



Terrestrial diet in prehistoric human groups from southern Poland based on human, faunal and botanical stable isotope evidence

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ABSTRACT

We present stable carbon and nitrogen isotope analyses of animal and human bones from south-eastern Poland, dated to the Neolithic and the Bronze Ages. The analyses are discussed against the background of archaeobotanical data from the studied sites from Miechów and Mozgawa. The mean values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ obtained from wheat grains from south-eastern Poland were used to model human palaeodiet. Our results show high levels of plant proteins in the diet, taking into account crop grain enriched in heavy nitrogen instead of the $\delta^{15}\text{N}$ values for plants estimated from herbivore collagen. Dental abrasion analyses suggests the contribution of a highly abrasive food component in the diet (e.g. from plants). As the number of samples was limited and there were no statistically significant differences between chronological and gender groups, we conclude that despite some small differences in carbon isotopic composition between genders, Miechów site societies were egalitarian in this respect. Despite the presence of millet in the studied area in the Bronze Age no evidence of C4 plant consumption was noted in the $\delta^{13}\text{C}$ of human and animal bones.

1. Introduction

The reconstruction of diet for past populations is currently one of the most dynamically developing areas of physical anthropology, and nitrogen (^{14}N and ^{15}N) and carbon (^{12}C and ^{13}C) isotopes are a core part of this research (Jørkov et al., 2010; Kozłowski et al., 2014; Polet and Katzenberg, 2003; Reitsema et al., 2017, 2010; Reitsema and Kozłowski, 2013; Szostek, 2009). Carbon isotopes in bone collagen reveal information about terrestrial or marine protein diet sources and about the photosynthetic pathways of the consumed plants. Analyses of nitrogen isotopes ratios allow trophic level estimation, generally distinguishing between herbivores, omnivores and carnivores (Reitsema et al., 2010; Ambrose, 1991; Ambrose and Norr, 1993; Bocherens and Drucker, 2003; Szostek, 2009).

In the last decade palaeodietary reconstructions have also involved stable carbon and nitrogen isotope data derived directly from archaeobotanical crop remains. $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values in plant tissues can vary between parts of the plant, however, intensive manuring caused heavy

N isotope enrichment in wheat and barley grains, giving $\delta^{15}\text{N}$ values up to ca. + 8‰ higher than in the grains of crops grown in plots without manuring (Bogaard et al., 2007), and this strongly affected dietary palaeoreconstructions (Bogaard et al., 2013; Fraser et al., 2013b; Goslar et al., 2018; Styring et al., 2016). Apart from manuring, other environmental factors can also affect isotopic fractionation and N isotopic ratios in plant tissues (Szpak, 2014; Styring et al., 2017; Mueller-Bieniek et al., 2019). The interpretation of past agriculture systems should thus be supported by other palaeoecological data (Bogaard et al., 2016). $\delta^{13}\text{C}$ values in crop grains are not substantially changed by charring, burial or laboratory pre-treatment (Aguilera et al., 2008; Fraser et al., 2013a, 2011), however a slight increase (ca. 1‰) in $\delta^{15}\text{N}$ due to prolonged heating was observed in experiments (Fraser et al., 2013a). In palaeodietary reconstruction, the exact mean level of $\delta^{15}\text{N}$ measured in archaeobotanical remains derived from the study area and period of time is taken into account (Fraser et al., 2013; Styring et al., 2016).

Archaeobotanical studies are still scarce, mostly due to insufficient

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number of specialists, additionally only very well preserved plant macroremains are methodologically allowed for taking measurements of carbon and nitrogen isotopic composition, thus in most palaeodietary research reference to plants is based on generally accepted ranges, measured for C3 and C4 recent plants (Ambrose and Norr, 1993; Tykot, 2004) or extrapolated from the mean $\delta^{15}\text{N}$ values of wild herbivorous collagen (Fraser et al., 2013b). In our research we used the average isotopic values of carbon and nitrogen derived from the archaeobotanical grains of crops found in the studied area. Data from the literature indicates that C4 (Hatch-Slack) photosynthetic pathway plants have $\delta^{13}\text{C}$ values between ca. -20 to -10‰ , in contrast to C3 (Calvin-Benson) photosynthetic pathway plants which have $\delta^{13}\text{C}$ values between ca. -34 to -20‰ (Sharp 2007: 152). Average $\delta^{13}\text{C}$ values in the literature are -12.5‰ for C4 plants, and -26.5‰ for C3 plants (Tykot, 2004). $\delta^{13}\text{C}$ values in C3 plants are also highly dependent on regional specific environment changes that may affect food-chain patterns. Until now it was thought that a significant limitation of water could be identified in $\delta^{13}\text{C}$ values in C3 plant tissues, including mature crop grains (Heaton et al., 2009), and then intentional irrigation of plots in semi-arid and arid areas can be indicated through studying stable carbon isotope ratios in archaeobotanical remains (Wallace et al. 2013, Flohr et al., 2019), but this does not apply to the study area, which is in a temperate zone. In forested areas of temperate Europe a 'canopy effect' should be clearly visible in plant tissues as depletion in ^{13}C (Sharp, 2007), theoretically followed by lower levels of ^{13}C in the collagen of animals grazing in the forest understory. The effect would not be well visible in light demanding plants, including the main crops. A strong relationship between the carbon isotopic depletion of plant tissues and lowered light intensity, with a shift up to 5‰ between grass grown in open and closed locations, was observed in a forested area of England. This was not directly mirrored in the $\delta^{13}\text{C}$ obtained from sheep grazed in open landscape or fallow deer from the forests of the same area, which probably reflects their grazing strategies (Bonafini et al., 2013). Nevertheless the 'canopy effect' can be visible in the lower levels of the food chain and can be proportional to the level of landscape forestation (Bonafini et al., 2013).

Most of the native and anthropogenic plants growing in temperate climatic zones have a C3 photosynthetic pathway. C4 plants (mainly millet; *Panicum miliaceum*, and grasses from Panicoidae group: *Setaria* sp., *Echinochloa* sp.) are more stable and resistant to environmental factors (Fiorentino et al., 2015; Tykot, 2004) and - as already mentioned - have distinctly higher values of $\delta^{13}\text{C}$ than C3. The position of C4 plants in environment and diet should also be clearly visible in the $\delta^{13}\text{C}$ derived from bone collagen (Laffranchi et al., 2016; Schoeninger and Moore, 1992; Goslar et al., 2018).

Tracking the introduction and dispersion of C4 plants and other food sources enriched in ^{13}C , as an important part of the human diet is very interesting in European, including Polish, populations. Common millet (known also as *Panicum miliaceum*, broomcorn millet or proso millet) is a crop of Eastern Asiatic origin introduced to Europe during the Bronze Age (Kapcia and Mueller-Bieniek, 2019; Miller et al., 2016; Motuzaitė-Matuzevičiūtė et al., 2013; Murphy, 2016; Spengler, 2015; Stevens et al., 2016; Valamoti, 2016). There are some finds of common millet archaeologically dated to the Neolithic (Lityńska-Zajac and Wasylkowa, 2005; Lityńska-Zajac et al. 2017; Lityńska-Zajac, 2018; Kirleis et al., 2012), but until now there has been no radiocarbon confirmation of the chronology of those findings. Significantly, every grain of common millet of supposed Neolithic origin gave younger radiocarbon ages: the 2nd millennium BC (Motuzaitė-Matuzevičiūtė et al., 2013; Mueller-Bieniek et al., 2017). Current studies showed that common millet spread from eastern China westwards to the Hexi Corridor about 2300 BCE (Xinying et al., 2016). Millet probably appeared in Europe in the late 3rd millennium BC, but it became well established only during the second half of 2nd millennium BC (Stevens et al., 2016; Valamoti, 2016; Kučera et al., 2019). The other grasses from the Panicoidae group probably appeared earlier, and are found from the

beginning of the Neolithic (for example, Lityńska-Zajac, 2005), but their absolute age is uncertain, as with 'Neolithic' common millet. Even if millets appeared earlier than the late 3rd millennium BC, however, their role in diet was marginal.

Based on comprehensive knowledge about plant and animal isotopic ratios and interrelationships within the trophic chain, with humans as the last link, it is possible to estimate not only the main food sources, but also their proportions in the human diet (Dewar and Pfeiffer, 2010; Fraser et al., 2013a, 2013b; Hedges and Reynard, 2007; Pate et al., 2016).

The main aim of this study is a complex human diet reconstruction based on the comprehensive data related to the isotopic C and N ratios for animals from different trophic levels, but also based on the isotopic ratios from plant samples derived from archaeological sites from the same region in southern Poland. This set of data, rarely used in physical anthropology, offers the opportunity to follow the trophic chain through from plants to humans to verify general correlations and sources of proteins. Attempts to establish the contribution of plants as a food source can be supported by studies of tooth enamel erosion. The consumption of meat or soft plant tissues is less destructive to tooth enamel than the consumption of plant seeds (Romero, 2012). Even manufactured grains are erosive for tooth crowns. We hypothesise that individuals with a significant plant component in the diet would have more damaged tooth crowns, than those in the same age with a less plant-based diet.

1.1. Archaeological background

Site no. 3 in Miechów (district of Miechów, Małopolskie voivodeship) is situated in the loess Miechów Upland, ca. 30 km north of Kraków (Fig. 1). A rescue excavation in 2011 and 2012 revealed the remains of multicultural human occupation in an area of over 4 ha, with more than 3,000 anthropogenic features. Investigations also yielded huge amounts of portable artefacts, particularly ceramics (ca. 80,000 fragments), but also flint (ca. 1,000 pcs.), stone, bone and antler tools (ca. 1,000 pcs.), metal items (12 pcs.), animal bones (ca. 10,000 pcs.), and hundreds of different plant remains (Moskal-del Hoyo et al., 2017). Twenty six human graves were discovered, containing 38 skeletons. Preliminary analyses of the archaeological material suggests that the site was settled in the Neolithic (including the Linear Band Pottery culture – the oldest Neolithic culture in Central Europe), the Bronze Age, the Iron Age and the Middle Ages. Altogether, the site was occupied from ca. 5300 BCE until CE 1300.

Site 1–3 in Mozgawa (district of Pińczów, Świętokrzyskie voivodeship) is located in the north-western outskirts of the western Lesser Poland loess uplands (Fig. 1). The site was surveyed and excavated in 2014–2017. As a result 77 anthropogenic features were unearthed as well as a plethora of pottery (ca. 12,000 pcs.), stone artefacts (ca. 1,000 pcs) and animal bones (ca. 7000 pcs.), not to mention other categories of the past material culture. Almost all findings should be referred to the Funnel Beaker culture (TRB) of the Middle Neolithic period. Radiocarbon dates based on taxonomically identified remains of short-lived plants and animal bones suggest that the site was occupied by the TRB communities from ca. 3550 BCE to ca. 3100 BCE (Nowak et al., 2017; Moskal-del Hoyo et al., 2018). Spatial data obtained during surveys and excavations demonstrate that TRB settlement covered an area of ca. 35 ha (Korczyńska et al., 2019). Thus, this settlement belongs to a group of sites of the south-eastern group of TRB which are of exceptional size, compared to typical, much smaller settlements of this entity (fluctuating between 1 and 3 ha). No relics of older Neolithic cultures were detected in the obtained materials, and therefore, the TRB groups occupying the site were the first farmers in the micro-region.

The Mozgawa and Miechów sites, despite lying in the same geographical unit of Lesser Poland (*Małopolska* in Polish) differ in types of occupation. The Miechów site was settled for a long time, probably by at least a dozen or so human populations, while Mozgawa site was

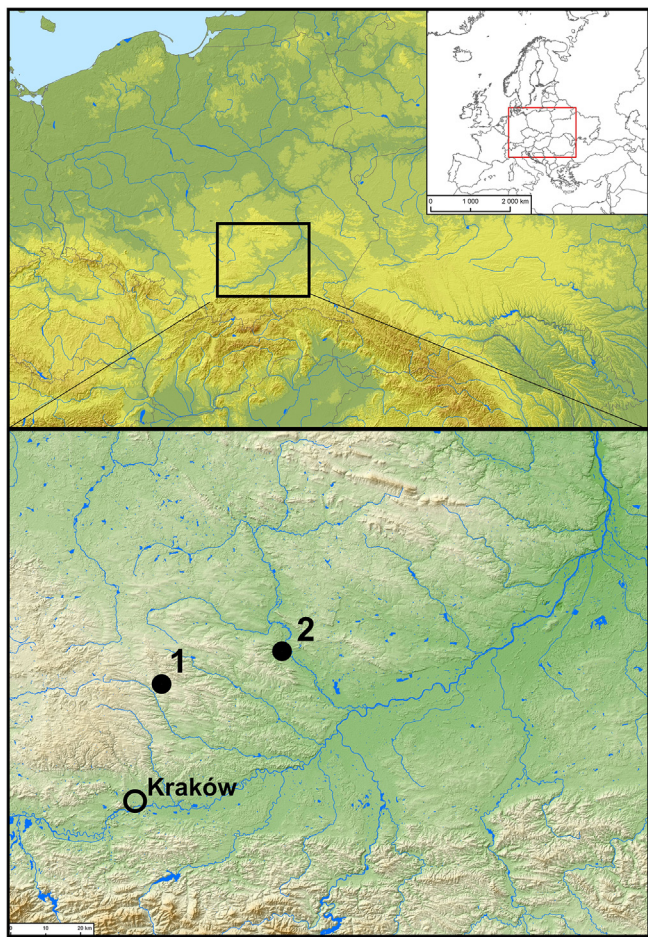


Fig. 1. Location of the archaeological sites: 1-Miechów, 2-Mozgawa.

occupied mostly by settlers of the Middle Neolithic TRB culture. Animal bone remains were preserved in both sites, but human inhumations were noted only in Miechów. Archaeobotanical sampling of Mozgawa site identified wheat grains appropriate for isotopic analyses, but there were no samples of well-preserved wheat remains dated clearly to the Neolithic or Bronze Age from the Miechów site.

1.2. Archaeobotanical data from the studied area

Botanical macroremains from dry, open air archaeological sites reflect past plant diet only fragmentary due to taphonomical reasons, however such type of data offers direct evidence of plants from the past (Colledge and Conolly, 2014; van der Veen, 2007). The studied area is relatively well examined archaeologically, but botanical and palaeoenvironmental data is still patchy. Broadly, it is similar to the picture known across central Europe (Colledge and Conolly, 2007; Coward et al., 2008; Kreuz et al., 2005). Hulled wheats (mainly emmer, *Triticum dicoccum* and einkorn, *T. monococcum*) and barley (*Hordeum vulgare*) were present in the Lesser Poland upland from the beginning of the Neolithic. The appearance of other large grained crops in the early Neolithic (spelt wheat, bread wheat, oats and rye) is also noted (Lityńska-Zajac et al., 2017; Kruk et al., 2016), however they were either not of great significance (oats, rye) or are not important in our isotopic studies (several species or subspecies of wheat and barley). The presence of millet (*Panicum miliaceum*) is more important (Lityńska-Zajac et al., 2017; Milisauskas et al., 2012), but in the light of radiocarbon, archaeobotanical and chemical data it seems that millet appeared in Europe in the 3rd millennium BC or later (Kapcia and Mueller-Bieniek, 2019; Kučera et al., 2019; Motuzaitė-Matuzevičiute

et al., 2013; Stevens et al., 2016). Pulses (peas *Pisum sativum* and lentils *Lens culinaris*) most probably appeared in the Early Neolithic as a part of the near eastern 'founder crops' but those remains are scarce in sub-fossil form, and usually strongly underrepresented (Mueller-Bieniek et al., 2016). The lack of plants known from surrounding areas is definitely no proof of their real absence in the palaeoeconomy of the given site. Archaeobotanical data from the sites analysed in the paper (Table S1, S2), reflects changes in the cultivated plants and environment over time (Miechów, Table S1, Moskal-del Hoyo et al., 2017) or enrich the current knowledge summarised in recently published book about Middle Neolithic plant husbandry and landscape in Bronocice site (Kruk et al., 2016), which is of the similar type as the studied here Mozgawa site, (Table S2, Moskal-del Hoyo et al., 2018). There is a visible dominance of emmer and einkorn in the Neolithic samples from the plant material of the Miechów site (Mueller-Bieniek et al., 2017, and Table S1, Figs. S1–S3), as well as the appearance of millet grains in the Late Bronze Age (the Lusatian culture) and their presence until Medieval times. The seeds of gold-of-pleasure (*Camelina* sp.) also appeared in the Lusatian samples. Pulses (peas and lentils) appeared in Miechów in samples younger than the Lusatian culture, but they were well represented in the intensively studied Middle Neolithic site of Mozgawa (Moskal-del Hoyo et al., 2018 and Table S2).

The last studies of stable carbon and nitrogen isotopes from Neolithic and Bronze age wheat grains originating from a large territory of Poland suggested differences in water accessibility between Kuyavia (*Kujawy* in Polish) and Lesser Poland, as reflected in $\delta^{13}\text{C}$ values (Mueller-Bieniek et al., 2019), which are less negative for Kuyavia than Lesser Poland in the Early Neolithic (ca. 5500–4000 BCE). It is more important for our study that a visible diachronic shift was noted in wheat grains from Lesser Poland, from lower (more negative) $\delta^{13}\text{C}$ values in the Early Neolithic samples (including the Linear Pottery culture and the Lengyel-Polgár complex), to increased $\delta^{13}\text{C}$ values in the Middle Neolithic samples (dated mostly to the Funnel Beaker culture) that imply drier agriculture conditions during the Middle Neolithic (Ferrio et al., 2005; Heaton et al., 2009; Wallace et al., 2013). Such an observation confirms Kruk's (1980) hypothesis of the change in agriculture at that time, due to moving settlements from the valleys to uplands (Mueller-Bieniek et al., 2019).

1.3. Archaeozoological context

Excavations at Site no. 3 in Miechów have provided about 20,000 animal bones and teeth. Such a vast and unique collection of animal remains, spanning nearly 7,000 years, offers an exceptional opportunity to trace the changes in animal husbandry (Moskal-del Hoyo et al., 2017). The number of animal bones varied in different cultural periods, but the remains of domesticated animals dominated in all phases. Cattle were predominant both in terms of the amount of bone and the number of individuals. Other domesticated animals included goat or sheep, pig, dog, and, in later phases of occupation, horse. The wild taxa from the Miechów site were mainly represented by roe deer, red deer and wild boar.

More than 7000 fragments of different groups of animals were found in 77 anthropogenic features during the excavations at the Mozgawa site (Moskal-del Hoyo et al., 2018; Wilczyński et al., in press). The most numerous animal remains belong to 12 mammal species, representing both domesticated and wild animals. Cattle remains clearly dominate, both in terms of the amount of bones and the number of individuals. Remains of other domesticated ungulates are less numerous. Among them pig and sheep/goat remains occur in similar number. Wild mammals represent typical spectrum of game species like horse, roe deer, red deer and wild boar. Additionally, presence of species related to aquatic environment, especially fishes and birds, is noteworthy.

Many traces of human activity were recognised on the animal remains. They were noted at both sites on domesticated and wild animals.

They reflect all stages of carcass processing and are especially numerous on remains belonging to cattle, sheep/goat, and pig. On the basis of archaeozoological analysis carried out for Miechów and Mozgawa bone assemblages we can state, that whole animal carcasses were transported to the settlements, slaughtered and processed there.

2. Materials and methods

2.1. Carbon and nitrogen isotope analyses

The stable carbon and nitrogen isotope analyses involved human and animal bone samples from Miechów and Mozgawa, and a range of seed samples from neighbouring archaeological sites in south-central Poland (Fig. 1). There were 26 humans from the Miechów site (6 females, 7 males, 13 with unknown sex) and one from the Mozgawa site (unknown sex). Faunal samples from both sites included omnivore/carnivore species; pig (*Sus scrofa* f. *domestica*), European badger (*Meles meles*), dog (*Canis familiaris*), fox (*Vulpes vulpes*); and herbivores, cattle (*Bos taurus*), goat/sheep (*Capra hircus/Ovis aries*), moose (*Alces alces*), roe deer (*Capreolus capreolus*), wild horse (*Equus ferus*)/domesticated horse (*Equus caballus*), and hare (*Lepus europaeus*). Plant data was obtained from several sites in the region, excluding Miechów from which there was no accessible well dated sample of a sufficient number of well-preserved grains. Plants from the studied region (24 samples) included 17 *Triticum dicoccum* (emmer wheat) samples, and fewer *Triticum monococcum* (einkorn wheat), *Triticum spelta* (spelt wheat), *Triticum* cf. *timopheevi* - emerald wheat also called the 'new' type of glume wheat (NGW, Fuller and Lucas, 2014; Jones et al., 2000), *Hordeum vulgare* (barley) - and *Panicum miliaceum* (common millet) (Mueller-Bieniek et al., 2019).

As most of the isotope data was from wheat grains, and only single measurements were taken from barley and millet, those two genera will be excluded from the comparison (Table 1). Barley grains have a different response to water stress in $\delta^{13}\text{C}$ (Wallace et al., 2013), and millet has incomparable values of $\delta^{13}\text{C}$ characteristic for C4 plants. The presence of millet (C4 plant) in a terrestrial diet should be reflected in the bone collagen $\delta^{13}\text{C}$ of its consumers (Cadwallader et al., 2012; Hermes et al., 2019; Isaakidou et al., 2019; Laffranchi et al., 2016).

Stable nitrogen and carbon isotopes from bone samples were analysed in two qualified laboratories: the Stable Isotope Laboratory, Institute of Geological Sciences, Polish Academy of Science (PAS) and The Scottish Universities Environmental Research Centre (SUERC). Collagen from the samples was isolated using the procedure proposed by Bocherens et al. (1997). 0.3 g of cleared, ground bone was poured into 10 ml 1 M HCl for 20 min, then the insoluble bone residue was moistened in 0.125 M NaOH for 20 h at room temperature. Afterwards, the bone dust was rinsed off, poured into 10 ml of 0.001 M HCl and incubated in a 100 °C water bath for approximately 17 h, to complete the dissolution of bone. 1–2 ml of dissolved bone solution was filtrated using a 5 µm filter test-tube. The filtrated collagen solution was freeze-dried and sent for mass spectrometry isotopic composition

measurement. Botanical samples were analysed in the Archaeology Research Laboratory, University of Oxford following protocol developed there (Bogaard et al., 2007; Fraser et al., 2013a, 2011; Mueller-Bieniek et al., 2019).

Carbon and nitrogen isotopic compositions are described using a delta notation ($\delta^{15}\text{N}$, $\delta^{13}\text{C}$) with the use of international laboratory standards: atmospheric nitrogen (AIR) and PeeDeeBelemnite (PDB). Bone material was analysed to identify diagenetic changes. Taphonomic collagen decomposition was identified by analysing the C/N ratio, and the results for the unaltered sample was in the range 2.9 to 3.6 (Jørkov et al., 2007; van Klinken, 1999). The percentage share of carbon in collagen should exceed 25% and nitrogen should exceed 10% (Pate, 1997; Pate et al., 2016; van Klinken, 1999). Seed suitability for isotopic analyses was macroscopically verified, based on the evaluation of carbonisation temperature (Fraser et al., 2013a).

In order to assess broad archaeological culture distribution, all human samples were divided into three chronological periods: Early Neolithic (Linear Pottery culture - LBK, Malice culture, Lengyel and Lublin-Volhynian cultures), Middle Neolithic (Funnel Beaker culture - TRB) and Bronze Age/Early Iron Age (Trzciniec and Lusatian cultures). Due to sample size, a non-parametrical multi-sample comparison Kruskal-Wallis test was used. Sample size or lack of normal distribution meant that a Mann-Whitney non-parametrical test was used to compare male vs. female and adult vs. child groups, as well as animal interspecies variation. Cluster analyses were carried out to identify elements in potential homogenous subgroups.

2.2. Dietary reconstruction models

A simple linear model based on stable carbon isotope values was used in order to determine the average C₃ based plant and animal component of the diet (Dewar and Pfeiffer, 2010; Pate et al., 2016). Because of the difference between past and present atmospheric CO₂, and the use of modern faunal control samples (modern 100% marine diet representatives), a 1.5‰ correction factor was employed (Dewar and Pfeiffer, 2010; Pate and Owen, 2014; Tykot, 2004). For the above analyses, -13‰ of $\delta^{13}\text{C}$ in bone collagen was used as a standard for a 100% marine-based diet (Pate et al., 2016). A value of -23‰ (Pate et al., 1993, 2016) was employed for a C₃-based terrestrial diet standard, and data from archaeozoological samples from Miechów and Mozgawa was used for comparison.

To verify the share of animal protein products in the diet, a mixed model based on $\delta^{13}\text{N}$, proposed by Fraser et al., 2013a, 2013b; Hedges and Reynard, 2007 was used. We used two scenarios in our study. The first is a standard model using the expected isotope value of plants consumed by herbivores (Hedges and Reynard 2007), and the second is modified using isotopic values observed in archaeological plant remains from the studied area (Table 1 based on Mueller-Bieniek et al., 2019). Data obtained from experimental crop grains showed that $\delta^{15}\text{N}$ values can be much higher than those estimated for fodder and vegetative parts of plants, reaching more than 9‰ (Bogaard et al., 2007; Fraser

Table 1
Isotopic results of plant samples.

C	Taxa	No. of samples	$\delta^{13}\text{C}$				$\delta^{15}\text{N}$					
			Mean	Median	Std. Deviation	Min.	Max.	Mean	Median	Std. Deviation	Min.	Max.
Early Neolithic	Emmer wheat (<i>Triticum dicoccum</i>)	6	-24.7	-24.69	0.4244	-25.38	-24.2	5.867	5.883	0.6736	5.08	6.62
Middle Neolithic	Emmer and Einkorn (T, <i>dicoccum</i> and T, <i>monococcum</i>)	13	-23.9	-23.85	0.5937	-24.9	-22.96	5.961	5.741	0.8871	4	7.26
Middle Neolithic	Emmer	11	-23.8	-23.69	0.6096	-24.9	-22.96	6.024	6.122	0.9554	4	7.26
Middle Neolithic	Einkorn	2	-24.4	-24.35	0.06905	-24.4	-24.3	5.615	5.615	0.1783	5.49	5.74
Bronze Age	Wheats (Emmer ann Spelt)	2	-22.8	-22.79	0.6398	-23.24	-22.34	6.012	6.012	0.06358	5.97	6.06
Bronze Age	Barley	2	-24.6	-24.6	0.4156	-24.89	-24.3	5.489	5.489	1.358	4.53	6.45
Bronze Age	Millet	1	-9.8	-9.804	NaN	-9.804	-9.804	5.313	5.313	NaN	5.31	5.31

Table 2
Isotopic results of human bone samples.

Sample ID	Site	Object	Archeological culture	Period	Sex	Age class	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C/N	
Mi 1.01	Miechów	1109 A	LBK	Early Neolithic	No data	no data	-20.4	9.7	46.5	17.4	3.1	
Mi 1.02	Miechów	1807	LBK		F	Adultus	-19.7	9.2	48.0	17.9	3.1	
Mi 1.03	Miechów	1935B	LBK		F	Senilis	-20.4	9.9	42.2	15.7	3.1	
Mi 1.04	Miechów	1951	LBK		F	Maturus/Senilis	-19.5	9.2	43.7	15.8	3.2	
Mi 1.05	Miechów	1433	Malice		No data	no data	-19.6	10.3	43.9	16.0	3.2	
Mi 1.06	Miechów	568	Malice		No data	Infans I	-19.3	11.7	46.9	17.2	3.2	
Mi 1.07	Miechów	1025	Malice		M	Adultus	-19.6	9.0	48.2	17.5	3.2	
Mi 1.08**	Miechów	639B	Lengyel		No data	no data	-21.5	5.4	43.8	16.6	3.1	
Mi 1.09	Miechów	316	Lublin-Volhynian		F	Maturus	-19.8	9.7	58.0	21.1	3.2	
Mi 1.10	Miechów	636/1	Lublin-Volhynian		M	Juvenis	-19.6	10.3	46.4	17.0	3.2	
Mi 1.11	Miechów	1066/2	TRB	Middle Neolithic	No data	Infans I	-19.4	8.9	51.2	18.8	3.2	
Mi 1.12	Miechów	173/2	TRB		No data	Infans II/Juvenis	-19.9	8.7	49.0	18.0	3.2	
Mi 1.13	Miechów	1066/1	TRB		M	Maturus/Senilis	-19.5	10.3	46.2	17.7	3.0	
Mi 1.14	Miechów	744	TRB		No data	Infans I	-19.6	8.5	47.9	17.9	3.1	
Mi 1.15	Miechów	540B	TRB		M	Adultus	-19.5	11.3	46.2	17.1	3.1	
Mi 1.16	Miechów	173/1	TRB		M	Maturus	-20.0	10.5	50.3	18.5	3.2	
Mi 1.17	Miechów	173/3	TRB		No data	Infans II	-20.4	9.2	45.4	16.6	3.2	
Mi 1.18	Miechów	3576/1	Trzciniec		Bronze Age /Early Iron Age	No data	Infans II/Juvenis	-19.8	8.8	47.8	17.2	3.2
Mi 1.19	Miechów	3576/4	Trzciniec			No data	Infans II/Juvenis	-20.0	9.0	48.0	17.2	3.2
Mi 1.20	Miechów	3576/2	Trzciniec			F	Juvenis	-19.9	9.2	45.6	16.5	3.2
Mi 1.21	Miechów	3576/5	Trzciniec	No data		Infans I	-21.0	9.0	49.1	17.9	3.2	
Mi 1.22	Miechów	3576/3	Trzciniec	No data		Infans II	-19.9	8.3	44.9	16.5	3.2	
Mi 1.23	Miechów	3576/6	Trzciniec	F		Juvenis/Adultus	-20.4	10.3	49.7	17.8	3.3	
Mi 1.24	Miechów	3590/1	Lusatian	M		Maturus	-18.2	8.5	50.2	18.5	3.2	
Mi 1.25	Miechów	2527	Lusatian	M		Juvenis/Adultus	-20.0	9.3	46.2	16.9	3.2	
Mi 1.26	Miechów	88	Lusatian	No data		Infans I	-21.2	9.8	46.9	17.4	3.1	
Mo 1.01*	Mozgawa	10 A/W	TRB	Middle Neolithic		No data	no data	-20.6	9.7	42.5	10.7	4.6*
Data for paleodietary model (Fraser et al., 2013a, 2013b; Hedges and Reynard, 2007)												
M all human							-19.9	9.5				
M all herbivores							-20.9	6.9				
M all plant samples							-23.5	5.9				

LBK - Linear Pottery culture, TRB - Funnelbeaker culture; *data excluded due to diagenesis; ** data excluded due to uncertain species recognition; M - mean

et al., 2011), and can also be relatively high in charred archaeological crop grains (Bogaard et al., 2013; Fraser et al., 2013; Styring et al., 2016; Vaiglova et al., 2014). Fraser et al. (2013) found that the $\delta^{15}\text{N}$ values of experimentally charred cereal grain and pulse seed tend to increase by + 1.0‰ (± 0.4), which must be taken into account in further interpretations. The model included data derived directly from archaeological crop remains results in an overstatement of animal proteins in the diet of prehistoric human populations, due to the different isotope composition in plants consumed by humans and herbivores (Fraser et al., 2013b). In the standard model (Hedges and Reynard, 2007) the starting point is the expected $\delta^{15}\text{N}$ value of vegetation calculated on the basis of isotope data for herbivores, taking into account isotopic fractionation, as the $\delta^{15}\text{N}$ values increase by 4‰ on average for each successive trophic level ($\Delta_{\text{plant-herbivore}} = 4\text{‰}$ and $\Delta_{\text{herbivore-human-100\%animal protein diet}} = 4\text{‰}$) (Sharp, 2007).

2.3. Dental abrasion

Age at death and dental abrasion were analysed to verify whether tooth wear in the Neolithic/Bronze age human group from the Miechów site might be correlated with diet. Age at death, estimated using complex anthropological methods (osteological age), was compared to age estimated based only on tooth wear (tooth-age) (Buikstra and Ubelaker, 1994). The degree of human teeth abrasion was estimated based on the visual evaluation proposed by Lovejoy (1985). Analysis included only molar teeth as they are most exposed to crown destruction during the grinding of plant tissues (Karme et al., 2016). Evaluation via teeth preservation was possible in 15 specimens. In the youngest specimens, it was only possible to apply three degrees of the crown destruction scale (weak/normal/extensive).

3. Results

3.1. Isotopic data

$\delta^{15}\text{N}$ values for wheat remains (from 4.0 to 7.3; average 5.94, median 5.97) reached levels observed for herbivore collagen. The values of $\delta^{13}\text{C}$ (from -25.4 to -22.3, average -24.02, median -24.18; giving $\Delta^{13}\text{C}$ from 16.2 to 19.4, average 18.06, median 18.13) are typical for wheat grains cultivated in fields that are moderately to well-watered (Wallace et al., 2013). When the samples are divided into three chronological groups (Early Neolithic, Middle Neolithic and Bronze Age/Iron Age) the $\delta^{15}\text{N}$ values show no statistical differences. When Neolithic wheat samples are divided into two chronological groups (the Early and the Middle Neolithic) they are statistically different according to their $\delta^{13}\text{C}$ values (Mann-Whitney test, $p = 0.007$). The millet seed sample presented an extremely distinct carbon isotope composition ($\delta^{13}\text{C} -9.3$; $\delta^{15}\text{N} 5.3$), typical for C4 plants (Table 1).

Only four of the 86 human and animal samples were excluded from further analysis. Two were excluded due to diagenetic changes, one human sample from Mozgawa and one animal sample from Miechów, where the C/N ratio exceeded the 3.6 upper limit (marked as "*" in Tables 2 and 3). One potential human and one cattle sample were also not included, due to uncertain species recognition, confirmed by very outlying results (marked as "***" in Tables 2 and 3). The rest of the samples were recognised as unchanged and eligible for diet reconstruction (25 human and 57 animal samples).

Isotope values from human samples varied from -21.2 to -18.2 for $\delta^{13}\text{C}$ (mean = 19.9 SD = 0.60), and from 8.3 to 11.7 for $\delta^{15}\text{N}$ (mean = 9.5 SD = 0.87). Human bone samples, divided into three chronological periods, indicated no statistically significant differences in either carbon or nitrogen isotopes ratios, between these groups ($p = 0.618$; $\delta^{13}\text{C}$, $p = 0.082$; $\delta^{15}\text{N}$). As a result, all human samples were analysed collectively in further diet analyses, without

Table 3
Isotopic results of animal bone samples.

Sample ID	Site	Object	Are	Level	Layer	Archeological culture	Species	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C/N
Mi 2.01	Miechów	173 cz. A	180/370	I-K	173	TRB	Cattle	-20.9	7.5	45.6	16.5	3.2
Mi 2.02	Miechów	1040	170/400	B-D	1040	TRB	Cattle	-21.2	8.1	45.2	17.0	3.1
Mi 2.03	Miechów	173 cz. A	180/370	K-L	173 a	TRB	Cattle	-21.0	8.4	46.1	17.2	3.1
Mi 2.04	Miechów	2093B	160/220	F-J	2093 a	TRB	Cattle	-21.0	6.5	45.6	17.3	3.1
Mi 2.05	Miechów	173 cz. A	180/370	K-M	173	TRB	Cattle	-22.0	7.4	50.8	18.6	3.2
Mi 2.06	Miechów	2271 A	190/280	H-J	2271 a	LBK	Cattle	-20.8	5.3	49.6	18.1	3.2
Mi 2.07	Miechów	2381B	200/250	F-H	2381 A	LBK	Cattle	-22.4	3.2	48.1	18.2	3.1
Mi 2.08	Miechów	2388B	200/260	H-J	2388 a	LBK	Cattle	-20.8	5.8	49.2	17.5	3.3
Mi 2.09	Miechów	309 strop	190/310	B-D	309 a	Malice	Cattle	-21.5	6.8	46.8	17.8	3.1
Mi 2.10	Miechów	3003	190/430	D-F	3003 A	Malice	Cattle	-21.7	5.8	47.3	16.9	3.3
Mi 2.11	Miechów	3003 cz. A	190/430	F-H	3003 A	Malice	Cattle	-20.9	6.0	47.4	16.8	3.3
Mi 2.12	Miechów	3003 cz. A	190/430	J-L	3003 A	Malice	Cattle	-20.4	5.5	44.9	15.4	3.4
Mi 2.13	Miechów	457B	200/210	H-J	457a	Lengyel	Cattle	-20.2	6.8	38.5	14.2	3.2
Mi 2.14	Miechów	310B	190/310	D-F	310 a	Lengyel	Cattle	-20.6	7.6	46.1	17.1	3.1
Mi 2.15	Miechów	1794 a	170/250	H-J	1794e	Lengyel	Cattle	-20.6	7.6	44.6	16.3	3.2
Mi 2.16	Miechów	2159B	160/210	H-J	2159 a	Baden	Cattle	-20.8	7.9	42.9	15.8	3.2
Mi 2.17	Miechów	1245 cz. A	170/350	H-J	1245 A	Lusatian	Cattle	-21.9	5.3	42.6	14.5	3.4
Mi 2.18	Miechów	173 cz. A	180/370	I-K	173 a	TRB	Pig	-20.9	6.9	45.7	16.8	3.2
Mi 2.19	Miechów	173 cz. A	180/370	K-M	173	TRB	Pig	-21.0	6.2	48.4	18.0	3.1
Mi 2.20	Miechów	426B	190/220	J-L	426 a	LBK	Pig	-20.5	6.5	50.1	18.2	3.2
Mi 2.21	Miechów	2381B	200/250	F-H	2381 A	LBK	Pig	-19.9	8.9	49.0	17.9	3.2
Mi 2.22	Miechów	309 strop	190/310	B-D	309 a	Malice	Pig	-20.0	8.5	27.7	10.0	3.3
Mi 2.23	Miechów	309B	190/310	D-F	309 a	Malice	Pig	-20.0	9.4	51.6	18.7	3.2
Mi 2.24	Miechów	457B	200/210	H-J	457a	Lengyel	Pig	-20.9	6.5	44.5	16.6	3.1
Mi 2.25	Miechów	2159B	160/210	H-J	2159 a	Baden	Pig	-21.3	7.9	42.5	15.5	3.2
Mi 2.26	Miechów	1923	150/280	F-H	1923 A	LBK	Pig	-20.9	6.8	43.1	14.4	3.5
Mi 2.27	Miechów	570 cz. B	190/400	F-H	570 A	Lusatian	Pig	-21.3	6.5	42.8	14.3	3.5
Mi 2.28	Miechów	1040	170/400	B-D	1040	TRB	Sheep/goat	-21.6	9.6	48.8	18.2	3.1
Mi 2.29	Miechów	1053 cz. A	170/390	D-F	1053 A	TRB	Sheep/goat	-20.5	7.8	44.0	16.4	3.1
Mi 2.30	Miechów	457B	200/210	H-J	457a	Lengyel	Sheep/goat	-20.5	5.8	45.1	17.0	3.1
Mi 2.31	Miechów	961 cz. B	160/280	D-F	961 A	Lusatian	Sheep	-20.9	6.5	42.2	14.1	3.5
Mi 2.32	Miechów	803B	190/200	G-I	803 A	TRB	Horse	-20.9	7.0	45.1	15.1	3.5
Mi 2.33	Miechów	2388B	200/260	K-J	2388 a	LBK	Horse	-20.9	5.1	41.3	13.9	3.5
Mi 2.34	Miechów	1407 cz.A	200/350-360	F-bottom	1407 A	Lusatian	Horse	-22.0	5.2	42.2	14.1	3.5
Mi 2.35	Miechów	1429 cz.B	200/230	D-F	1429 a	LBK	Dog	-19.5	8.4	44.1	14.6	3.5
Mi 2.36	Miechów	3040 A	170/420	D-F	3040 A	Lengyel	DOG	-19.6	8.2	40.8	13.6	3.5
Mi 2.37	Miechów	2093B	160/220	F-J	2093 a	TRB	dog	-20.4	9.5	43.3	14.5	3.5
Mi 2.38	Miechów	2542	130/280	F-H	2542 A	Lusatian	Dog	-18.5	9.3	44.0	14.5	3.5
Mi 2.39	Miechów	639 A	190/370	M-O	639 A	Lengyel	Roe deer	-20.6	5.6	44.0	14.5	3.5
Mi 2.40*	Miechów	1947	170/250	F-H	1947 A	LBK	Roe deer	-20.4	6.3	40.0	12.7	3.7
Mi 2.41	Miechów	15B	150/380	I-K	15 a	TRB	Fox	-19.3	9.1	43.7	15.0	3.4
Mi 2.42	Miechów	1449 cz. A	200/230	J - bottom	1449 A	TRB	Badger	-20.0	8.3	43.7	15.0	3.4
Mi 2.43	Miechów	1499 cz.B	180-190/240	N-P	1499 A	LBK	Hare	-22.1	3.8	43.1	14.5	3.5
Mi 2.44	Miechów	355 A	200/220	H-J	355 a	Lengyel	Moose	-21.4	5.0	42.7	14.6	3.4
Mo 2.01	Mozgawa	10	404/1	230-240 cm	-	TRB	Cattle	-20.7	8.5	43.8	16.2	3.1
Mo 2.02**	Mozgawa	10	404/1	120-130 cm	-	TRB	Cattle	-19.7	13.1	49.1	18.0	3.2
Mo 2.03	Mozgawa	10	404/1	200-210 cm	-	TRB	Cattle	-20.7	7.1	51.9	18.8	3.2
Mo 2.04	Mozgawa	6 cz. W	437/1	40-50	-	TRB	Cattle	-21.0	8.5	51.3	18.2	3.3
Mo 2.05	Mozgawa	10A cz. W	404/1	200-210	-	TRB	Cattle	-21.1	8.9	49.0	17.7	3.2
Mo 2.06	Mozgawa	10A	404/1	80-90	-	TRB	Pig	-20.4	6.3	42.0	13.9	3.5
Mo 2.07	Mozgawa	10	404/1	150-160 cm	-	TRB	Pig	-21.3	6.5	46.2	16.3	3.3
Mo 2.08	Mozgawa	6	437/3	50-60	-	TRB	Pig	-21.5	7.7	49.7	18.2	3.2
Mo 2.09	Mozgawa	6	437/1	80-90	-	TRB	Pig	-19.0	9.5	51.4	18.6	3.2
Mo 2.10	Mozgawa	10	404/1	130-140 cm	-	TRB	Sheep/goat	-21.0	8.3	52.4	18.5	3.3
Mo 2.11	Mozgawa		402/1	30-40	-	TRB	Sheep/goat	-19.5	7.1	43.7	15.5	3.3
Mo 2.12	Mozgawa	10A cz. E	404/1	190-200	-	TRB	Sheep/goat	-20.6	9.2	50.0	18.2	3.2
Mo 2.13	Mozgawa	10	404/1	230-240 cm	-	TRB	Sheep	-19.4	8.0	48.7	17.5	3.2
Mo 2.14	Mozgawa	10 A cz. W	404/1	200-210	-	TRB	Horse	-21.6	4.6	41.9	13.8	3.5
Mo 2.15	Mozgawa	12 cz. SE	404/2	120-130	-	TRB	Dog	-19.4	10.1	42.3	14.1	3.5

chronological divisions. The last initiatory test was a Mann-Whitney test for the “after weaning” group ($N = 18$) vs. young children group (*Infans I*; $N = 5$) isotopic comparison, which indicated no differences in $\delta^{13}\text{C}$ ($p = 0.910$) and $\delta^{15}\text{N}$ ($p = 0.765$) values. The next step was a comparison of isotopic level between males and females. A Mann-Whitney test indicated no statistically significant differences in $\delta^{13}\text{C}$ ($p = 0.170$) and $\delta^{15}\text{N}$ ($p = 0.516$) values. A simple linear model based on stable carbon isotope values, estimated C3 based plant and animal protein components in the diet as 84% and a range of 67–97% for all human samples (Table 4). The results were obtained based on published data for standard value of $\delta^{13}\text{C}$ for 100% terrestrial diet (Pate et al.

2016). Additional calculations were undertaken, based on data obtained for local herbivorous animals, using the mean $\delta^{13}\text{C}$ of cattle from Miechów, and the increased percentage of mean C3-based plant and animal food component in the analysed population (Table 4).

The next step was a preliminary analysis of the results from the animal samples, which were differentiated by site, date and species. The most represented species were cattle, pig and goat/sheep. Statistically significant differences between sites were observed only in $\delta^{15}\text{N}$ isotope values in cattle ($p = 0.017$), with a higher median for $\delta^{15}\text{N}$ values in cattle from Mozgawa. Within cattle group, cluster analysis was performed to verify potential diversity between sites (furthest neighbour

Table 4
Linear model results of food component analysis.

Sample	Raw data		Mean $\delta^{13}\text{C}$ (1,5‰ corr.)		Range (1,5‰ corr.)		-23‰* (100% C3-based terrestrial diet, literature data ^{***})		-22,6‰* (C3-based terrestrial diet, experimental data for cattle)	
	n	Mean $\delta^{13}\text{C}$ (‰)	Range (‰)	Mean $\delta^{13}\text{C}$ (1,5‰ corr.)	Range (1,5‰ corr.)	Mean C3-based plant and animal component (%)	Range (%)	Mean C3-based plant and animal component (%)	Range (%)	
Total	13	-19,9	-18,2 ; -21,2	-21,4	-19,7 ; -22,7	84	67-97	87,5	70-100	
Male	7	-19,5	-18,2 ; -20,0	-21,0	-19,7 ; -21,5	80	67-85	84	70-89	
Female	6	-19,9	-19,5 ; -21,2	-21,4	-21,0 ; -22,7	84	80-97	87,5	83-100	

* After 1,5‰ correction ** Pate et al., 2016; Dewar and Pfeiffer, 2010.

method, squared Euclidean) (Fig. 2). Two clusters were established among cattle, with a common area of collections. One cluster contains all samples from Mozgawa, but also eight samples of cattle from Miechów. It confirms that despite statistical differences in medians between the groups, the range of the cattle samples from Miechów almost completely includes the samples from Mozgawa. The two separate clusters do not include only site specific samples. This might suggest that diversity in carbon and nitrogen isotopic ratios in this species could be the result of individual variability caused by the age or sex of the animal, or that the local environments of Miechów and Mozgawa were very similar. As a result, cattle samples from both sites were taken into account for further interpretations as a broad isotopic horizon for cattle variety.

The samples from the rest of the species were not numerous enough to proceed with statistical analyses, however, results of the animal isotopic ratios from Mozgawa mostly overlap with those from Miechów.

A similar procedure was conducted for identification of diachronic animal diversity. A Mann-Whitney test was used, indicating no differences in $\delta^{13}\text{C}$ values between cattle in the Early Neolithic and the Middle Neolithic groups ($p = 0.225$), but showing some differences in $\delta^{15}\text{N}$, with higher values for the latter group ($p = 0.003$), as there was no chronological isotopic differences in human samples, diachronic variability in cattle was not considered during further analyses. No differences were observed in either of the analysed elements between Early Neolithic and Middle Neolithic periods for pig species. It was not possible to use statistical methods to analyse the other less numerous species, but there was no clear correspondence with chronology.

Cluster analysis of isotope values, indicates isotopic specific dietary strategies. Herbivorous and omnivorous (including omnivorous opportunists) groups were distinguished, however several species were scattered among both groups (Fig. 3). There was a characteristic shift from strictly herbivorous species (*Lepus-hare*, *Equus-horse*, *Capreolus-roe deer*, *Alces-moose*), including all representatives in the second cluster, to classic carnivores (with some omnivorous species) marked by the first cluster (*Canis-dog*, *Vulpes-fox*, *Meles-badger*). This relationship is observed mostly in the increase of nitrogen isotope values (mean difference $\approx 4\text{‰}$) (Gigleux et al., 2017; Hedges and Reynard, 2007). The rest of the animals (cattle, pig and goat/sheep) can be identified in both clusters (there was a prevalence of cattle samples in the “herbivorous” cluster). The diversity of $\delta^{15}\text{N}$ in these three species of domestic animals probably reflects different breeding strategies. All data obtained from bones sampled at Miechów and Mozgawa sites fits the range of carbon and nitrogen isotope values characteristic for terrestrial animals from Poland (Reitsema et al., 2017; Reitsema and Kozłowski, 2013). A comparison of the means between seeds, animal and human samples is presented in Table 5.

A second analysis was used to verify whether the human diet was mostly based on C3 plant protein or protein from animals feeding on C3 plants (Hedges and Reynard, 2007; Fraser et al., 2013a, 2013b). The standard model initially calculates (‘infers’) the plant diet $\delta^{15}\text{N}$ values by subtracting a fractionation (Δ plant-herbivore) amount from the herbivore collagen $\delta^{15}\text{N}$ value (here, c. + 6.9‰), (Table 2, Fig. 4a). In this case the standard model initially calculates (‘infers’) the plant diet $\delta^{15}\text{N}$ values (2.9‰) by subtracting a fractionation (Δ plant-herbivore) amount from the herbivore collagen $\delta^{15}\text{N}$ value. Then, to value of herbivore $\delta^{15}\text{N}$, a + 4‰ enrichment is added to set down the $\delta^{15}\text{N}$ endpoint value of the linear-mixing model (10.9‰), which represents the $\delta^{15}\text{N}$ value of a human diet based only on animal protein. Where there was no archaeobotanical data and with a mean $\delta^{15}\text{N}$ value for human remains equal 9.5‰ (Table 2), the fraction of the animal protein in the human diet was estimated at 65% (Fig. 4a).

In the second model (Fig. 4b) we used the mean $\delta^{15}\text{N}$ value of charred crop grains derived from several archaeological sites in the region (5.9‰) (Table 2). 9.9‰ is a starting point for the human cereal based diet model (3‰ higher than in the first model). In this case, the nitrogen isotope ratio in human remains is lower than the point which

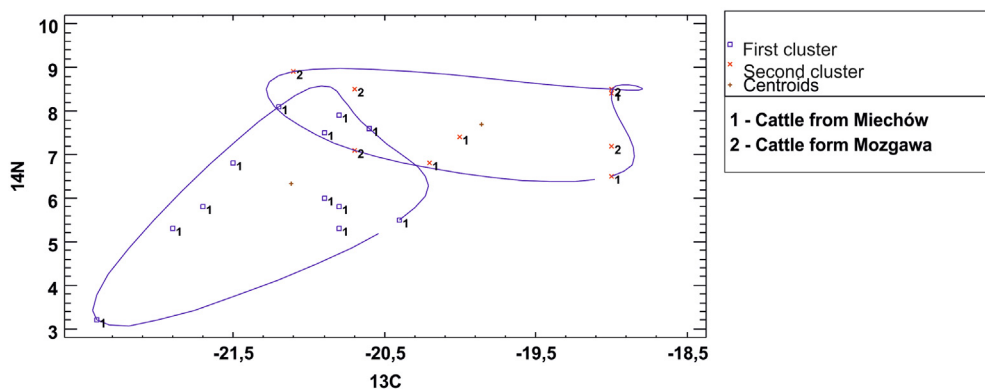


Fig. 2. Cluster scatterplot: cattle from Miechów vs. cattle from Mozgawa (furthest neighbor method, squared Euclidean).

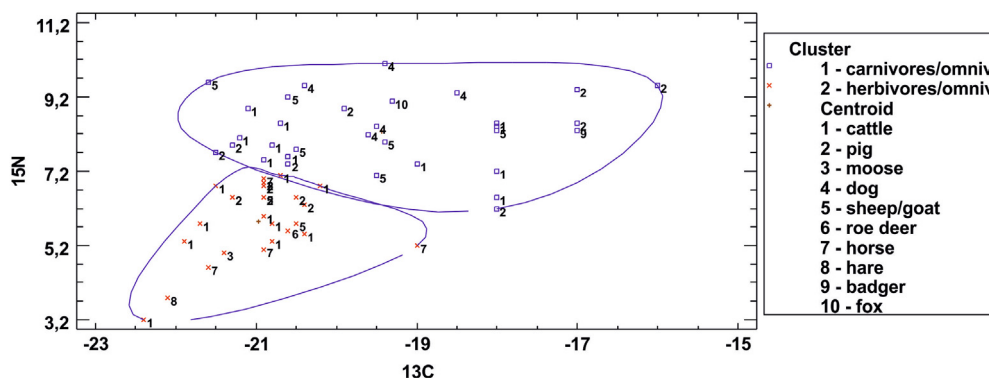


Fig. 3. Cluster scatterplot: animals dietary strategies (furthest neighbor method, squared Euclidean).

Table 5
Species isotopic comparison.

	dC	dN
Seeds vs. Bos sp.	-3.1	1.3
Seeds vs. Sus sp.	-3.5	1.5
Seeds vs. Human	-4.3	3.9
Bos sp. vs. Human	-1.2	2.6
Sus sp. vs. Human	-0.8	2.4

indicates on 100% cereal based diet. This indicates that the human diet was based exclusively on plant protein (including cereals). Similar findings are presented by Fraser et al. (2013b), who indicated a noticeably low level of animal protein in the Vaihingen Neolithic population. The diet of this human group was mostly based on cereals or/and leguminous plants. It is important to note that this result may also be affected by grains charring which can increase $\delta^{15}\text{N}$ in the plant tissues by about 1‰ (Fraser et al., 2013a). The second prediction line was marked to present results considering a 1‰ correction (5.9–1 corr. = 4.9 after corr.), which set the starting point for the model at 8.9‰. This modified the results, indicating 15% of animal protein in the human diet.

3.2. Dental wear estimation

Dental wear estimation results were processed in two groups: children with deciduous teeth and children with permanent molars together with adults (Table 6). Extensive abrasion of deciduous teeth was observable among children, which might indicate strong abrasion caused by consuming grinding food from early childhood. Two of the specimens in late childhood and adolescence presented slightly more extensive tooth wear than indicated by complex osteological age estimation and one with tooth wear indicated an osteological age

approximately 15 years higher. All adults presented enamel erosion generally in accordance with osteological age at death, with only one exception, where abrasion were slightly stronger.

4. Discussion

Direct correlations in the trophic chain could be seen through the animal samples and unique botanical background of the Miechów site (Fig. 5). All individuals who had definitely completed the weaning process were used in the reconstruction of the trophic chain. As we did not obtain sufficient, well-dated plant material for isotope studies from the Miechów site and only four samples of emmer wheat from the Mozgawa site were analysed as a pilot study, the mean values of the whole set of plant isotope data from Małopolska were used as the background (details in Mueller-Bieniek et al., 2019). The plant samples were chronologically uniform in $\delta^{15}\text{N}$ which is the main source of information when tracking the food chain. The values of $\delta^{13}\text{C}$ were significantly different for the Early and Middle Neolithic samples, however they probably reflect environmental condition variation between typical C3 plants. Due to the small number of samples the observations need to be confirmed by further studies, and the mean value of all samples will be taken into account here. One millet sample was used as a C4 plant isotope indicator, and it fits within the isotopic ranges for C4 plants presented in the literature (Pate et al., 2016; Reitsema et al., 2017). Most of the studied plant samples belonged to hulled wheat, of which emmer wheat was the most numerous; other crops were rare. As already mentioned, the position of millet (*Panicum miliaceum*) in European prehistory has been debated in the last decade (Kapcia and Mueller-Bieniek, 2019; Lityńska-Zajac, 2018; Lityńska-Zajac et al., 2017; Motuzaite-Matuzeviciute et al., 2013; Mueller-Bieniek et al., 2017) and direct radiocarbon data indicates its late arrival in Europe, in the Bronze Age. Isotopic results from bones seem to support this hypothesis. Direct analysis of human samples regarding seed and animal

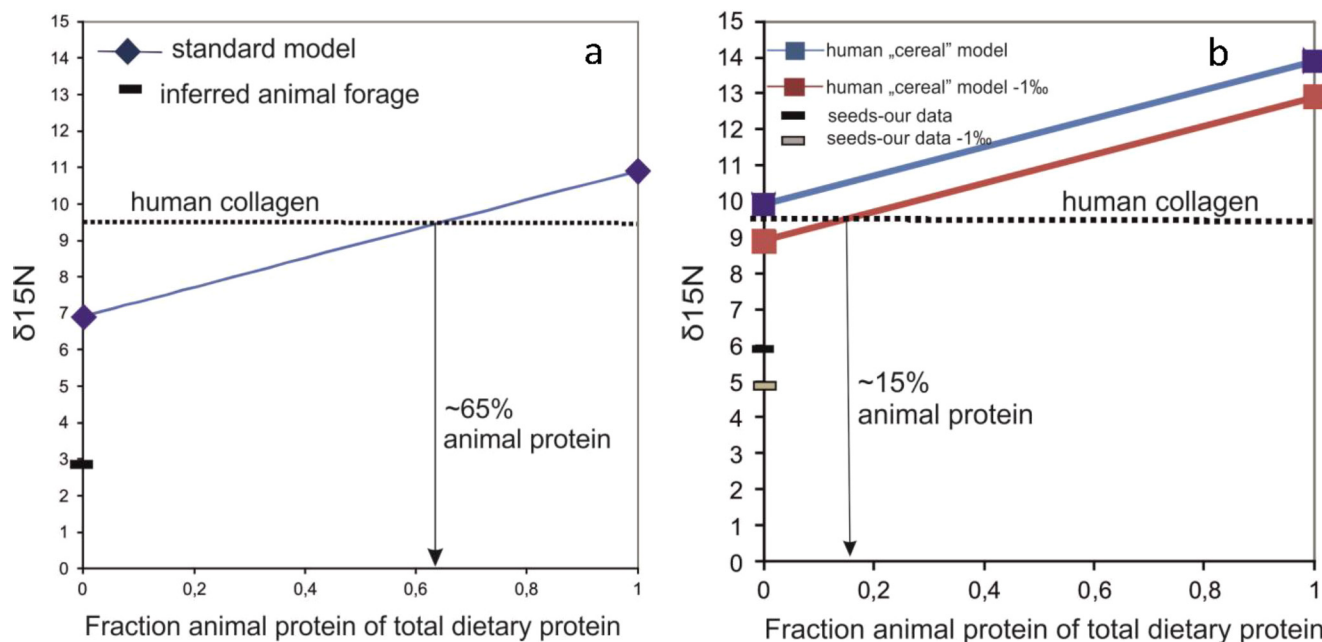


Fig. 4. (a) Standard model estimating fraction of the animal protein in the human diet. (b) Human-cereal model estimating fraction of the animal protein in the human diet.

Table 6
Tooth wear estimation.

Object	Bone age	Age class	Deciduous teeth wear	Tooth-wear age
744	5–7	<i>Infans I</i>	Extensive	
88	6–7	<i>Infans I</i>	Extensive	
3576/3	7–8	<i>Infans II</i>	Extensive	
173/3	9–11	<i>Infans II</i>	Extensive	
3576/1	12–14	<i>Infans II</i>		12–18
3576/4	+/- 14	<i>Infans II</i>	Extensive	16–20
3576/2	15–17	<i>Juvenis</i>		16–20
540	+/- 20	<i>Juvenis</i>	Extensive	20–30
636	Less than 20	<i>Juvenis</i>		20–24
2527	+/- 20	<i>Juvenis</i>	Extensive	35–40
1025	25–30	<i>Adultus</i>		24–30
1807	Greater than 30	<i>Adultus</i>		24–35
173/1	35–40	<i>Maturus</i>	Extensive	40–50
1951	+/- 50	<i>Maturus/Senilis</i>		45–55
1066/1	Greater than 50	<i>Maturus/Senilis</i>		45–55

background exclude C4 plants as an important vegetal source in the diet, and also exclude the possibility of consuming the meat of animals fed with C4 plants. None of the results for the human sample, excluding the Lusatian sample described above (the highest value $\delta^{13}\text{C} = -18.2$) were even close to the isotopic value of C4 plant ($\delta^{13}\text{C} = -9.8$) (Fig. 6), which should be higher if millet grains were consumed (Reitsem et al., 2017).

Cattle and pig were chosen as an animal background, for specify food-chain analysis. As the most common bone fragments found on the archaeological site, these animals were supposed to be main meat source in the diet. Isotopic differences (Bocherens and Drucker, 2003) between the next trophic levels (seeds vs. animals) may indicate that those animals were not consuming wheat grains as a main food source. In the means comparison for both species, seeds vs. cattle and seeds vs. pigs, $\delta^{13}\text{C}$ values exceeded 2‰, with differences in $\delta^{15}\text{N}$ values lower than 3‰ (Table 5). This does not fit a simple one level shift in the trophic chain. This might be caused by cattle consuming C3 plants with

different isotopic levels and an omnivorous strategy for pigs, which makes observation of simple relationships impossible.

Isotopic enrichment values between domestic animals and humans present more a regular relationship. Trophic level differences below 2‰ for $\delta^{13}\text{C}$ might indicate animal meat as a one of the main sources of protein in the human diet, but differences between animal and human $\delta^{15}\text{N}$ means of less than 3‰ might indicate other food sources with lower N isotopic values (such as plants) as another important diet component.

4.1. Diet reconstruction models based on isotopic data

These general assumptions were confirmed by more precise mathematical models. A simple linear model proposed by Dewar and Pfeiffer, (2010) and Pate et al. (2016), indicate C3 plants and terrestrial animals as a dominant food source for human population from the studied region (about 84%). The other 16% probably comes from other food sources, with more positive carbon isotope values. As we know, the main food sources with higher $\delta^{13}\text{C}$ are C4 plants (-7‰) and marine animals (-13‰) (Pate et al., 2016). As the results of the analysed human groups living in Miechów from the Neolithic to the beginning of the Iron Age did not confirm C4 plants as an important food source, and it is implausible that our ancestors could consume marine products in the south of Poland, more than 700 km away from the sea, other dietary components with more positive $\delta^{13}\text{C}$ were present. Although there were no statistically significant differences between males and females, the observed depletion in $\delta^{13}\text{C}$ in the females bones analysed compared to the males may indicate a higher proportion of something other than C3 based plant and animal dietary resources in the male diet (Table 4). Regardless of the model applied (based on data in the literature for herbivores or site-based animals results) the observed difference between males and females is only 4%, although this might be a result of a slightly greater contribution to the male diet from food products with higher $\delta^{13}\text{C}$. As we know, this could not be C4 plants or fish, but it was noted (Table 3) that facultative omnivorous animals (e.g. pigs) had a higher $\delta^{13}\text{C}$ than typical herbivores. The small dimorphic differences observed in humans might therefore also be the result of a distinct (increased) omnivorous-like diet in males. Those assumptions could be confirmed through published data from the

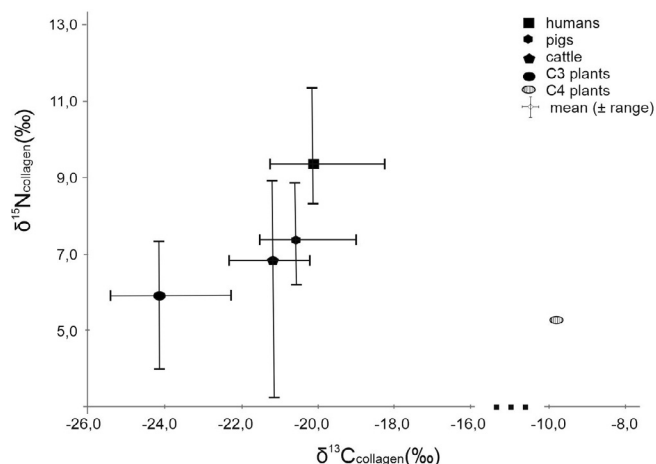


Fig. 5. Trophic correlations based on Miechów site plant, animal and human samples.

Neolithic Ostonki site, in central Poland, where trace elements and archaeological data indicate that cattle was mainly used for milk production, not as a meat source (Szostek et al., 2005).

The second applied model gave us more precise information about proportions of dietary components (Fraser et al. 2013a). A more than 3‰ difference between archaeobotanical grains (Fig. 4b) and the predicted values of δ¹⁵N for plants which were food source for herbivores (Fig. 4a) indicate that cereals were not part of the Miechów and Mozgawa herbivore diet. This is also confirmed by slight difference in isotopic value between site herbivores and cereals. The value of δ¹⁵N in human collagen is almost 4‰ higher than the isotopic value of grains, which is consistent with the theory of overestimating the fraction of animal protein in the human diet (Fraser et al., 2013a). These conclusions suggest that assumptions of diet prediction models based on herbivorous diets common for animals and humans might lead to over interpretation of the results. According to the two models, it is more probable that the diet of the population from Miechów was predominantly based on plants rather than on animal meat.

Only one sample (ob. 3590/1) fit the range close to C4 plant consumers (Table 2). This might be due to the later date of the sample (the Lusatian culture) when C4 plant consumption was demonstrated in the studied site and the whole region (Table S1, Fig. S3) (Kapcia and Mueller-Bieniek, 2019; Moskal-del Hoyo et al., 2017; Mueller-Bieniek et al., 2017) and these plants might have been one food source. Due to a presence of only three samples dated to this culture, and only one isotopic ratio close to the characteristics of C4 plant consumers, however, we cannot exclude the effect of individual isotopic variation. Results from Gruczno (Middle Ages, central Poland) which are interpreted as a classic diet rich in the meat of terrestrial animals and C3 plants (Fig. 6) are almost identical to those from the Miechów human samples (Reitsema et al., 2017; Mnich et al., 2018). These findings support the conclusions from this study. Two Corded Ware sites from south-eastern Poland with δ¹³C values similar to those from the Miechów site are interpreted as having an omnivorous C3-based plant and animal diet (Szczepanek et al. 2018). Similarly, no sex-dependent diet differences were found in those sites (Szczepanek et al., 2018). A mean δ¹³C isotopic ratio from Hallstatt period in Austria higher of about 1.5‰ than our results was interpreted by the authors as meaning a diet including a C4 plant component (Le Huray and Schutkowski, 2005). According to this assumption, we cannot define the Neolithic-Bronze Age diet of at Miechów as C4 plant-based.

4.2. Odontological findings

According to dental analysis, except for one prominent sample (ob. 2527), where a complex osteological method indicated the age at death as about 20 years old and dental wear indicated it at 35–40 years, the other specimens did not present significant differences between age at death and tooth wear in relation to age tooth wear (Table 6). Individual examples might be the result of individual enamel durability and diet preferences. Tooth wear is not necessarily caused by a very tooth-destructive plant-based diet, and it might be connected with the consumption of softer plant foods (Forshaw, 2014). Grains were probably an important dietary component, however, as reflected in less resistance to erosion in deciduous teeth. This might confirm a mixed meat-plant-based diet for this group.

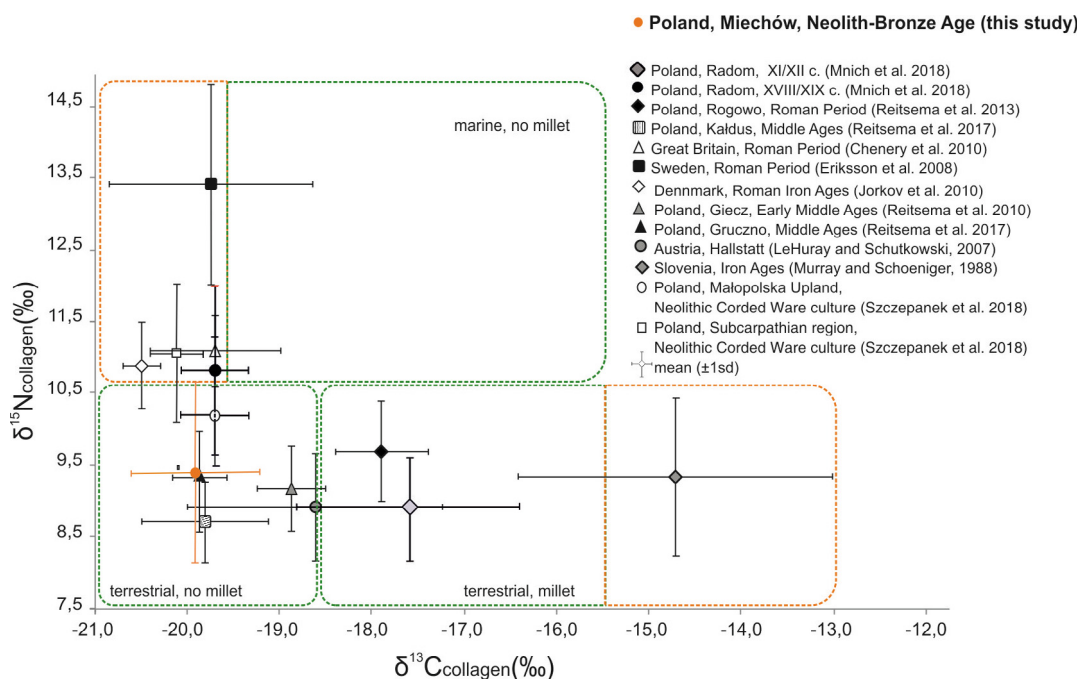


Fig. 6. Carbon and nitrogen isotopic results comparison for selected European population, with marked trophic background (followed by: Mnich et al. 2018; Reitsema et al. 2017, modified).

5. Conclusions

Complex isotopic analyses of particular trophic chain levels provide an opportunity to reconstruct the main human food components and their contribution to diet. The diet of Neolithic-Bronze Age groups from southern Poland was dominated by C3 plants, including crop grains despite there was an evidence of millet (*Panicum miliaceum*) in archaeobotanical assemblages dated to the Bronze Age. Small differences between wheat grains, herbivores and pigs in C and N isotopic composition indicate that these animals were not fed with crop grains as probably valuable food intended for people. Additionally similar $\delta^{15}\text{N}$ values in crop grains to this observed in herbivores, reflect manuring practices with heavy nitrogen isotope enrichment, and confirm that the animal fodder did not contain crop grains. We cannot exclude that other parts of wheat plants, including chaff and straw, were used as fodder together with wild growing herbaceous plants, leaf feed and other plant resources. The observed difference of $\delta^{15}\text{N}$ between archaeological wheat grains and values inferred for animal fodder, reaching more than 3‰, cause that reconstruction of human palaeodiet based on the same inferred, average values for plants consumed by people and their animals may lead to an overstatement of animal protein intake. Moreover, odontological analyses which reveal extensive wear off the less resistant for abrasion deciduous teeth, may confirm plants as an important part of the diet. No statistical differences between chronological and gender groups of settlers at the Miechów site were found. Summarizing, the use of models, based on nitrogen isotopic values derived from archaeological wheat grains, allows for more precise and actual estimation of protein contribution in the human diet. Estimated isotopic values usually used for plant components in palaeodietary models result in an incorrectly identified increase in animal proteins as the main component of diet in the past.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2020.102382>.

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