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ORIGINAL PAPER

Animal husbandry in the Early and Middle Neolithic settlement at Kopydłowo in the Polish lowlands. A multi-isotope perspective

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Abstract The aim of this article is to examine the isotopic characterisation of domestic animals as it relates to birthing location and seasonality, diet, pasturing pattern, foddering and climatic conditions of herding and to determine variation between these aspects of cattle and caprine husbandry of the Neolithic *Linearbandkultur* (LBK) and *Trichterbecherkultur* (TRB) communities from Kopydłowo in Kujavia—one of the major centres of early farming in the European lowlands. Carbon and nitrogen stable isotope analysis was undertaken on faunal bone collagen; carbon, oxygen and strontium isotope ratios were measured from tooth enamel. Isotopic signatures may have been caused by different strategies of management of herds of these animal species. Different and more widely distributed carbon, nitrogen and strontium isotopic data for TRB cattle in comparison with its LBK counterparts is indicative of the exploitation of increasingly diverse ecological zones and more varied pastoral practises. The distribution of oxygen isotope values on caprine tooth made it possible to recognise herding seasonality. Irrespective of the chronology, cattle, sheep and goats kept by the inhabitants had C_3 plant-based diet.

Keywords European Neolithic · Linearbandkultur · Trichterbecherkultur · Animal husbandry · Stable isotopes

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Introduction

The most important domesticated species in the Early and Middle Neolithic of the Polish lowlands are cattle, sheep, goat, pig and dog. As indicated by faunal evidence, cattle are the most frequent species, often representing more than 50% of the identified bones. Their meat is believed to make the biggest contribution to the diet (e.g. Bogucki 1988; Marciniak 2005, 2013a) but other products such as cheese and milk were also important dietary components (e.g. Salque et al. 2012; Evershed et al. 2008). Sheep and goat were most often the second preferred species followed by pig. Species composition in addition to age-at-death determinations has been used to discern the pattern of herd management. Zooarchaeological studies have recently been enriched by the developments outside the realm of this discipline, such as the study of ceramic lipids or bone and tooth enamel collagen stable isotopes, which can effectively contribute to an in-depth understanding of the complex nature of animal production and exploitation (e.g. Pearson et al. 2007; Hongo et al. 2009; Marciniak 2014). Stable isotopes, in particular carbon, nitrogen, oxygen and strontium, are of significant heuristic potential, in particular whilst combined with the results of faunal studies. Increasing numbers of stable isotope measurements of fauna remains have shown how wild animals can be tentatively distinguished from domestic animals (Balasse et al. 2016; Hongo et al. 2009) and how the increasing management and later herding of animals can be detected through changes in animal diet as herbivory preference by individual species is replaced by food provided by pastoralists (Pearson et al. 2007; Szpak et al. 2014; Cucchi et al. 2016. The interpretation of these isotopes in combination have been used to good effect at Neolithic Çatalhöyük, Central Anatolia (Bogaard et al. 2014; Pearson et al. 2015) and central Europe (Bickle and Whittle 2013).

The aims of the carbon and nitrogen stable isotope analyses are to assess the evidence for changes in animal diet that would point to differences in animal management and herding strategies across the LBK and TRB periods. Stable isotope analyses have shown great potential for understanding these practises from a range of time periods. In the LBK in Germany, Oelze et al. (2011) reported that aurochs and domestic cattle in LBK Germany had different diets, suggestive of feeding in different locations, whilst Fraser et al. (2013a, b) suggest that pigs and cattle were likely kept and herded locally. Pearson et al. (2007) showed how stable carbon and nitrogen values in the bone collagen of sheep and goats in Neolithic Anatolia differed according to hunting, management and herding regimes as sites expanded from small- to large-scale communities. Szpak et al. (2014) illustrated how camelids in Northern Peru during the Early Intermediate Period were likely being managed by small social units, possibly family groups. Most recently, Cucchi et al. (2016) have shown how carbon and nitrogen stable isotope analysis of pig bone collagen enabled an investigation of animal husbandry and increasing social complexity in ancient China.

The major sources of isotope variation in a food web relate to the environment in which an animal lives and the foods it consumes there. The movement of carbon through the food chain results in average trophic level shifts of ~5‰ between plants and herbivores collagen, and ~1‰ between herbivore and carnivore (DeNiro and Epstein 1978). For nitrogen, the trophic level is an average of ~4‰ (Hedges and Reynard 2007). Much of the variation is assimilated from plants, which themselves are affected by the soils on which they grow. Wild and domestic ungulates consume two types of plants as the bulk of their diet: C_3 and C_4 plants. Greater isotopic discrimination against the heavier isotope ^{13}C during C_3 photosynthesis results in distinctive isotope values for C_3 versus C_4 plants. Carbon isotope values in global C_3 plants typically range between: −34 and −22‰, whilst in C_4 plants this range is between −20 and −7‰ (O'Leary 1981). One of the key C_4 crop plants in central Europe would have been millet (Hunt et al. 2008), but it is not clear how abundant other wild C_4 plants would have been that may have been available to animals. C_4 plants are thought to be generally avoided by most animals, due to their poorer nutritional quality relative to C_3 plants (Heckathorn et al. 1999), although these plants have been used as foddering by humans in the past (e.g. Copley et al. 2003; Fuller et al. 2012; Cucchi et al. 2016). More modest sources of isotope variation are often the result of local conditions: temperature, rainfall, canopy effect of dense woodland and soil nutrient content (Tieszen 1991; Van der Merwe and Medina 1991; Glagoleva and Chulanovskaya 1992; Tieszen and Fagre 1993; Heaton 1999).

Nitrogen isotope values in consumers are also influenced by a range of environmental and physiological factors, most of which result in raised nitrogen isotope values. In plants, these are aridity (e.g. Heaton 1987; Ambrose 1991; Cormie and Schwarcz 1994; Gröcke et al. 1997; Schwarcz et al. 1999) and soil salinity (e.g. van Groenigen and van Kessel 2002; Robinson et al. 2000). In animals, these include the physiological effects of environmental phenomena including body water conservation (Ambrose 2000), rumination in animals such as sheep and cattle (Macko et al. 1982; Sealy et al. 1987; Wattiaux and Reed 1995; Cormie and Schwarcz 1996) and starvation (Fuller et al. 2005; cf. Barboza et al. 1997; Ambrose 2000; Faber et al. 2003; Stewart and Smith 2005). In addition, Bogaard et al. (2007) and Fraser et al. (2013a, b) have shown that manuring also causes ^{15}N enrichment and higher nitrogen isotope values in crops.

Isotopic analyses of sequential enamel samples have the resolution to provide seasonal information on herd management practises (Balasse et al. 2002, 2003; Fricke and O'Neil 1996; Henton 2012). Oxygen isotope sequences in *Ovis/Capra* were used to elucidate the seasonality of water ingested within their food (Bryant and Froelich 1995; Iacumin and Longinelli 2002). Tooth enamel is sequentially deposited over a fixed period without re-modelling (Weinreb and Sharav 1964); in caprine second and third molars formation takes approximately 1 year (Suga 1982). In caprine tissue, oxygen is primarily sourced from ingested water derived ultimately from precipitation, and the ratio of its isotopes varies with climate and with seasonal changes in temperature and precipitation (Dansgaard 1964; Rozanski et al. 1993). The seasonal signature can, however, be lost if ingested water derives from large reservoirs of mixed-season water (Darling 2004), if the animals are moved to areas with different temperature and precipitation regimes (Poage and Chamberlain 2001) or if they are foddered on food collected out of season.

The objective of this article is to use carbon, nitrogen, oxygen and strontium isotopes from a Neolithic settlement at Kopydłowo in the southern part of Kujavia in the Polish lowlands to address different facets of cattle and caprine husbandry practises. The settlement was occupied by the first Early Neolithic farming groups of the *Linearbandkultur* (LBK) in the lowlands and then by the first genuinely indigenous Middle Neolithic farmers of *Trichterbecherkultur* (TRB). An application of the multi-isotope approach with its unprecedented heuristic potential makes it possible to address a complex character of cattle and caprine husbandry of early farming groups and reflect the hitherto unexplored dimension of existence of two distinctively different Neolithic communities occupying the lowlands areas of northern Europe. In particular, the article addresses birthing place and season, diet, foddering, the movement of cattle and caprines across landscapes, including seasonality and pasture location of both herds, as well as potential impact on inter-annual climate variations in rainfall, temperature and seasonality onto herding strategies.

The settlements at Kopydłowo and the central European Neolithic

The first Neolithic communities of the LBK culture in the lowlands of central Europe appeared ca. 5500–5400 cal BC (Czerniak 1998, 23; Milisauskas and Kruk 1989, 404). These earliest groups of the so-called Danubian Neolithic immigrated to the lowlands from the south. LBK sites are scattered throughout the Polish lowlands—in Kujavia, Chełmno Land and Pyrzyce along the lower Oder—almost exclusively on fertile rich brown and black soils, similar in quality to the loess soil of the uplands. The period following the demise of the LBK in the Polish lowlands at the end of the 6th millennium BC brought about a complete disintegration of the hitherto dominant cultural and social arrangements. The first half of the 5th millennium BC marked the discontinuous development of new forms of spatial organisation in all major parts of the early Neolithic oecumene in the Polish lowlands. In the second half of the 5th millennium cal BC, a completely different picture of lowland Neolithic communities emerged and represented by the Late Lengyel culture. These were fully fledged farming communities organised in the form of individual households (e.g. Grygiel 2008; Grygiel and Bogucki 1997). The demise of these arrangements towards the end of the 5th millennium BC marks the end of the Danubian Neolithic. The emergence of the TRB in the following millennium marked the beginning of a new phase in the development of the Neolithic on the North European Plain. These groups were formed as a result of the increasingly independent development of lowlands framers, far distanced from any external influences, additionally strengthened by the systematically developing relations with local foragers. These can rightly be defined as the first genuinely local farming groups of the Polish lowlands. They exploited increasingly diverse ecological zones by applying a number of diverse exploitation strategies involving exploitation of areas with poor soils or forested zones (see Marciniak 2008).

This trajectory of development of local communities in the Polish lowlands is well manifested at the settlement at Kopydłowo, site 6 (see Marciniak et al. 2015a). It is located in the southern part of Kujavia, near its western border with Greater Poland (Fig. 1). The site was excavated in the years 1984–1985 but unearthed materials have only been analysed very recently as a part of the large-scale project funded by the Polish Ministry of Culture and National Heritage. Altogether, an area of ca.

Fig. 1 Kopydłowo, site 6. Location of the site

3 acres has been excavated. It led to the discovery of 62 archaeological features (Fig. 2), most of which dated to the LBK, Late Lengyel and TRB cultures, over 7000 pottery sherds, ca. 2700 animal bones and over 200 flint artefacts, in addition to a number of materials that are post-Neolithic in date. A small part of the Late Lengyel settlement has also been discovered. The LBK settlement from phase IIA (the so-called Note phase) is represented by two pits (25B and 25C) with numerous artefacts. The Late Lengyel settlement is represented by four pits and a burial in addition to pottery sherds. Remains of the TRB culture, dated to classic Wiórecka, i.e. IIIB-IIIC phase, are much more numerous. They are represented by pits of different function and character as well as postholes indicative of the presence of large house (Marciniak et al. 2015b). Due to a dearth of faunal material from the Late Lengyel settlement, the article is focused on husbandry practises in the LBK and TRB groups. The data from the Late Langyel community are only used in places for a comparative purpose.

The bone assemblage from LBK and TRB settlements at Kopydłowo derive from household post-consumption refuse and bone working. The majority of bones were found in a few sunken featured buildings. One of TRB pits included a stack of cattle, aurochs and goat horn cores used for horn working (Lisowski 2014, 2015). The LBK assemblage (minimum number of elements, $N = 97$) is dominated by cattle (45.4%), followed by pigs (30.9%) and caprine (7.2%) (Lisowski 2015). The TRB assemblage (MNE $N = 234$) has a similar composition with cattle being the most common species (55.1%), followed by pigs (25.2%) and then caprine (12.0%) (Lisowski 2015).

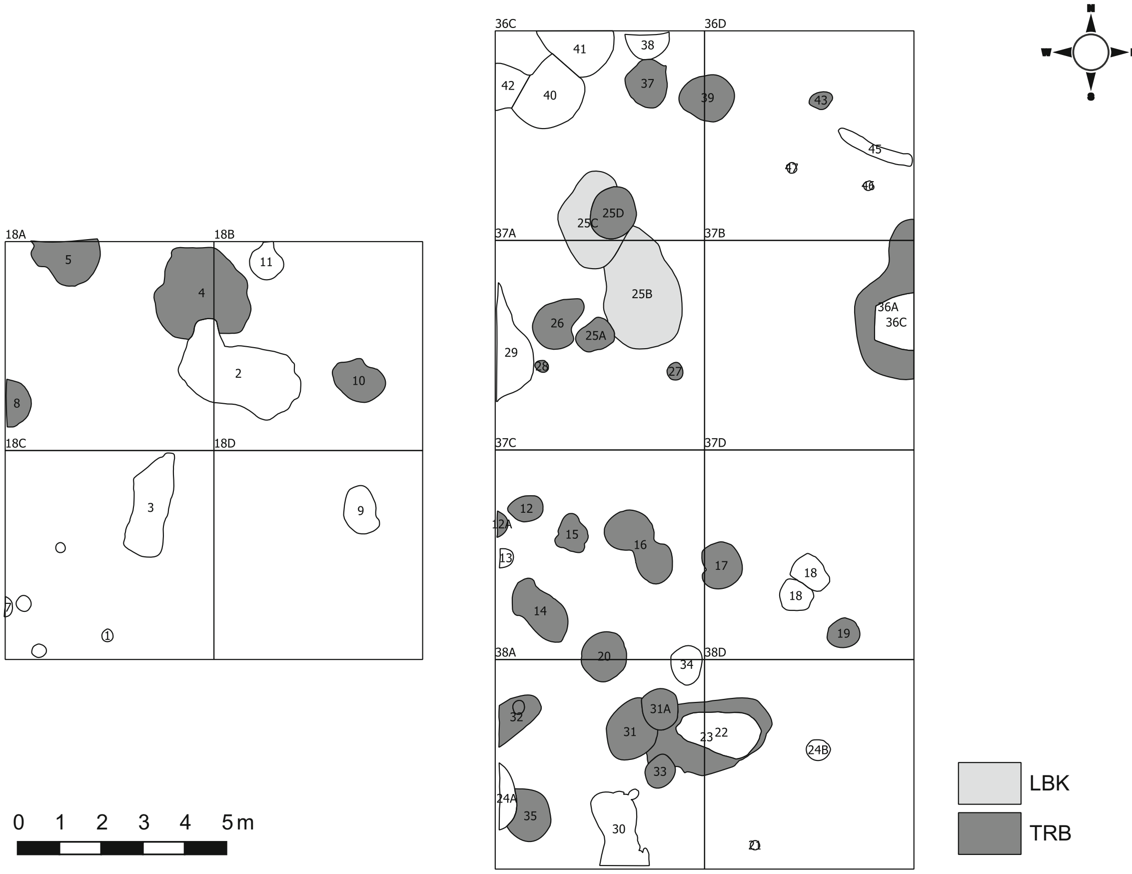

Fig. 2 Kopydłowo, site 6. A plan of the excavation areas and distribution of archaeological features

Materials and methods

Bone and teeth remains recovered from archaeological features from the LBK and TRB Kopydłowo settlements have been analysed isotopically. Altogether, bone collagen from 29 cattle and caprine specimens was subjected to carbon and nitrogen analyses (Table 1). Five Kopydłowo caprine molars were subjected to sequential oxygen isotopic analyses of the enamel (Table 2). Strontium isotope of nine samples of tooth enamel were measured to determine the life signal of the source animal and three bone samples were analysed to give an indication of the local burial values at the site (Table 3). In this article, we use 0.005 *P* value as the threshold for a statistically significant result.

Samples for bone collagen extraction were taken as a chunk of compact cortical bone (c.500 mg) using a diamond powder-coated cutting wheel from the broken end of the bone diaphysis avoiding articulations, cut marks, pathologies, glue and identification number. All reagents used were analytical grade (AR/Analar); water used was of ultrapure (18.2 MΩ) quality. The bone collagen extraction protocol follows the modified Longin (1971) method (Brown et al. 1988). Collagen integrity was assessed using the atomic C/N ratio range of 2.9–3.6, %C range of 22.6–47.0%, and %N range of 8.1–16.6% criteria of DeNiro (1985) and Ambrose (1993). All samples with ratios outside of the acceptable ranges for these were discarded. They were measured in duplicate at the NERC Isotope Geosciences Laboratory (NIGL), UK, and analysed using an Elemental Analyzer (Flash/EA) coupled to a Thermo Finnigan Delta^{Plus} XL isotope ratio mass spectrometer via a ConFlo III interface. All data are reported drift-corrected and measurement precision was 0.1‰ for both carbon and nitrogen.

Samples for stable isotope ratio analysis of oxygen were retrieved and prepared following methods established by Balasse (2002). The mesial tooth column buccal surface of each specimen was cleaned, and six sequential samples of c15mg were drilled at measured distances from the enamel-root junction (Fig. 3); contamination and diagenetic carbonates were removed following Balasse et al. (2002). The carbonate fraction of each sample was analysed for $\delta^{18}O$ by isotope ratio mass spectrometry at UCL Bloomsbury Environment Isotope Facility on their ThermoFinnigan DeltaPLUS XP stable isotope mass spectrometer attached to a ThermoScientific Gas Bench II. The raw data is presented in Table 2. Interpretation of the oxygen isotope data draws on a model constructed from monthly data collected over a number of years from four stations within 300 km of Kopydłowo

Table 1 Kopydłowo, site 6. Results of $\delta^{13}C$ and $\delta^{15}N$: analyses of collagen samples

Sample name	Feature	Culture	Species	Element	%C	%N	Atomic C:N	δ13C PDB (‰)	δ15N AIR (‰)
KOP25	25B	LBK	Caprine	Humerus	36.5	12.6	3.4	−20.5	5.7
KOP27A	25B	LBK	Caprine	Radius	41.6	15.1	3.2	−19.8	6.7
KOP28	25C	LBK	Caprine	Metatarsal	24.0	8.2	3.4	−20.3	7.7
KOP1	25B	LBK	Cattle	Tibia	37.5	13.0	3.4	−20.8	6.3
KOP10	25B	LBK	Cattle	Radius	36.8	13.1	3.3	−20.4	6.3
KOP11	25B	LBK	Cattle	Metacarpal	43.0	15.7	3.2	−19.9	6.0
KOP12	25B	LBK	Cattle	Metacarpal	35.5	11.6	3.6	−20.1	6.6
KOP24	25B	LBK	Cattle	Phalanx 1	42.5	14.9	3.3	−20.2	6.4
KOP26	25C	LBK	Cattle	Phalanx 2	41.7	13.9	3.5	−20.7	6.7
KOP7	25C	LBK	Cattle	Phalanx 2	35.0	12.1	3.4	−21.0	6.0
KOP8	25C	LBK	Cattle	Astragalus	38.4	14.1	3.2	−20.2	6.2
KOP9	25B	LBK	Cattle	Metatarsal	36.1	12.5	3.4	−20.8	6.0
KOP5	36	LBK/TRB	Sheep	Radius	42.7	15.6	3.2	−20.0	6.2
KOP04	4	TRB	Caprine	Radius	37.6	12.8	3.4	−21.0	6.7
KOP30	31	TRB	Caprine	Metacarpal	40.5	14.8	3.2	−19.9	5.9
KOP16	4	TRB	Cattle	Radius	36.3	13.2	3.2	−21.1	7.8
KOP13	4	TRB	Cattle	Femur	41.5	14.6	3.3	−21.2	7.2
KOP14	5	TRB	Cattle	Metacarpal	35.6	12.4	3.4	−20.6	8.2
KOP18	31	TRB	Cattle	Skull	46.3	15.5	3.5	−20.2	8.3
KOP19	31	TRB	Cattle	Skull	42.8	15.5	3.2	−20.7	6.3
KOP20	31	TRB	Cattle	Radius	38.8	13.7	3.3	−22.1	6.7
KOP21	4A	TRB	Cattle	Humerus	28.7	9.4	3.6	−22.7	6.8
KOP22	4A	TRB	Cattle	Metatarsal	41.3	14.5	3.3	−21.2	7.6
KOP29	4A	TRB	Cattle	Radius	38.0	13.6	3.3	−21.0	8.7
KOP3	4A	TRB	Cattle	Phalanx 1	44.9	15.2	3.5	−21.0	7.7
KOP6A	31	TRB	Cattle	Skull	38.5	13.7	3.3	−21.7	7.0
KOP2	31	TRB	Cattle/Aurochs	Skull	36.8	11.9	3.6	−21.4	6.8
KOP15	31	TRB	Goat	Skull	41.8	15.0	3.3	−21.0	8.2
KOP23	31	TRB	Goat	Skull	42.5	15.6	3.2	−20.4	7.7

(IAEA/WMO 2014) (Table 4), which was used to model the seasonal distribution of oxygen isotopic values at both Neolithic settlements (Fig. 4).

Samples for stable isotope ratio analysis of strontium were prepared as described in Neil et al. (2016). Strontium was loaded onto a single Re Filament following the method of Birck (1986), and the isotope composition and concentrations were determined by thermal ionization mass spectroscopy (TIMS) using a Thermo Triton multi-collector mass spectrometer. The international standard for $^{87}Sr/^{86}Sr$, NBS987, gave a value of 0.710250 ± .000006 ($n = 8, 2\sigma$) during the analysis of these samples. Blank values are better than 100 pg (Table 3). All samples were measured at the NERC Isotope Geosciences Laboratory (NIGL), UK. It is important to stress that because of the high porosity of the bone, the Sr isotope composition determined will be dominated a diagenetic signal reflecting the burial area and will not reflect a life signal. As the bone is taking up strontium from the soil during burial, the Sr concentrations in it are so high.

Different facets of cattle and caprine herd management strategies at settlements of both cultures at Kopydłowo recognised isotopically were then considered alongside with their picture by zoorchaeological methods, in particular the estimation of age-at-death (Vigne and Helmer 2007, Marciniak 2011). It was assessed using mandibular teeth wear and eruption following Payne (1973) for sheep/goat, and Grant (1982) and Grigson (1982) for cattle. Epiphyseal fusion dates are based on Silver (1969) and were grouped into age stages (cf. Wilson et al. 1978; Halstead 2011). For cattle, 4 stages were distinguished; animals killed (1) before 7–10 months, (2) before 12–18 months, (3) before 24–36 months and (4) before 36–48 months. Sheep and goat bones were divided in 3 stages; animals killed (1) before 7–10 months, (2) before 18–28 months and (3) before 30–42 months (see

Table 2 Kopydłowo, site 6. Results of $\delta^{18}O$ analyses of enamel samples—six samples taken at measured intervals along the tooth columns of five tooth specimens

No.	Context	Specimen	Tooth pillar height	Sample details						Explanation of rows
				1 ERJ	2	3	4	5	6 Occlusal	
5	TRB 261 1872	Sheep (*Ovis*) loose R M_2	28.9	2.3	6.1	11.3	14.6	20.8	28.7	mm from ERJ
				13	15	13	14	18	15	Weight (mg)
				-6.42	-8.82	-10.64	-11.28	-10.75	-10.66	δ18O
						Max −6.42	Min −11.3	Range 4.86		Tooth summary
2	TRB 314 1332	Caprine (*Ovis/Capra*) loose R M_3	27.8	2.5	6.2	11	15.6	20.4	24.6	mm from ERJ
				13	14	12	18	11	18	Weight mg
				-8.84	-6.05	-4.4	-6.62	-7.91	-7.67	δ18O
						Max −4.4	Min −8.84	Range 4.44		Tooth summary
3	TRB/Late Lengyel 306,569	Caprine (*Ovis/Capra*) loose L M_3	31.5	1.3	4.8	8.2	13.1	19.6	24.1	mm from ERJ
				21	23	20	20	17	12	Weight (mg)
				-5.51	-7.75	-7.44	-9.83	-6.97	-5.91	δ18O
						Max −5.51	Min −9.83	Range 4.32		Tooth summary
7	Late Lengyel 345 2458	Goat (*Capra*) jaw L M_2	25.7	2.9	6.9	11	14.2	18.9	23.6	mm from ERJ
				13	16	14	27	21	19	Weight (mg)
				-7.22	-5.39	-6.83	-9.03	-9.19	-4.45	δ18O
						Max −4.45	Min −9.19	Range 4.74		Tooth summary
1	Late Lengyel 345 2457	Goat (*Capra*) jaw L M_3	25.3	1.9	4.1	8.2	13	16.6	22.6	mm from ERJ
				11	14	12	13	17	13	Weight (mg)
				-4.97	-4.93	-7.1	-7.9	-6.89	-4.84	$\delta^{18}O$
						Max −4.84	Min −7.9	Range 3.06		Tooth summary

Table 3 Kopydłowo, site 6. The strontium isotope compositions and Sr concentrations form the enamel and bone samples.

Inv. No.	Feature	Culture	Sample code	Type of sample	Body part	Sr ppm	87Sr/86Sr
k6/60/677	4	TRB	ML - 01	enamel - pig	Mandibular M2 (with parts of the socket)	148	0.71249
k6/60/673	4	TRB	ML - 02	enamel - cattle	Mandibular M2	184	0.71300
k6/92/125	5	TRB	ML - 04	enamel - cattle	Mandibular M1/2	147	0.71214
k6/228/1638	31	TRB	ML - 06	enamel - cattle	Maxillar molar	200	0.71301
k6/220/2261	25B	LBK	ML - 07	enamel - cattle	Mandible (P2, P3, M1, M2)	117	0.71195
k6/207/1912	25B	LBK	ML - 08	enamel - pig	Mandibular M2	90	0.71169
k6/220/2270	25B	LBK	ML - 09	enamel - cattle	Mandibular M3	141	0.71199
k6/114/926	4A	TRB	ML - 10	enamel - cattle	Mandibular M2	158	0.71269
k6/220/2262	25B	LBK	ML - 15	enamel - cattle	Mandible (P2, P3, M1, M2)	160	0.71189
k6/314/1326			ML - 13	bone	Bone sample for background value	308	0.712619
k6/100/194			ML - 11	bone	Bone sample for background value	253	0.712319
k6/309/464			ML - 12	bone	Bone sample for background value	285	0.712735

Lisowski 2015). Due to a small number of mandibles, most of ageing data derives from epiphyseal fusion.

Results

Cattle, sheep, goats and caprine specimens yielded carbon isotope values ranging from −22.7 to −19.8‰ and from 5.7 to 8.7‰ in case of nitrogen isotope values (Table 1). The results of 8 collagen samples from sheep, goats and caprines (specimens that could not be identified with confidence to sheep or goat) are as follows: the single sheep has a carbon isotope value of −20.0‰ and a nitrogen isotope value of 6.2‰. The carbon and nitrogen isotope values of the two goats differ from each other to a small degree (δ^{13}C −21.0‰, δ^{15}N 8.2‰ and δ^{13}C −20.4‰, δ^{15}N 7.7‰). The results of five caprines range from −21.0 to −19.8‰ in carbon isotope values and 5.7 to 7.7‰ in nitrogen isotope values. These values have a mean of −20.3 and 6.5‰ and one standard deviation of 0.5 and 0.8%. The results of 21 collagen samples from *Bos* spp. (cattle and possible aurochs) are as follows: the carbon isotope range is −22.7 to −19.9‰ and in nitrogen the range is 6.0 to 8.7‰ with mean ratios of −20.9 and 6.9‰, and a standard deviation of 0.7 and 0.8‰ in carbon and nitrogen, respectively. Within the two chronological periods, the *Bos* pp. data is distributed as follows. For the LBK period, the δ^{13}C range is −21.0 to −19.9‰, the mean is −20.5‰ and the standard deviation 0.4‰ and in δ^{15}N the range is 6.0 to 6.7‰, the mean is 6.3‰ and the standard deviation 0.3‰. For the TRB period, the δ^{13}C range is −22.7 to −20.2‰, the mean is −21.2‰ and the standard deviation 0.7‰ and in δ^{15}N the range is 6.3 to 8.7‰, the mean is 7.4‰ and the standard deviation also 0.7‰. Comparing the cattle across the two periods, Student's *t* test indicated a significant difference was found in both carbon (p = 0.003) and nitrogen (p = <0.001) ratios, suggesting that the two cattle

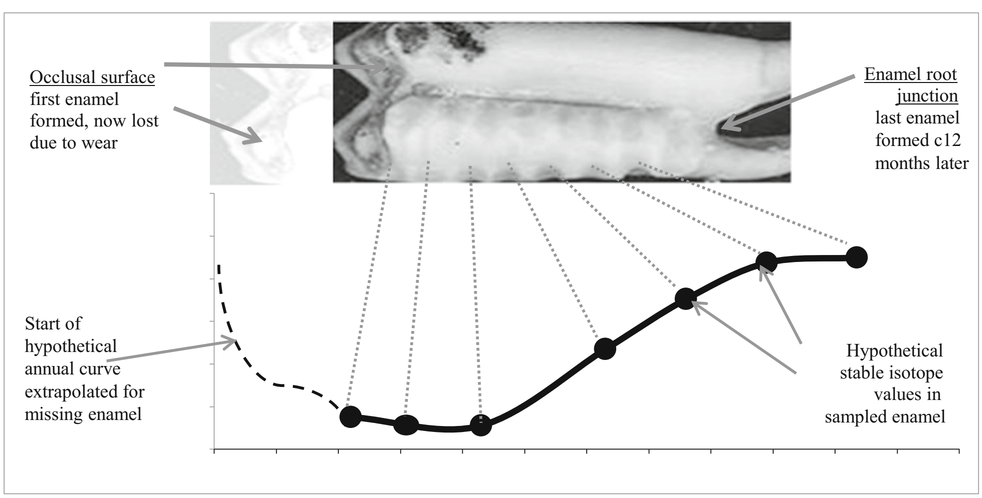

Fig. 3 Typical enamel development in an ungulate molar, with a hypothetical graph constructed from isotope values in sequential samples

Table 4 Geospatial information on Kopydłowo and nearby GNIP collecting stations, including GNIP station average maximum and minimum seasonal $\delta^{18}O_{VSMOW}$ values (data retrieved 30.04.2015) and modelled Kopydłowo values extrapolated from Brest and Berlin GNIP data

Collection station (no years)	Position relative to Kopydłowo	Map coordinate	Altitude masl	Climate	Average maximum $\delta^{18}O_{VSMOW}$/	Average minimum $\delta^{18}O_{VSMOW}$/	Range in $\delta^{18}O_{VSMOW}$ ‰
Kraków, Poland (34)	215 km SSE	50° 3′ 42″ 19° 50′ 55’	205	Cool, fully humid winters with warm summer	-6.72	-13.54	6.82
Brest, Belarus (4)	294 km E	52° 5′ 40″ 23° 42′ 21”	136		-5.38	-14.78	9.4
Berlin, Germany (27)	257 km W	52° 28′ 12″ 13° 24′ 00”	50		-6.4	-9.94	3.54
Uhlirska, Czech (4)	220 km SW	50° 49′ 57″ 15° 8′ 52”	823		-5.6	-12.95	7.35
Kopydłowo	x	52° 45′ 60″ 18° 19′ 70″	104		-6.05	-12.28	6.23

populations had either significantly different diets, or were subject to different environmental conditions. In addition, the TRB group were slightly more widely distributed than the LBK group, suggesting that the later TRB group may have been subject to more varied pastoral practises.

For comparative purposes, 60 compound-specific $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ values of residues identified as animal fats from the LBK and TRB periods were also used (Roffet-Salque and Evershed 2015) (Table 5). For the LBK period, the $\delta^{13}C_{16:0}$ range is −29.3 to −25.3‰ whilst the $\delta^{13}C_{18:0}$ range is −31.7 to −27.2‰. For the TRB period, the $\delta^{13}C_{16:0}$ range is −28.9 to −25.8‰ and the $\delta^{13}C_{18:0}$ range is −33.3 to −27.0‰. The $\Delta^{13}C$ (=$\delta^{13}C_{18:0}$-$\delta^{13}C_{16:0}$) proxy was used in order to identify the fat types by emphasizing the influence of animal metabolism (Copley et al. 2003; Dunne et al. 2012). The ruminant carcass fats most likely originate from cattle; however, at this stage, it is impossible to exclude other ruminants, such as sheep and goats, as sources of carcass fats in the pots because their bulk collagen $\delta^{13}C$ values have yet to be recorded.

The oxygen isotope raw data for each analysed sample, presented in Table 2, include the maximum, minimum and range in $\delta^{18}O_{PDB}$ values for each tooth specimen. The total variation was 6.9‰ (−4.4 to −11.3‰) and the intra-tooth variation ranged from 3.06 to 4.86‰. The analytical precision was tested with two standards which showed 0.087‰ (FBS) and 0.079‰ (LES) variations. In comparison to the variation seen in the archaeological samples, this variation of <1‰ is considered satisfactory in order to proceed with interpretation.

The curves constructed from the $\delta^{18}O_{PDB}$ values in the sequential sampling of each tooth specimen are displayed in Fig. 5. The curves in the left column are of second mandibular molars and on the right are the third mandibular molars. The curves in the top row are TRB specimens, the middle row has the TRB/Late Lengyel specimen and the bottom row has the Late Lengyel specimen—the goat second and third mandibular molars. The $\delta^{18}O_{PDB}$ curves of the goat (bottom row) and caprines (middle and top row) show maximum and minimum peaks points that can be related to water ingestion that is

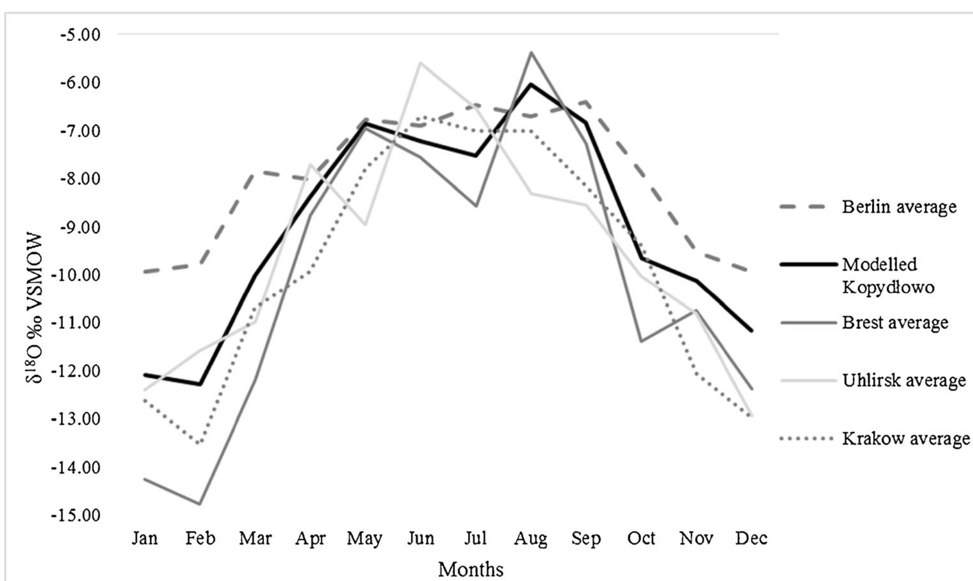

Fig. 4 Averaged annual cycle of $\delta^{18}O_{VSMOW}$ values in GNIP stations near Kopydłowo (data retrieved 30.04.2015), and modelled annual curve for Kopydłowo derived from Brest and Berlin data

Table 5 Kopydłowo, site 6. List of potsherds sampled for lipids' analysis (after Roffet-Salque, Evershed, 2015)

Sample name	Vessel type	Culture	$\delta^{13}C_{16:0}$ [‰]	$\delta^{13}C_{18:0}$ [‰]	$\Delta^{13}C$ [‰]
KOP2921	sieve	LBK	−26.0	−31.7	−5.7
KOP2922	kümpfe D	LBK	−25.7	−27.9	−2.2
KOP2923	kümpfe D	LBK	−26.6	−26.8	−0.3
KOP2924	kümpfe D	LBK	nd	nd	nd
KOP2925	kümpfe D	LBK	-	-	-
KOP2926	kümpfe D	LBK	nd	nd	nd
KOP2927	kümpfe D	LBK	−26.8	−29.6	−2.9
KOP2928	sieve	LBK	−26.5	−31.0	−4.5
KOP2929	kümpfe D	LBK	−26.2	−28.1	−2.0
KOP2930	kümpfe D	LBK	-	-	-
KOP2931	kümpfe D	LBK	−29.3	−30.5	−1.1
KOP2932	kümpfe D	LBK	−26.6	−28.5	−1.9
KOP2933	kümpfe D	LBK	−26.2	−28.1	−1.9
KOP2934	kümpfe D	LBK	−25.9	−27.5	−1.6
KOP2935	bowl C	LBK	-	-	-
KOP2936	kümpfe D	LBK	−26.7	−29.0	−2.4
KOP2937	bowl C	LBK	−26.0	−27.8	−1.7
KOP2938	kümpfe D	LBK	−25.7	−27.9	−2.2
KOP2939	sieve	LBK	-	-	-
KOP2940	amphora?	LBK	-	-	-
KOP2941	kümpfe D	LBK	−27.0	−28.4	−1.4
KOP2942	kümpfe D	LBK	−26.8	−28.7	−1.9
KOP2943	kümpfe D	LBK	−26.5	−28.3	−1.8
KOP2944	kümpfe D	LBK	−26.2	−27.2	−1.0
KOP2945	bowl C	LBK	-	-	-
KOP2946	kümpfe D	LBK	−25.3	−28.0	−2.6
KOP2947	kümpfe D	LBK	nd	nd	nd
KOP2948	kümpfe D	LBK	−26.8	−28.6	−1.8
KOP2949	kümpfe D, miniature	LBK	−25.5	−29.4	−3.9
KOP2950	kümpfe D	LBK	−26.5	−28.9	−2.4
KOP2951	beaker	TRB	−26.4	−32.4	−6.0
KOP2952	beaker	TRB	−26.7	−32.4	−5.7
KOP2953	beaker	TRB	−26.7	−30.9	−4.3
KOP2954	bowl	TRB	−26.8	−32.2	−5.4
KOP2955	beaker	TRB	-	-	-
KOP2956	beaker	TRB	−26.7	−32.6	−5.9
KOP2957	?	TRB	-	-	-
KOP2958	beaker	TRB	-	-	-
KOP2959	beaker	TRB	−26.8	−29.6	−2.7
KOP2960	beaker?	TRB	−28.9	−33.3	−4.4
KOP2961	amphora	TRB	-	-	-
KOP2962	beaker	TRB	−27.6	−33.1	−5.4
KOP2963	beaker	TRB	−27.5	−32.8	−5.3
KOP2964	beaker	TRB	−26.8	−31.4	−4.6
KOP2965	casserole	TRB	−27.7	−29.3	−1.7
KOP2966	pot	TRB	-	-	-
KOP2967	pot	TRB	−27.0	−29.7	−2.7
KOP2968	beaker	TRB	−28.3	−33.0	−4.8

Table 5 (continued)

Sample name	Vessel type	Culture	$\delta^{13}C_{16:0}$ [‰]	$\delta^{13}C_{18:0}$ [‰]	$\Delta^{13}C$ [‰]
KOP2969	bowl without base	TRB	-	-	-
KOP2970	bowl?	TRB	−25.8	−27.0	−1.2
KOP2971	collared flask	TRB	-	-	-
KOP2972	?	TRB	-	-	-
KOP2973	collared flask	TRB	-	-	-
KOP2974	beaker	TRB	−27.0	−31.2	−4.2
KOP2975	amphora	TRB	−26.4	−27.9	−1.6
KOP2976	?	TRB	−26.6	−28.9	−2.3
KOP2977	beaker	TRB	−28.1	−32.8	−4.7
KOP2978	beaker	TRB	−27.2	−32.2	−4.9
KOP2979	beaker	TRB	−27.4	−32.8	−5.4
KOP2980*	conical pot	TRB	−27.2	−30.0	−2.8

Footnote:

* - Ruminant adipose fat

enriched in summer and depleted in winter. The $\delta^{18}O_{PDB}$ curve for the sheep (top row) neither tops nor bottoms out clearly; nevertheless, this truncated range is the highest at 4.86‰. All these curves allow discussion of variations in seasonal water uptake over nearly an annual cycle.

Considering the $\delta^{18}O_{PDB}$ curves generated from sequential sampling of both goat teeth (Sp. 7 and 1), the continuation of the curve from one to the other with only a slight overlap is consistent with the timing of second and third mandibular molar tooth development. This extends the period of analysis, incorporating three consecutive summers and two winters, and allows inter-annual variability in water intake and potentially in precipitation to be discussed. The sequence in these two teeth also reveals the relationship in curve progression between second and third mandibular molars.

Figure 6 presents the maximum, minimum and range in $\delta^{18}O_{PDB}$ values for each tooth specimen. The maximum $\delta^{18}O_{PDB}$ values range from −4.4‰ (Sp. 2) down to > − 6.42‰ (Sp. 5). The minimum $\delta^{18}O_{PDB}$ values range from −7.9 (Sp. 1) down to <−11.3 (Sp. 5). The ranges extend from 3.06‰ (Sp. 1) to 4.74‰ (Sp.7).

The data from the enamel shows a range of Sr isotope between 0.7117 and 0.7130 (Table 3). Such values would be typical of Palaeozoic rock substrate in the UK (Evans et al. 2010). The Sr concentrations show a moderately wide range of results between 90 and 184 ppm. The data from the bone samples has significantly higher Sr ppm, reflecting re-equilibration with the burial environment. The Sr isotope values from the bone provide an estimate for the local burial environment.

Animal husbandry practises in the lowland LBK and the TRB communities from the stable isotope perspective

Stable isotopes make it possible to address the unexplored dimensions of prehistoric animal husbandry practises going far beyond the heuristic potential of zooarchaeological studies. A number of intertwined aspects of cattle and caprine husbandry of the LBK and TRB communities from Kopydłowo have been scrutinised, including birthing location and seasonality, diet, pasturing pattern, foddering and herding responses to inferred changes in climate. However, the small sample for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{18}O$ analyses from both settlements does not allow to formulate far-reaching conclusions. As the results are showcasing the potential of this approach, it invites large sample size from the region to produce a more complex picture of husbandry practises.

Caprine birthing

As presented above, the sequential $\delta^{18}O$ curves taken from the goat second and third molars makes it possible to offer tentative speculations on their birth seasonality (Fig. 5). Both the goat and the TRB/Late Lengyel caprine have similar curve progressions, suggesting that the seasonality of enamel formation, and therefore the birth of both animals, was the same (Balasse et al. 2003; Blaise and Balasse 2011). The curve of $\delta^{18}O$ values in the TRB sheep M2 ends only slightly earlier in the annual cycle, suggesting it was born slightly later in the same season. Whereas the curve of $\delta^{18}O$ values in the TRB

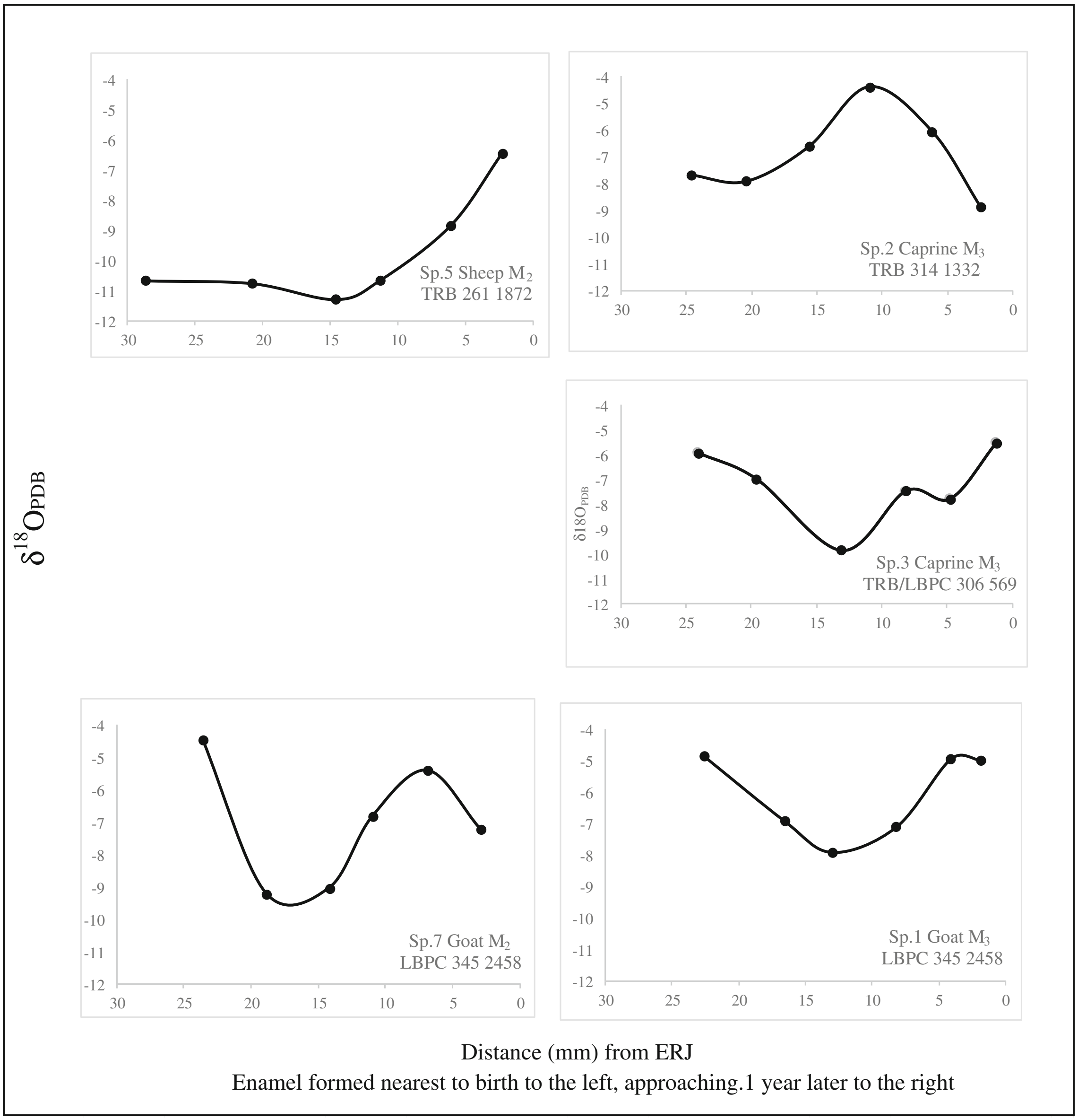

Fig. 5 Kopydłowo, site 6. Charts of $\delta^{18}O_{PDB}$ values in sequential samples taken from five tooth specimens

caprine ends at the opposite point of the annual cycle, consistent with a 6-month difference in the timing of enamel precipitation due to it having been born in a different season 6 months apart. This interpretation should be taken cautiously due to low sample resolution and non-normalised tooth length; nevertheless, both caprine ethology and early husbandry practises offer some support to seasonal variation on birthing season. In temperate climates, sheep and goat births are largely confined to spring, although autumn births rarely occur. The TRB caprine might have been born in a different season as a result of poor mating management or conversely, with intensive control of the breeding condition of both ewe and ram by controlling the dietary nutritional plane (Dahl and Hjort 1976), might possibly be the result of managed birth season manipulation.

Cattle and caprine diet

Carbon isotopes of cattle, sheep, goats and sheep/goats from both LBK and TRB settlements range from −22.7 to −19.8‰ and show a C_3 plant-based terrestrial diet (Fig. 7). The carbon isotope value cut-off for pure C_3 plant consumption according to O'Leary (1988) (based on global averages of plants) should be −22‰, with most researchers using > − 19‰ (see Fuller et al. 2012 for discussion). Individuals with higher carbon isotope values would suggest the input of some C_4 plants in their diet. Using the local LBK Vaihingen mean plant carbon isotope value of −24‰ (Table 6), no animals at Kopydłowo, site 6, are implicated as having consumed C_4 plants since the highest carbon isotope value is −19.8‰ (applying the 5‰ enrichment factor between plant and consumer). A number

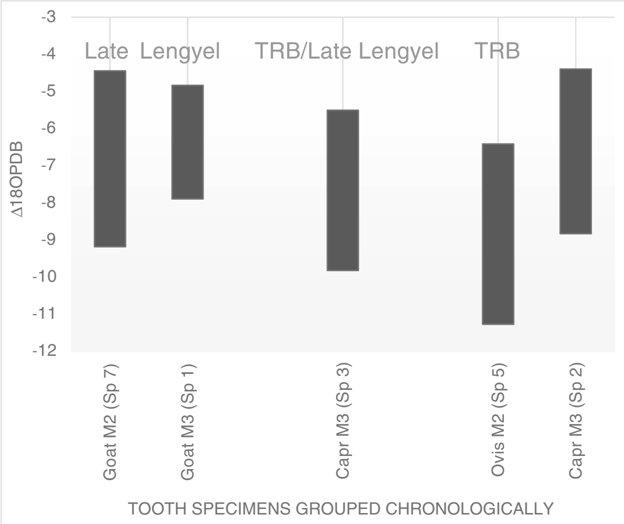

Fig. 6 Kopydłowo, site 6. Chart displaying maximum (*top of columns*), minimum (*bottom of columns*) and range (*length of columns*) in $\delta^{18}O_{PDB}$ values for each tooth specimen

of individuals have carbon isotope values as low as −21 and −22‰, many of which are cattle. Without the range for C_3 and C_4 plants in the area, it is difficult to interpret these data as evidence of environment in which they were herded.

It is notable that the $\delta^{13}C$ values of lipids ($\delta^{13}C_{16:0}$) preserved in LBK and TRB potsherds (−26.4 and −27.1 ‰, respectively) are ca. 6 ‰ more depleted than bulk $\delta^{13}C$ values of collagen from cattle bones (see Roffet-Salque and Evershed 2015). This difference can be explained in the light of feeding experiments showing that $\delta^{13}C$ values of lipids are ca. 6 ‰ more depleted than bulk $\delta^{13}C$ values of collagen (Howland et al. 2003). Hence, the mean $\delta^{13}C$ values of bulk collagen from bones are in an agreement with the ruminant carcass fats preserved in pots. Both lines of evidence show that domestic animals at both settlements in Kopydłowo had a C_3 plant-based terrestrial diet.

The nitrogen isotope values are ranging from 5.7 to 8.7‰ and are similar to Vaihingen an der Enz (Fraser et al. 2013a, b). The source of this variation is difficult to determine without further work, but at present seems to be largely related to chronological period, with the earlier LBK phase exhibiting values lower than in the later TRB phase, making it very similar to the distribution of carbon isotope values from both settlements.

Cattle pasturing

Carbon and nitrogen isotope values on bone collagen have also been used for identifying type of environment in which the cattle were herded, both in the LBK and TRB periods. Lighter carbon isotope values can be indicative of a more wooded environment (e.g. van der Merwe and Medina 1989; Drucker et al. 2008), although other explanations cannot be ruled out. A significant difference in both carbon (p = 0.003) and nitrogen (p = <0.001) values in cattle from both settlements seems to imply that the cattle populations were subject to different environmental conditions or alternatively they had significantly different diets (Fig. 7). Moreover, the TRB group was slightly more widely distributed than the LBK group, suggesting that it may have been subject to more varied pastoral practises.

The Kopydłowo settlements were located next to a lake (Marciniak et al. 2015b), and one could have expected that animals could have consumed a diet richer in aquatic plants in

Fig. 7 Kopydłowo, site 6. *C* and *N* values for animal bones (n = 30). *Filled symbols* represent the LBK phase, whilst *empty symbols* represent the TRB phase

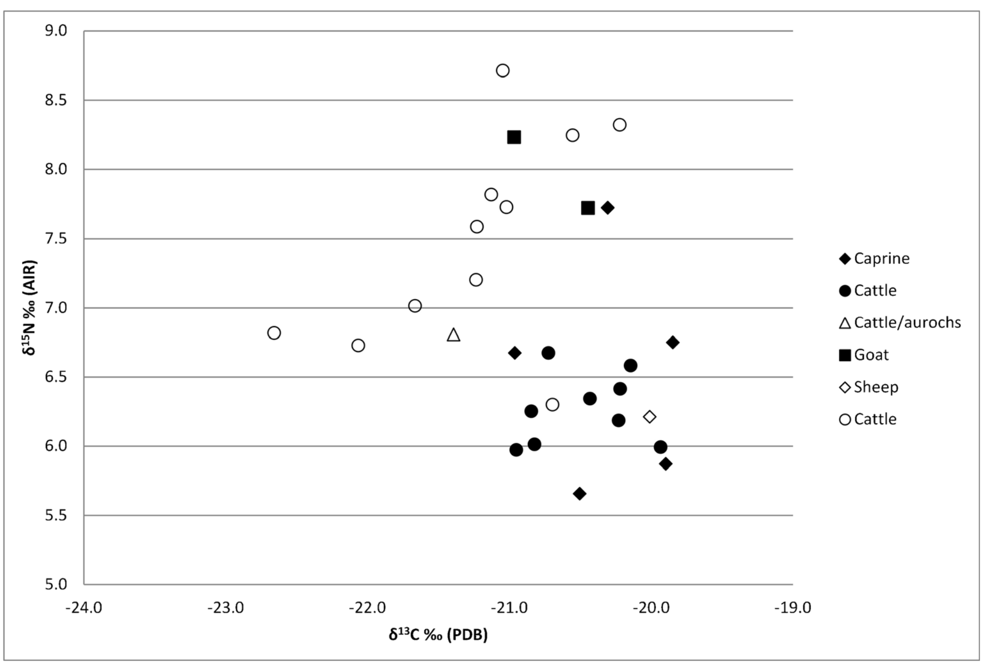

Table 6 Plant stable isotope data from Vaihingen an der Enz (after Fraser et al. 2013a, b)

Taxon/takson	Number	δ^{13}C ‰ (PDB)
Einkorn (1-seeded)	25	-24.8
Einkorn (1-seeded)	25	-24.2
Einkorn (1-seeded)	25	-24.3
Einkorn (1-seeded)	25	-24.2
Einkorn (1-seeded)	15	-23.6
Einkorn (1-seeded)	25	-23.8
Einkorn (2-seeded)	15	-23.6
Einkorn (2-seeded)	25	-24.5
Glume wheat (new type)	25	-24.7
Emmer	25	-24.6
Emmer	25	-23.9
Emmer	25	-23.5
Emmer	25	-23.4
Lentil	25	-23.1
Pea	25	-24.0
Pea	25	-23.7
Average		*-24.0*
Standard deviation		*0.5*

both periods. As pointed out by Mukherjee et al. (2005), the main source of variation in δ^{13}C values of ruminant carcass fats can relate to contribution of C_3, C_4 and aquatic resources to the diet of animals; however, the 'canopy' effect cannot be ruled out here. However, this has been contradicted by mean $\delta^{13}C_{16:0}$ values of animal fats identified as ruminant carcass as well as isotope values from bone collagen. As mentioned above, the mean $\delta^{13}C_{16:0}$ values of animal fats identified as ruminant carcass fats extracted from LBK, Late Lengyel and TRB sherds are −26.5, −27.2 and −26.8 ‰, respectively. The $\delta^{13}C_{16:0}$ values are significantly ca. 0.7 ‰ depleted in Late Lengyel sherds compared to LBK sherds (Kruskal-Wallis test, $p = 0.002$), and ca. 0.3 ‰ depleted in TRB sherds as compared with LBK sherds (Kruskal-Wallis, $p = 0.215$) (see Roffet-Salque and Evershed 2015).

A slight depletion in δ^{13}C values of carcass fats from the TRB period in comparison to LBK may have also been caused by the practice of herding ruminant animals in more forested environments (Drucker et al. 2008). However, foddering with twigs and tree leaves would have affected their δ^{13}C values in a similar way. This seems to be corroborated by a detailed multiproxy study of the palaeoenvironment carried out at Osłonki, a region situated around 50 km to the NW of Kopydłowo (Bogucki et al. 2012), where settlements from the LBK and Late Lengyel periods (5500 and 4000 BC) were excavated (Grygiel 2004, 2008). Pollen diagrams imply the Late Lengyel groups utilised the surrounding forests for grazing and gathering more than during the preceding LBK period (Bogucki et al. 2012). Given this observation, it seems that the more likely explanation for the changes in carbon isotopic composition from the LBK to the Late Lengyel and then TRB is the increased role played by the forests in animal's diet in the latter Kopydłowo settlement.

A different dimension of pasturing practises was revealed by the Sr isotope analysis. The samples from the tooth enamel of TRB animals have higher $^{87}Sr/^{86}Sr$ values than those from the LBK animals (Table 3; Fig. 8), which suggests the inhabitants of two Kopydłowo settlements exploited different aspects of the environment. The TRB enamel samples are similar in isotope composition to the control bone samples, the values from which reflect the local burial environment. The LBK animals are lower than the estimate for the local environment, suggesting that they may have been raised on terrain that is different. What cannot be determined, due to lack of reference data, is whether the difference in values from the two groups reflects relatively local variation or necessitates the LBK coming from significantly further away. It is worth reiterating that as the sample sizes are small, further work with larger sample sizes is needed to explore this further.

Caprine pasturing and foddering

The distribution of oxygen isotope values on TRB caprine tooth has been used for the recognition of herding seasonality (Fig. 5). The δ^{18}O values form the sinusoidal curve imply most that are consistent with ingested water derived from seasonal Northern Temperate rain, as modelled by modern isotopes in precipitation data in Fig. 4. Caprines receive almost all their water intake from plant tissue, and it is likely that the TRB caprine ate plants which were rain-fed and not irrigated from wells or springs. Irregularities in the sinusoidal curve are indicative of loss of seasonality that might be due to winter fodder. Summer-grown plants added enriched δ^{18}O values to the expected winter signature. Conversely, loss of seasonality might be due to summer relocation to cooler wetter pastures with depleted δ^{18}O values contributing to the expected summer signature (Henton 2015).

The smooth sinusoidal curves for the caprines and the goat from the TRB settlement at Kopydłowo (Fig. 5) are indicative of both animals remaining in the same place all year round feeding on plants watered throughout the cycle of that location's seasons. There is no suggestion of uphill movement as the summer peak is not flattened due to the more depleted isotopic values associated with cooler, damper uphill summers (Henton 2012; Poage and Chamberlain 2001). However, it cannot be dismissed that foddering accounts for the δ^{18}O differences in inter-annual minima between the 2 years of the goat second and third molar formation, but only during its second winter (Henton 2015).

The δ^{18}O curve from the Late Lengyel/TRB caprine and the TRB sheep clearly deviate from the sinusoidal but their

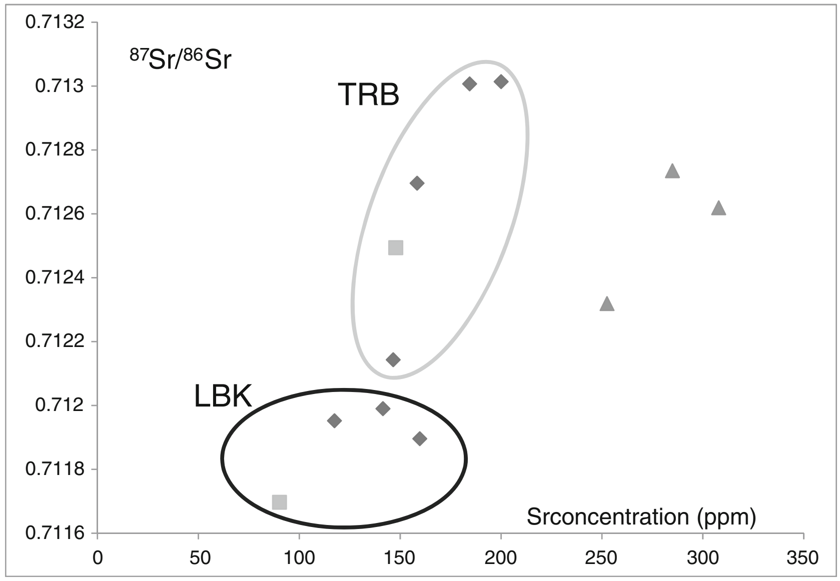

Fig. 8 Kopydłowo, site 6. The Sr isotope ratios from the enamel and bone plotted against the Sr concentrations. *Filled rombs* represent cattle enamel, *filled squares* represent pig enamel, whilst *filled triangles* represent bone

interpretation is far from straightforward. The caprine curve deviates in early summer, which is the time in which pastures are at their most productive and temperatures are rising, making foddering or herd movement to warmer locations unlikely strategies. The $\delta^{18}O$ curve for the sheep has the long depleted section in autumn but it is unlikely it was moved uphill in the period of the year when temperatures would be falling, nor that it was foddered during a dew-led autumn flush of grass (Henton 2015).

Climatic conditions of caprines herding

Climate volatility (Gronenborn 2009) rather than foddering appears to be the more likely explanation for the Late Lengyel/TRB caprine curve deviating in early summer. It may have been caused by an unseasonably hot spell in early summer that year. Lower than expected maximum and minimum $\delta^{18}O$ values for the sheep (Fig. 6) may be the result of the animal experienced a particularly cool summer and winter

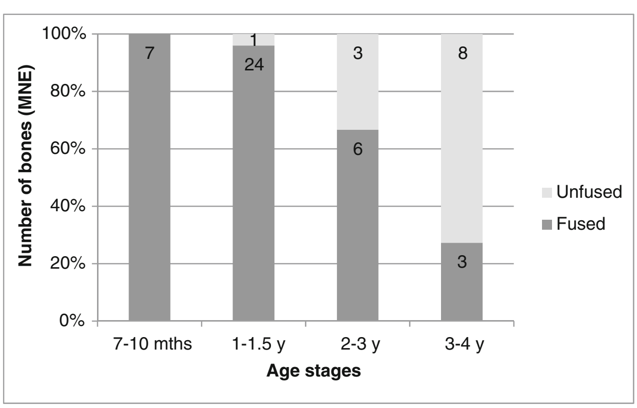

Fig. 9 Kopydłowo, site 6. TRB cattle age-at-death stages based on epiphysial fusion of postcranial skeleton

with a hard autumn that year. Rather than the introduction of fodder in the second year for the TRB goat, climate volatility may well be responsible for the detected difference in the two annual minima (Henton 2015).

Husbandry practises in the Early and Middle Neolithic in the Polish lowlands. An integrated perspective

Whilst studies of carbon and nitrogen isotopes to address animal husbandry strategies in the European Neolithic are relatively common (see, e.g. Le Bras-Goude et al. 2010; Oelze et al. 2011; Robson et al. 2015), an integrated analysis of four major stable isotopes: carbon, nitrogen, oxygen and strontium from a single site marks the new development in these studies. It made it possible to address a number of hitherto unrecognised dimensions of animal husbandry practices such as birthing, seasonality of food provision, animal diet or herd movements, significantly expanding a heuristic potential of faunal studies. It also revealed significant differences in subsequent aspects of husbandry practises performed by the LBK and TRB farming communities from Kopydłowo. Moreover, by combining with faunal, molecular and archaeological strands of evidence, one can set up an integrated and multiproxy research model of animal husbandry studies. Its results can further contribute to addressing a wide range of broader issues, such as resource sharing, landscape exploitation or humans' responses to changes in climate.

Cattle, sheep, goats and sheep/goats from LBK and TRB settlements at Kopydłowo seemed to have terrestrial C_3 plant-based diet of temperate climate, as indicated by carbon isotope values (Oelze et al. 2011:273; see also Dürrwächter et al. 2006). Both groups, however, may have implemented different strategies of livestock management, in particular in terms of herding and feeding practises, as indicated by a significant difference in carbon and nitrogen isotope values of cattle, with earlier LBK settlement exhibiting values lower than in later TRB settlement (see Oezle et al. 2011:277). This variation might be introduced by browsing or grazing in different habitats with distinct isotopic baselines. However, use of different foddering cannot be ruled out. TRB cattle most likely exploited increasingly diverse ecological zones and may have been subject to more varied pastoral practises, as compared with its LBK counterparts, considering their carbon and nitrogen isotopic data was more widely distributed. Expansion of grazing territory for TRB cattle is further corroborated by more variable $^{87}Sr/^{86}Sr$ values. Changes in these values between these two periods imply that some of the cattle were not all local to the Kopydłowo settlements, which may have been linked with the increase in grazing lands over larger geographic ranges (Giblin 2009:496). LBK cattle and caprine may have been fed on a similar diet and used a similar kind of pasture, most likely semi-open woodlands, as implied by elevated and the narrow range of $\delta^{13}C$ values, similar to that reported for wild herbivores from the German LBK sites (Oelze et al. 2011: 274). They were neither grazed in dense deciduous or boreal forests or open landscape. However, this interpretation has to be treated with caution as a wide range of environmental factors could be affecting the values observed (such as water/rainfall, etc.).

One cannot rule out that grazing of the cattle in the forest may have been supplemented by the feed with tree leaves and/or twigs, which appears to have been more frequently practised. The development of a proxy for the determination of the input of lignin-rich foodstuffs (tree leaves and twigs) in the animal's diet using compound-specific amino-acid $\delta^{15}N$ analyses of collagen will doubtless reveal more insights into management practises at this site (see Roffet-Salque and Evershed 2015). The slightly enriched $\delta^{15}N$ values in some of TRB cattle (see Fig. 7) can be the effect of nitrogen enrichment in the fodder plants, which happens when they were intensively cultivated and fertilised with animal manure (e.g. Bogaard et al. 2007, 2013). A similar isotopic 'manuring-effect' is not confirmed for LBK cattle, which stands in contrast with some of the cattle at the LBK settlement in Karsdorf in Saxony-Anhalt in Germany (Oelze et al. 2011:275). Caprines may have been exposed to yearly winter volatility indicated by sequential oxygen isotope values.

A different dimension of husbandry practises was revealed by zooarchaeological studies,[1] in particular by examining slaughtering profiles of different species (Lisowski 2015). A vast majority of cattle in TRB was slaughtered in the third or fourth year of age with only few surviving this threshold. A mortality among young cattle was clearly insignificant (Fig. 9). This visible lack of post-lactation slaughter and small number of individuals of the oldest group may represent a more meat-oriented economy. Whilst the absence of the youngest animals, culled after lactation, may be explained by taphonomy (Brain 1983; Munson and Garniewicz 2003), the taphonomic bias against the oldest animals is less likely. It would suggest that the lack of old individuals, which would include old dairy cows, is native to the assemblage. However, it is possible that their remains might have been a subject to different consumption and depositional practises or the assemblage is just statistically too small to include them. The TRB caprine were also slaughtered after reaching their adulthood. In this group, a number of female goats has been recorded. This observed bias towards older caprine and female goats may be connected to a milk-oriented economy. The preference of cattle with possibly little dairying importance over caprine, conceivably kept for their milk, may suggest the inferior role of dairy in the economy in the TRB communities.

It needs to be reiterated, however, that the presented character of animal husbandry in the LBK and TRB settlements in Kopydłowo needs to be treated with caution. It is based on sheep, goats and cattle, and only some of those data point to differing management. The small sample for carbon, nitrogen and oxygen analyses does not allow chronological comparisons to be made for caprine specimens. Whilst interpretations of birth seasonality inferred from oxygen isotopes sample size for each individual might suggest some manipulation of the breeding cycle, a more robust sample size, where tooth column lengths have been normalised would allow an assessment of the distribution of births by season, and more insight into whether these were due to lack of breeding control or to highly skilled management. Larger sample sizes would also provide a better basis for untangling conflicting explanations, especially between climate and herd management causes. In addition, with more robust sampling, a climate-led interpretation might elucidate whether climate volatility was confined to one season, and might provide evidence supporting increasing dryness over time. Oxygen isotope evidence from comparative samples of at least 10 specimens each might elucidate differences indicating separate herding strategies for goat and sheep, particularly considering a dominance of sheep over goats at majority of settlements. Should such inter-species differences emerge, climate-led explanations become weaker, and it would become possible to disentangle birthing strategies and foddering versus herd movement. A more comprehensive understanding of the causes of variation in $^{87}Sr/^{86}Sr$ values is also required to more reliably interpret results of strontium isotopes in addition to systematic isotope mapping of the region.

Despite these limitations, the reconstructed character of husbandry practises and a shift in the exploitation of cattle and caprine at LBK and TRB settlements at Kopydłowo is evident and seems to correspond well with the tempo and character of the intensively researched process of multifaceted developments of the lowlands Neolithic communities. The

[1] Due to a dearth of satisfactory number of animal bones from the LBK settlement, no herd reconstruction is possible.

LBK farming groups, moving into previously uninhabited areas, most likely with domestic animals, had a form of the collective and communal rather than individual and kin-based social arrangements. Starting in the Late Lengyel period and further developed in TRB in the Middle Neolithic sites increased in number, became significantly differentiated and spread out in the landscape. These developments were initiated by the emergence of the household that triggered major social developments of far-reaching consequences including changes in the organisation of production activities, and contacts with indigenous foragers (see Marciniak 2013b). Local communities started to practice mixed agriculture, cultivated a wide range of cereals and began extensive mode of husbandry of major domestic species. Cattle and caprine were integrated, forming a stable agro-pastoral economy. Their breeding conditions were getting controlled, the animals grazed in a wide range of ecological zones and husbandry practises were becoming increasing heterogeneous. This eventually led to the intensification of animal exploitation for milk, wool and traction. More intense use of different ecological zones, including forests and wooden area, led also to the increased exploitation of wild species (see Marciniak 2013a).

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