{15}N$ values of all cereal grains included in this study, colour-coded by taxa. The shape of the symbols corresponds to the archaeological period.

Fig. 3. $\delta^{15}N$ values of carbonized cereal grains from Poland dating to between the Early Neolithic and Iron Age. The shapes of the symbols represent different archaeological contexts within each time period and region, i.e. all barley and millet grains from northern Poland dating to the Bronze/Early Iron Age derive from a single archaeological context.

Fig. 4. $\delta^{13}C$ values of carbonized cereal grains from Poland dating to between the Early Neolithic and Iron Age. The shapes of the symbols represent different archaeological contexts within each time period and region.

Table 1. Simplified periodisation of Neolithic and Bronze/Early Iron Age archaeological units mentioned in the paper

Table 2. Archaeological sites. More detailed data, including archaeobotanical context, are given in ESM (S1 and S7). [1] These data refer to the context of the sample from which isotope values were obtained (i.e. some of the sites were occupied in different prehistoric and early historic periods); [2] dates in bold are based on absolute dating and other evidence from the site itself, i.e. they present the most probable timeframes of site occupation. Dates not in bold are based on data external to the site, i.e. they rather present possible dates between which occupation of the site could have taken place

Table 3. Stable isotope results of the Neolithic and Bronze Age/Early Iron Age sites from Poland. The last column: EN -Early Neolithic, MN - Middle Neolithic, B – Bronze Age, B/I -Bronze/Iron Age.

Supplementary files:

Table S1. General archaeological and environmental characteristics of the studied sites. [1] data refer to the context of the sample from which isotope values were obtained (i.e. some of the sites were occupied in different prehistoric and early historic periods); [2] dates in bold are based on absolute dating and other evidence from the site itself, i.e. they present the most probable timeframes of site occupation; dates not in bold are based on data external to the site, i.e. they rather present possible dates between which occupation of the site could have taken place. Place of plant material storage: IAE PAS – Institute of Archaeology and Ethnology, Centre for Archaeology of Hills and Upplands, Polish Academy of Sciences; MAK – Archaeological Museum in Kraków; IB PAS – W. Szafer Institute of Botany, Polish Academy of Sciences, IA UJ 0 Institute of Archaeology, Jagiellonian University, Kraków; Potential natural vegetation after Matuszkiewicz 2008.

Table S2. General archaeological and archaeobotanical information about the studied features. **[1]** all ^{14}C datings obtained from a given feature, including those from samples with isptopic determinations (highlighted in bold); **[2]** if there are no more detailed dates or comments the general timeframes should be considered as identical to those cited in Table S1 for the whole site.

Table S3. Simplified archaeobotanical information from the studied samples. Dom – dominant cultivated plant, Ad/Cont – admixture in the main crop, Eq – dominant plants represented equally, probably from two or more different plots, ? – uncertain, y – presence, n – absence.

Table S4. Archaeobotanical context of the features from Mozgawa 1-3 site studied in the paper (after Kotynia 2016 and Mueller-Bieniek unpubl., stored in ArboDatMulti). Seed - inludes also fruits and grains; ch - charred; mi - mineralised; ot - uncharred, recent contamination.

Table S5. Botanical context of the samples from Mozgawa 1-3 site studied in the paper (after Kotynia 2016 and Mueller-Bieniek unpubl., stored in ArboDatMulti). All specimens charred eccept from 2 seeds of Tabacco

Table S6. Ludwinowo 7, feature B32 (sample 7/560), botanical context of the sample studied in the paper (Mueller-Bieniek unpubl.). All specimens charred.

Table S7. Botanical data from the studied samples from Sobiejuchy (after Palmer 2004).

Table S8. Sample and standard EA-IRMS δ13C data.

Table S9. Sample and standard EA-IRMS δ15N data.

Table S10. Calibration of the results from Session 1 and Session 2.

Table S11. Uncertainty calculations for d13C.

Table S12. Uncertainty calculations for d15N

Supplementary Text1

Archaeobotany of the studied sites

Detailed data about the sampled archaeological features and their archaeobotanical context are given in tables S2 – S7.

1. **Brzezie** site 17 was studied within an environmental program for motorway rescue excavations (Lityńska-Zając et al., 2014). In total, 1952 soil samples from diverse types of LBK features (constructional pits, pits connected with different activities, near-house pits, storage pits, hearths, ovens, post-holes, ditches, and graves) were analyzed archaeobotanically. The majority of charred plant remains were found in two samples taken from a utility pit (feature no. 1357). In addition to 1961 grains of wheats, only six chaff remains and two fruitlets of *Polygonum* sp. were noted here. Apart from the mentioned feature, only 268 crop grains (including *Hordeum vulgare*, *Secale cereale*, *Triticum aestivum*, *T. spelta*, *T. monococcum* and *T. dicoccum*), 46 chaff remains, and 102 fruits or seeds of wild plants were noted in the whole LBK material from this multicultural site. The authors of the study underlined the possibility of redeposition and contamination of the LBK features by younger material. The archaeological and botanical context of the material taken for isotopic studies seems undisturbed, but on the basis of this pure storage deposit (fine sieve product according to Jones, 1984, 1987), we cannot get any botanical information from weed seeds about the methods of cultivation.

2. At the site of **Iwanowice Klin**, a sample from feature 8, dated to the L-PC but with a radiocarbon date from the LBK, as well as samples from TRB pits with isolated impressions of emmer grains were studied (Lityńska, 1990). Feature 8 contained a mixture of emmer and einkorn grains, mostly fragmented but charred at a relatively low temperature, based on visible inspection. In the feature wild plants were also noted, of which the most numerous were brome grass grains (mostly *Bromus hordeaceus* L., and a few grains of *B. tectorum* L.) and *Lithospermum arvense* L. diaspores. One seed of *Agrostemma githago* was also noted, a field weed which became frequent in archaeobotanical samples from the Middle Neolithic TRB (Hellmund, 2008; Lityńska-Zając, 2007, 2005).

3. **Zakrzowiec** 6/8 was studied during motorway rescue excavations. Archaeological and archaeobotanical studies of this multicultural site have not yet been published, except for the Early Bronze Age materials (Lityńska-Zając et al., 2015). The subsample selected for isotopic analysis was taken from a cleaned grain deposit (fine sieve product). Apart from emmer grains it also contained some wheat chaff remains as well as single brome grass grains (*Bromus* sp.). At the site several wild plants were noted including *Agrostemma githago*, however the dating of the samples is still unknown (Lityńska-Zając unpubl.).

4. At the multiperiod site of **Kraków-Mogiła** 62, a large amount of wheat grains with only limited admixture of other plants (fine sieve product) was found in pit no. 395 (or group of pits) as a thick layer of black sediment. The material was provisionally studied and published in a paper focused on wood charcoal (Gluza et al. 1988). New subsamples were recently studied, including archaeological documentation and radiocarbon dating of grain samples from the top and the bottom of the layer

(Kapcia and Mueller-Bieniek, 2018). The material is dated to the TRB. A large proportion of the wheat and brome grass grains (mostly *Bromus racemosus*) had germinated before charring. In the material single remains of corn cockle (*Agrostemma githago*) and feather grass (*Stipa* sp.) were also noted. The other feature from that site (no. 416), connected to the Lengyel-Polgár complex, which was archaeobotanically studied by I. Gluza (1984), was not sampled for this research.

5. The plant material from **Kraków-Pleszów** 17-20 was studied and stored at the Institute of Botany PAS (IB PAS) and results were published in a paper about wood charcoal (Gluza et al., 1988), in which the site was assigned to the Baden culture. In that area archaeobotanical and palaeoenvironmental studies were focused mostly on the beginning of the Neolithic (LBK and L-PC) and based on waterlogged sediments taken as cores from the transitional zone between a loess terrace and the Vistula palaeochannel (Wasylikowa, 1989; Wasylikowa et al., 1985). Archaeological dating is based on unpublished information stored together with the material at IB PAS. The composition of the plant assemblage suggests that it was a storage deposit of a fine sieve product. In the site 13 features, dated to the L-PC, and 26 features, dated to the Baden culture, were also studied (Gluza et al., 1988) but the plant material was generally scarce.

6. At **Kraków Prądnik Czerwony** there was a large storage deposit of emmer with a small admixture of einkorn and wild plants and several chaff remains of those wheats (fine sieve product) dated to the TRB. From that sample several subsamples were taken for isotopic analyses (Lityńska-Zając, 2005; Rook and Nowak, 1993).

7. Site 1-3 at **Mozgawa** was recently subject to intensive archaeobotanical investigation (Kotynia, 2016; Moskal-del Hoyo et al., 2018; Nowak et al., 2017). A large part of the samples is still under study. Detailed data derived from the subsampled features are given as supplementary material (Table S4). At the site mostly grains of wheats were noted, including emmer and einkorn but possibly also spelt. Several seeds of flax (*Linum usitatissimum*) and lentils (*Lens culinaris*) were noted. Also peas (*Pisum sativum*) were present in the material. Barley is very rare and only its naked form is confirmed. Among the wild plants, brome grass (*Bromus* sp.), fat-hen (*Chenopodium album* type), *Lithospermum arvense* (=*Buglossoides arvensis*), as well as *Fragaria* sp., dominated. *Agrostemma githago*, *Fallopia convolvulus*, *Sambucus ebulus*, *Rumex acetosella* and *Stipa* sp. were also numerous. At the site traces of activity other than those dating to the TRB are scarce and the samples selected to isotopic studies contained almost pure charred material with very scarce traces of recent contamination (Table S5).

8. The archaeobotanical material from **Jerzmanowice** (Nietoperzowa Cave) was sent to IB PAS by W. Chmielewski in 1962. It was identified by K. Wasylikowa and is not yet published. The charred grains

were embedded in a carbonate dripstone cave. Apart from wheat grains (mostly emmer and einkorn), numerous wheat chaff remains belonging to those two taxa were also noted. No wild plants were found (fine sieve product).

9. The material from **Słonowice** site G is partly published (Calderoni et al., 2000; Lityńska-Zając, 2005). The isotopically studied sample from feature 28 contained a large number of hulled barley grains with some admixture of pea seeds and a few species of weeds eg.: *Agrostemma githago*, *Bromus secalinus*, *Galium spurium* and *Setaria viridis*. In several samples derived from other features at the site ruderal plants were noted, indicating anthropogenic changes to the local environment (Lityńska-Zając unpubl.).

10. At **Gwoździec** site 2, a sample of pure emmer grain was taken for isotopic studies (fine sieve product). At this LBK site apple remains were also noted (Bieniek and Lityńska-Zając, 2001), as well as several other plants, including root crop weeds (*Echinochloa crus galli*, *Setaria viridis/verticillata*, *Polygonum minus*, *P. persicaria*). Fat-hen seeds (*Chenopodium album* type) and brome grass grains (*Bromus hordeaceus*, *B. tectorum* and *B*. sp.) were numerous. Single remains of flax (*Linum usitatissimum*), *Mentha* sp., *Capsella bursa-pastoris* and *Rumex acetosa* were also found (Lityńska-Zając, 2007; Lityńska-Zając et al., 2017a).

11. The studied sample from **Maszkowice** 1 was taken from a pure storage deposit of hulled barley, with admixture of only small seeded grasses (cf. *Apera spica-venti*). The pit was excavated in the 1970s and studied by I. Gluza (unpubl.). During the last ten years new archaeobotanical studies have been carried out using a denser sampling method. New studies show that the most numerous remains at the site are of cultivated plants including millet, barley, spelt, emmer and einkorn. Wild plants are also found (*Corylus avellana*, *Rubus* sp., *Trifolium* sp., *Galium aparine*, *Urtica dioica*, *Chenopodium album*, *Bromus* sp. and several fragments of fruit stones of probable Rosaceae) (Mueller-Bieniek and Przybyła unpubl).

12. At the site of **Lipnik** 5 usually only small samples were taken from a few features and they produced no plant remains except for wood charcoal and single millet grains. However in one pit (302), a concentration of charred acorns was noted and the feature was well sampled for archaeobotanical study (Kapcia and Mueller-Bieniek, 2019, 2017). The pit contained a mixed storage deposit of acorns, millet (*Panicum miliaceum*), spelt, emmer, einkorn and barley (naked and hulled). Millet dominated in terms of the number of items and acorns in terms of volume. Seeds and fruits of wild taxa were very numerous and usually well preserved. Weeds and ruderals (*Chenopodium album*, *Digitaria ischaemum* and *D*. sp., *Echinochloa crus-galli*, *Polygonum persicaria*) dominated in terms of the number of items, but plants growing in more natural habitats (grasslands and forests) were

represented by numerous taxa and items (*Medicago lupulina*, *Plantago lanceolata*, P. *major/media*, *Rhinanthus* sp., *Scleranthus annuus/perennis*, *Trifolium* cf. *pretense*, *Origanum vulgare*, *Verbascum* sp., *Verbena officinalis*, *Linum carthlicum*, *Hypericum* sp., *Agrimonia eupatoria*, *Astragalus cicer/glycyphyllos*, *Astrantia major* and others). The site is important for understanding the subsistence strategy of the Bronze Age settlers in a marginal area of the Carpathian Foothills. Among the very rich plant material no remains of *Agrostemma githago* were noted.

13. **Miechowice** site 4 yielded plant macroremains dated to the LBK and L-PC. In the samples dated to the LBK, mostly wheat chaff remains were noted (einkorn, *Triticum monococcum*; emmer, *T. dicoccum* and the 'new' type of glume wheat) as well as numerous seeds of fat-hen (*Chenopodium album*), while other plant remains were not numerous (single remains of flax and peas, some remains of *Fallopia convolvulus* and others) (Bieniek, 2007; Mueller-Bieniek et al., 2018b). In samples dated to the L-PC, wheat chaff remains (emmer, einkorn and the 'new' type) dominated but wheat grains were also noted (in three samples more than 15 grains of emmer in each). However only one sample (from pit 30) contained a number of well-preserved wheat grains suitable for isotopic analysis. Additionally numerous remains of feather grass (*Stipa* sp.) were found. Other wild plants were not numerous (*Bromus hordeaceus*, *B. racemosus/arvensis*, *Chenopodium album* type, *Fallopia convolvulus*, *Galium aparine*, *G. spurium*, *G. verum* type, *Hierochloë/Alopecurus*, *Trifolium* sp.).

14. At **Osłonki** site 1 only L-PC samples were studied. The material is dominated by wheat grains but remains of feather grass were also very numerous. Wheat chaff remains were numerous but not as dominant as at other Kuyavian sites (Bieniek, 2007; Mueller-Bieniek et al., 2016). In Osłonki 1 a storage deposit of wheat was found (pit 149), which contained mostly emmer with an admixture of einkorn and probably the 'new' type of glume wheat. Some of the grains were probably immature prior to charring. The representation of other plants and their proportion is not clear because the samples were sieved in diverse ways, including using a coarse sieve in the field (ca. 2 mm mesh size). Additionally, among wild plants, single or very few items of *Bromus racemosus/arvensis*, *B. sterilis/tectorum*, *Chenopodium album* type, *Fallopia convolvulus*, *Fragaria vesca*, *Galium verum* type, *Hierochloë cf. australis* and *Setaria viridis/verticillata* were found. From the mentioned pit 149, four subsamples of emmer and two subsamples of einkorn were selected for isotopic analysis. The other three samples were taken from two other features (Table 3).

15. From **Ludwinowo** site 7 no Neolithic crop grains suitable for isotopic analysis were available despite detailed analysis of 438 LBK samples (Mueller-Bieniek et al., 2018a). Samples from younger periods were also analyzed at the site, including a sample from feature B32, dated to the Lusatian culture. In the sample lots of wheat grains were found (spelt, emmer and einkorn), (Tables S2, S3 and S6), ca. 4000 in 1 liter of sediment, with admixture of numerous wheat chaff remains and brome

grass grains (*Bromus* sp.). From the pit two subsamples of spelt and emmer were selected for isotopic analysis (Table 3). In the samples dated to younger than the Neolithic (200 samples), most probably dated to the Lusatian culture, millet (*Panicum miliaceum*) grains were frequent as well as hulled wheats and several wild plants, however no seeds of *Agrostemma githago* were found at the whole site (Mueller-Bieniek unpubl.)

16. At the fortified settlement of **Sobiejuchy** in Pałuki the material was selected from samples containing high numbers of crop grains. At the site, remains of several cultivated plants were noted, including millet (*Panicum miliaceum*), barley (*Hordeum vulgare*), spelt (*T. spelta*), emmer (*T. dicoccum*), lentil (*Lens culinaris*), pea (*Pisum sativum*), horse bean (*Vicia faba* var. *minor*) and possibly cultivated gold-of-pleasure (*Camelina* sp.) and oat (*Avena* sp.) (Palmer, 2004). Several remains of at least 35 wild plant taxa were also noted, both weeds and perennials. The subsamples of barley, millet, emmer and spelt were taken from three contexts (Table 3) and the detailed plant composition of these is given in Table S7 (after Palmer, 2004).

17. **Kamieniec** is the other fortified settlement from northern Poland (Chełmno Land) analyzed in our study. The archaeobotanical analysis and following reexamination was done by Z. Tomczyńska and K. Wasylikowa (1988). The sample contained mostly spelt and emmer with admixture of barley, peas, horse bean and lentils. Among the wild plants the only numerous taxa was brome grass grains (*Bromus secalinus*), while other wild taxa were represented by single or a few items (*Fallopia convolvulus*, *Polygonum aviculare*, *P. lapathifolium*, *Chenopodium album*, *C. hybridum*, *Elymus repens*, *Vicia sativa*, *Galium spurium*). In the sample ergot was also identified (*Claviceps purpurea*), but no remains of *Agrostemma githago*. Two subsamples of spelt and emmer were selected for isotopic analysis (Table 3).

18. The site of **Poganice** was studied archaeobotanically by an international team comprising H. Luijten, A. E. van Giffen and M. Polcyn (Luijten, 1995; Wierzbicki, 1999). The sample of emmer grains was analysed earlier by K. Wasylikowa (1977), however, and was stored at IB PAN. The sample of pure grain represents a fine sieve product or reflects the method of archaeological sampling.