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Human–environment interactions in medieval Poland: a perspective from the analysis of faunal stable isotope ratios

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ABSTRACT

Stable isotope analyses of faunal remains provide valuable information about human–environment interactions in the past, including insights into past animal husbandry and land management strategies. Here, we report stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values of collagen and carbonate from archaeological fauna from Kałdus, a medieval settlement in North-Central Poland, to better understand human–environment interactions during a period of increasing urbanism and marketization. Wild and domestic animals can be separated on the basis of their isotopic values. The mean $\delta^{15}N$ value for 12 domesticated animals is 7.6 ± 1.2‰ and for 5 wild animals is 4.3 ± 0.5‰ ($p = 0.002$). The mean collagen $\delta^{13}C$ value for domesticated animals is −20.6 ± 1.1‰ and for wild animals is −22.0 ± 0.5‰ ($p = 0.004$). The mean carbonate $\delta^{13}C$ value for domesticated animals is −13.14 ± 1.3‰ and for wild animals is −14.14 ± 0.9‰ ($p = 0.034$). The "canopy effect" and anthropogenic effects that alter stable isotope ratios of plants (manuring, swidden agriculture and ploughing) are discussed in relation to these differences. Fish are isotopically variable, which suggests broad-spectrum fishing strategies and/or trade, and increases our awareness of the difficulties in interpreting human paleodiet when freshwater fish were on the menu.

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1. Introduction

A comprehensive understanding of past human behavior and biology begins with knowledge of humans' subsistence strategies and relationships to the environment. Food is a critical link between human culture, biology and the environment and for this reason, investigations of plant and animal remains at archaeological sites are commonplace in anthropology. Faunal assemblages provide information about whether animals were used for primary or for secondary products, the relative importance of different species to humans, whether certain foods advertised high or low status, and how animals were cared for and managed (Bartosiewicz, 1995; Makowiecki, 2010). As a complement to morphological analyses, stable isotope analysis of faunal remains provides another view into the interactions between humans and animals. Stable carbon and nitrogen isotope ratios ($\delta^{13}C$ and $\delta^{15}N$, respectively) provide information about the diets and environmental niches of animals, because isotopic signatures in bone reflect niche-specific differences in the isotopic signatures of foods consumed (for a review, see Schoeninger, 2011). Stable isotope analysis of archaeological human bone collagen and carbonate is widely-used for studying past food-webs.

A principal reason for studying stable isotope signatures of animal bones from archaeological sites is to provide the critical faunal baseline required for interpreting human stable isotope signatures; thus, faunal stable isotope analyses often accompany isotopic human paleodiet reconstructions. Beyond this supplemental use in reconstructing human diets, stable isotope analyses of animal bones also reveal valuable information about the animals themselves, such as their specific ecological niches within an environment (Barberena et al., 2011; Finucane et al., 2006; Noe-Nygaard et al., 2005; Stevens et al., 2013). Because stable isotope ratios of plants and animals are sensitive to anthropogenic effects, they also offer insights into human–environment interactions. For time periods from which human skeletal remains are scarce, such as the period preceding Christianization in Europe when cremation was a prevailing mortuary custom, or in cases where destructive analyses of human remains is impossible, isotopic information on human–

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environment interactions from animal remains at archaeological sites is especially important.

1.1. Goals

Here, we apply stable carbon and nitrogen isotope analysis to bone collagen and carbonate of animals recovered from an early medieval site (12–13th c. AD) at Kałdus in North-Central Poland. The sample is small ($n = 32$), but representative of the overall species diversity from the sites archaeozoological assemblages (Makowiecki, 2010). The goal of this study is to use isotopic analyses of terrestrial animals as a gauge of anthropogenic land modification and ecological niche-splitting in Poland. Studying such issues helps shed light on the economic foundations of the Polish state after its inception and consolidation in the 10–11th c. AD, and has potential to inform on other demographic transitions including transitions to agriculture, settlement aggregation and population mobility. We also investigate stable isotope ratios of freshwater fish recovered from Kałdus to better characterize isotopic variability of the aquatic environments in and around the Vistula River, and to better understand human fishing strategies at this time. This work contributes to a growing interest in the extent and significance of isotopic variation in animal communities in Europe (Fuller et al., 2012a; Fuller et al., 2012b; Grupe et al., 1999; Müldner and Richards, 2007a,b; Pearson et al., 2007; Stevens et al., 2013; Vika, 2011), and in the potential for stable isotope data to illuminate animal husbandry and soil improvement strategies in the past (Bogaard et al., 2007; Commisso and Nelson, 2008; Finucane, 2007; Fiorentino et al., 2012; Fraser et al., 2011; Kanstrup et al., 2012; Szpak et al., 2012).

2. Stable isotope analysis with a focus on fauna

2.1. Stable isotopes in terrestrial foodwebs

Stable isotope values are reported as a per mil (‰) value according to the following equation, which compares the ratio of two isotopes from a sample to the same ratio from a laboratory reference standard, and referred to using a delta (δ) symbol: $\delta = (([^{13}C/^{12}C \text{ sample} - {}^{13}C/^{12}C \text{ standard}]/[^{13}C/^{12}C \text{ standard}] - 1) \times 1000)$. In isotopic studies of human paleodiet, $\delta^{13}C$ values often are used to identify types of plants consumed. This is possible because different classes of plant (e.g., C_3 and C_4 plants; Smith and Epstein, 1971) exhibit systematically different $\delta^{13}C$ values depending on which strategy of photosynthesis they employ, and these differences are passed up the food chain to human consumers (Smith, 1972; van der Merwe and Vogel, 1978; Vogel and van der Merwe, 1977). $\delta^{13}C$ values also help to distinguish between aquatic and terrestrial foods, because the source carbon in freshwater, marine and terrestrial environments differs isotopically (Chisholm et al., 1982; Schoeninger and DeNiro, 1984). Commonly, $\delta^{15}N$ values are used to investigate animal protein consumption among humans. This is possible because in-vivo fractionation of nitrogen isotopes causes $\delta^{15}N$ signatures of consumer tissues to be higher than those of the diet (DeNiro and Epstein, 1981; Schoeninger and DeNiro, 1984; Steele and Daniel, 1978). Both $\delta^{13}C$ and $\delta^{15}N$ values from collagen primarily reflect protein sources in diet, rather than all macronutrients equally (Ambrose and Norr, 1993; Tieszen and Fagre, 1993).

The information sought from $\delta^{13}C$ and $\delta^{15}N$ analyses is slightly different for animals. For example, $\delta^{13}C$ values have been studied to estimate whether animals foraged in dense forests or open fields (Bocherens et al., 1995; Cerling and Harris, 1999; Fizet et al., 1995; Krigbaum, 2003; Lynch et al., 2008; Rodiere et al., 1996). This is possible because of the so-called "canopy effect" (van der Merwe and Medina, 1989; van der Merwe and Medina, 1991) in which ^{13}C-depleted CO_2 is recycled in closed-canopy forests, causing $\delta^{13}C$ values of plants and animals occupying closed-canopy habitats to be less ^{13}C-enriched than those outside the canopy. Low light intensities and water surfeit also contribute to low $\delta^{13}C$ values of plants in closed forests (Farquhar et al., 1982; Lynch et al., 2008). The canopy effect appears to be most pronounced in tropical and mid-latitude forests, where foliar $\delta^{13}C$ show lower minimum values (Kohn, 2010; van der Merwe and Medina, 1991), but also has been reported for temperate and boreal forests (Drucker, 2008; Drucker et al., 2010; but see Stevens et al., 2006). It has been possible to distinguish between wild and domestic species on this basis (Lynch et al., 2008; Rodiere et al., 1996; Vogel, 1978). Stable nitrogen isotope data can reveal whether animals consumed plant foods exclusively, or if scraps of meat, offal or dairy from among human foods and/or human and animal waste also were eaten by animals, which is especially likely in sedentary or agglomerated contexts in which animals and humans share close quarters (c.f. Fuller et al., 2012b; Müldner and Richards, 2007a,b). Stable nitrogen isotope signatures of plants and the animals eating them also indicate when humans used fertilizers in their pasturelands, and when swidden agriculture was used in the past, providing nuanced information about land management strategies (Bogaard et al., 2007; Commisso and Nelson, 2008; Grogan et al., 2000). Grazing intensity also has been shown to influence $\delta^{15}N$ variation in plants (c.f. Han et al., 2008). Because of such variations, stable isotope data have been used to assess the economic role of animals, such as the importation of domesticated animals by urban settlements from rural outskirts (Berger et al., 2010; Stevens et al., 2013). Used together, $\delta^{13}C$ and $\delta^{15}N$ values from different domestic taxa help identify whether care for animals was specialized (dissimilar isotopic profiles among species) or generalized (similar isotopic profiles among species) (c.f. Finucane et al., 2006).

2.2. Stable isotopes in aquatic foodwebs

Whereas CO_2 is the only source of carbon in terrestrial foodwebs, there are several, isotopically variable sources of carbon in aquatic foodwebs, including CO_2, bicarbonate, dissolved inorganic carbon and decomposing plant matter (Hoefs, 2004). Along with differences due to water temperature and pH, the relative contributions of these different carbon sources in various aquatic zones (e.g., littoral vs. pelagic) creates a considerable range of $\delta^{13}C$ variation among fish (Hecky and Hesslein, 1995), even from the same species (Barrett et al., 2011; Orton et al., 2011). In brackish waters, $\delta^{13}C$ values vary with salinity moving inland from the ocean. It is often possible to distinguish marine from freshwater fish (Fuller et al., 2012a; Grupe et al., 1999), because marine fish typically exhibit ^{13}C-enriched values due to weathering of ^{13}C-enriched limestone. However, $\delta^{13}C$ ranges of marine and freshwater fish do overlap (Katzenberg et al., 2010). Anadromous and brackish water fish can exhibit intermediate bone $\delta^{13}C$ values in comparison to freshwater and marine fish (Fuller et al., 2012a; Grupe et al., 1999; Schoeninger and DeNiro, 1984), although it is worth noting that muscle tissue, with its more rapid turnover rate, may more closely reflect the environmental values at the specific place of capture.

Partly because aquatic foodwebs are longer than terrestrial foodwebs, fish $\delta^{15}N$ values are quite variable (Fuller et al., 2012a). This helps distinguish between phytoplanktivorous, zooplanktivorous, and piscivorous species, for example. Additionally, as predatory fish grow larger with age, they may catch a wider variety of prey (other fish, amphibians, molluscs, and even small mammals) which can increase $\delta^{15}N$ values of older, larger fish compared to younger fish of the same species (Sweeting et al., 2007). This, along with other sources of $\delta^{15}N$ variation in water bodies (c.f. France, 1994), mean systematic $\delta^{15}N$ variations occur not just between species, but between niches as well (Sherwood and Rose, 2005).

Only through traditional faunal analyses of fish bones from archaeological contexts can information about which species were targeted by humans be obtained. Stable isotope analysis of fish bones contributes an understanding of the actual *niches* to which the fish targeted by humans belonged (which vary within a single species), offering a more nuanced understanding of the fishing strategies in the past. For example, Orton et al. (2011) were able to discern six separate isotopic "spaces" within the Baltic Sea using stable isotope values from cod cranial bones. Because cranial bones are removed near the site of the catch before transporting the filets, they are assumed to reflect the stable isotope signatures of nearby waters. Filets, in comparison, were preserved and transported long distances. The authors compared vertebral stable isotope values from filets to the isotopic spaces estimated from cranial bones to identify where the fish at archaeological sites may have originally been caught prior to transportation (Orton et al., 2011). Their results support the hypothesis that fish were imported over long distances and not raised locally in fisheries.

3. Biocultural context

Population growth and a demographic shift to living in agglomerated settings shaped subsistence changes during the medieval period, which in Poland is considered to have begun in approximately AD 1000. Whereas formerly, human populations were largely self-sufficient and farmed their own land, urbanization increasingly divorced the population from food production. This trend instigated a settlement structure in which *suburbia* supplied towns and strongholds with agricultural produce (Gieysztor et al., 1979). Even in rural areas, family economies were replaced by or at least included in market economies, and producing a surplus gained new importance. Medieval strategies to maximize agricultural productivity included manuring fields, fire-clearing fields, employing a rotating field system, ploughing with animal power, and feeding household wastes to animals such as pigs and chickens (Gieysztor et al., 1979), practices that can affect the stable isotope signatures of the animals involved.

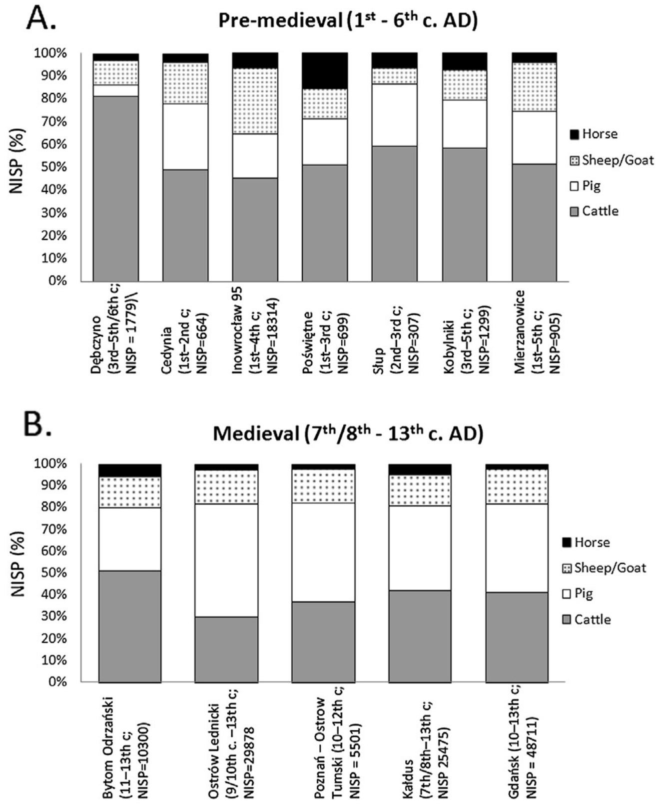

Fig. 1. Animal remains from archaeological sites in Poland. Differences in the faunal assemblages from pre-medieval and medieval periods in Poland. In general, cattle are more common in the pre-medieval period whereas pigs and sheep/goat are more common in the medieval period (Makowiecki, 2006).

Bos taurus, which, in the period of Roman influence (ca. 1st–4th c. AD) were the most common domestic mammal, decrease in economic importance in the medieval period in the area forming the core of the Polish state, falling from approximately 50%–30% of the number of identified specimens present (NISP) (Fig. 1) (Makowiecki, 2006). In the medieval period, pigs and chickens increase in assemblages. Domestic fowl, nearly absent in sites from the period of Roman influence, comprise up to 8% of the faunal assemblages from various sites at Kałdus (Fig. 2) (Makowiecki, 2004, 2010). *Gallus gallus domesticus* was the most common bird in early medieval Poland. Its importance is evident from the fact that, on average and including many sites in Poland, it makes up almost 60% of the NISP from avifaunal assemblages (Makowiecki, 2006). *Sus scrofa domesticus* remains make up approximately 30–50% of the NISP from medieval Polish sites (Makowiecki, 2006, 2010). Chicken and pigs could be tended near a household with little space required, and were often more appropriate to feed agglomerated populations than large-bodied grazing cattle or wild animals, the hunting of which was restricted by the developing sociopolitical nobility. Chickens were kept for eggs as well as meat, as evidenced by the facts that males were selectively culled (Waluszewska-Bubién, 1979) and medullary bone found in several specimens of domestic chicken retrieved from assemblages in the early medieval period suggest females were egg-layers (e.g., Makowiecki and Gotfredsen, 2002). Historical records corroborate that eggs were an important food item in medieval Poland (Dembińska, 1999; Żabiński, 1959).

Urban settings with their markets and trade links provided more variety in available foods (Herrscher et al., 2001). This increased variety in foods was not necessarily accessible to the population at large, as social hierarchies and disparate costs of perceived high- and low-status foods structured what people ate (Dembińska, 1999).

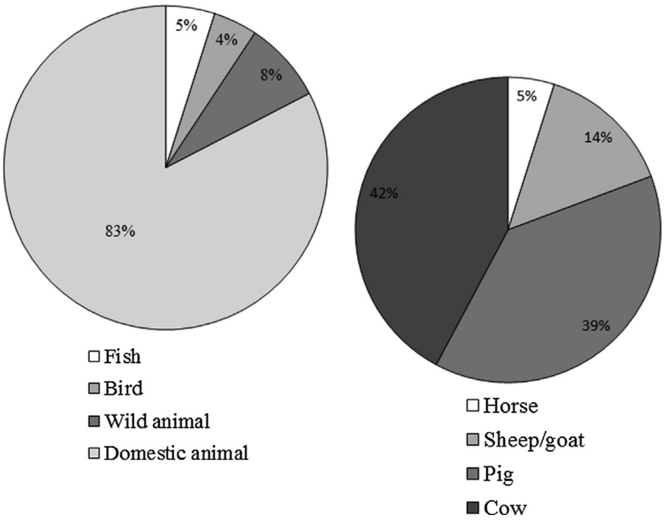

Fig. 2. *Animal remains at Kałdus.* Bone remains at Kałdus (NISP) according to animal group ($n = 31,242$) (Makowiecki, 2004).

3.1. The medieval settlement complex at Kałdus

Kałdus is a medieval settlement complex located along the Vistula River in North-Central Poland, north of modern-day Toruń (Fig. 3). Preceding settlement of the region, which began at approximately the 10th c. AD, the Kałdus microregion was dominated by forests of alder, elm, ash, oak, beech, hornbeam and pine, as well as swampy wetlands and peat bogs (Cyzman and Kamiński, 2004; Krzymińska, 2004; Noryśkiewicz, 2004). Intense deforestation concomitant with settlement and agriculture occurred until the 14th c., at which point the vicinity was almost entirely converted to open land (Noryśkiewicz, 2004). Original forest patches would have persisted on the Vistula valley's steeper slopes and ravines, and patches of willows and poplars, as well as orchards, replaced former natural forest stands near the settlement (Cyzman and Kamiński, 2004).

The Kałdus settlement complex consists of a stronghold (site 3), a surrounding settlement area (site 2), and three associated cemeteries (sites 1, 2 and 4). Most of its occupation and use dates to the 12th–13th c. AD. Kałdus is located at the confluence of trade routes, including the important route running south from the Baltic Sea. Although not populous enough to be considered urban, Kałdus was one of the larger occupation centers in North-Central Poland in the medieval period. It was an economic hub in the 11th and early 12th c. AD, although its importance waned in the late 12th and 13th c. AD (Chudziak, 2003). The economy of Kałdus supported socioeconomic differentiation; distribution of skeletal pathology suggests some individuals are thought to have been "craftsmen" (Kozłowski, 2012). Differences in the faunal assemblages of the town and stronghold at Kałdus (both dating to the 12–13th c. AD) reveal socioeconomic variation – for example, remains of more wild animals and younger animals in the stronghold (Makowiecki, 2007, 2010). Here, we seek to identify variation in the ecological niches of the animals excavated from the stronghold and settlement sites from stable isotope data of animal bone collagen to illuminate human strategies in either raising or targeting these animals for food in this proto-urban context.

4. Materials and methods

Faunal specimens for this study were collected from the large assemblage (ca. 70,000 specimens) recovered during excavations carried out in 1996–2005. The assemblage was described by D. Makowiecki (2010) as part of the interdisciplinary project titled "The Early Medieval settlement complex in Kałdus – *Sedes Regni Principalis* in the Chełmno land," headed by W. Chudziak at the Institute of Archaeology, Nicolaus Copernicus University in Toruń.

Collagen samples were prepared by demineralizing ground bone particles in 0.2 M HCl for several days, soaking in 0.125 M NaOH to remove humic contaminants, dissolving the residues in dilute HCl overnight, and filtering through coarse glass frits and freeze-drying the dissolved collagen. This method was previously determined to be appropriate for fish bones from this time period (Reitsema et al., 2010), which is a concern because fish bones differ in structure from other animal bones (Szpak, 2011) and are more susceptible to both degradation in the depositional environment and to chemical treatment. Carbonate samples were prepared from terrestrial animal bones by removing the organic component of bone with NaOCl and removing diagenetic carbonates by soaking for four hours in 0.1 M acetic acid.

Subsamples of collagen powders were weighed into tin capsules in the Stable Isotope Biogeochemistry Laboratory at the Department of Earth Sciences at The Ohio State University. Collagen samples were analyzed on a Costech Elemental Analyzer coupled to a Finnigan Delta IV Plus stable isotope ratio mass spectrometer under continuous flow using a CONFLO III interface in the Stable

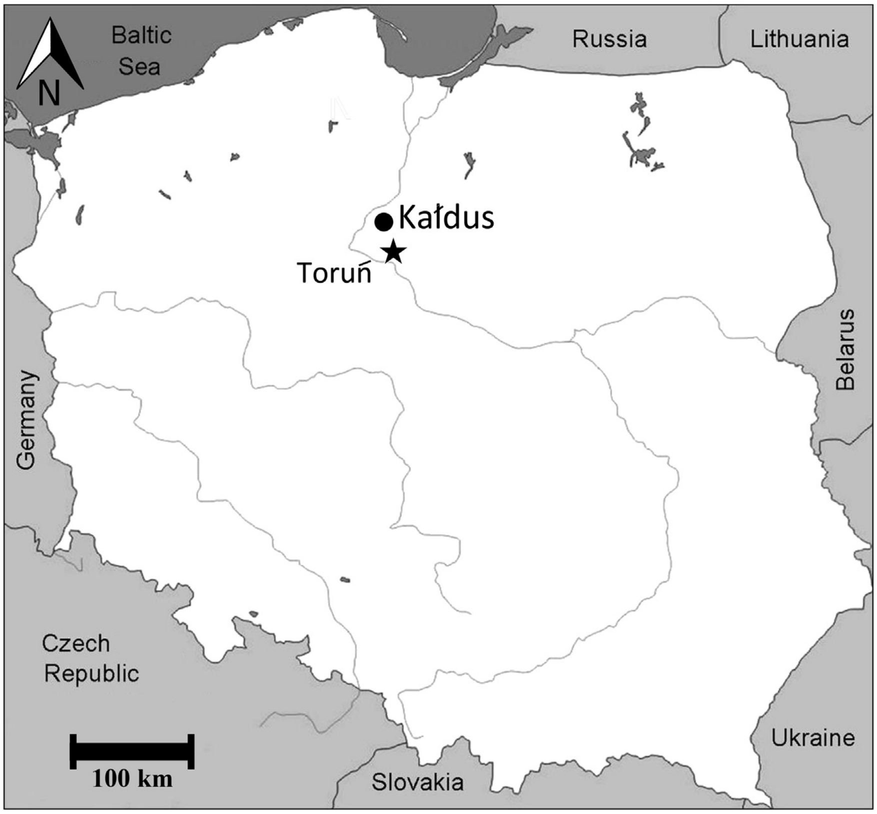

Fig. 3. Map of study area.

Isotope Biogeochemistry Laboratory at The Ohio State University. Stable carbon ($\delta^{13}C$ = per mil deviation of the ratio of ^{13}C:^{12}C relative to the Vienna Peedee Belemnite Limestone standard) and stable nitrogen ($\delta^{15}N$ = per mil deviation of ^{15}N:^{14}N relative to AIR) isotopic composition measurements were made where repeated measurements of the USGS24 and IAEAN1 standards were ±0.06‰ for $\delta^{13}C$ and ±0.17‰ for $\delta^{15}N$.

A 1.0–1.2 mg subsample of carbonate was analyzed for $\delta^{13}C$ ($\delta^{13}C$ = per mil deviation of ^{13}C:^{12}C relative to VPDB) using an automated Carbonate Kiel device coupled to a Finnigan Delta IV Plus stable isotope ratio mass spectrometer in the Stable Isotope Biogeochemistry Laboratory at The Ohio State University. Samples were acidified under vacuum with 100% ortho-phosphoric acid, the resulting CO_2 cryogenically purified, and delivered to the mass spectrometer. The standard deviation of repeated measurements of a limestone internal standard (NBS-19) for $\delta^{13}C$ was ±0.03‰.

Mann–Whitney U non-parametric tests were used for pair-wise comparisons and Kruskal–Wallis non-parametric tests were used to compare more than two groups. Non-parametric tests are appropriate for samples whose distributions deviate from normality.

5. Results

Collagen was deemed well-preserved on the basis of carbon content (%C), nitrogen content (%N), atomic carbon-nitrogen (C/N) ratios, and a subset of collagen content from bone (%coll) values, described in more detail elsewhere (Ambrose, 1990; Szpak, 2011; van Klinken, 1999). These quality indicators, along with stable isotope values, are presented in Tables 1 and 2. Although no carbonate quality measurements were taken from animal bone apatite, analyses of medieval human bone carbonate from Kałdus using Fourier transform infrared spectroscopy (method described in greater detail by Wright and Schwarcz, 1996) suggests minimal or no diagenetic alteration of bone from this region and time period (Reitsema, unpublished data).

The mean $\delta^{15}N$ value for 16 fish is 9.5 ± 2.2‰ and the mean $\delta^{13}C_{coll}$ value is −21.9 ± 5.7‰. The mean $\delta^{15}N$ value for 12 domesticated animals is 7.6 ± 1.2‰ and for 5 wild animals is 4.3 ± 0.5‰ ($p = 0.002$). The mean $\delta^{13}C_{coll}$ value for domesticated animals is −20.6 ± 1.1‰ and for wild animals is −22.0 ± 0.5‰ ($p = 0.004$). When chickens and dogs are omitted, the $\delta^{13}C_{coll}$ value for the remaining domesticated animals is −21.1 ± 0.6‰, which is still significantly different from the $\delta^{13}C_{coll}$ values of wild animals ($p = 0.009$). The mean $\delta^{13}C_{ca}$ value for domesticated animals is −13.1 ± 1.3‰ and for wild animals is −14.14 ± 0.9‰ ($p = 0.034$). When chickens and dogs are omitted, the $\delta^{13}C_{ca}$ value for the remaining domesticated animals is −13.49 ± 0.6‰, which is no longer significantly different from the $\delta^{13}C_{ca}$ values of wild animals ($p = 0.361$). This could be due to the fact that fewer samples were analyzed for $\delta^{13}C_{ca}$ ($n = 13$) and the groups for analysis are even smaller.

6. Discussion

6.1. Terrestrial animals

The differences in $\delta^{15}N$ and, to a lesser extent, $\delta^{13}C$ of wild versus domestic animals reflect the different ecological niches of these groups, including their relationships with humans. These differences are displayed graphically in Figs. 4 and 5.

One possible explanation for less ^{13}C-enriched values observed among the wild animals is the canopy effect (Drucker, 2008; Drucker et al., 2010). This could signify these animals occupied closed forest environments, while domesticated animals inhabited more open areas. However, it should be noted that these values are not as low as those of deer from Bialowieza forest in Poland, which after calibrating for changes in atmospheric CO_2 values (Feng, 1998), are below −23.0‰ (Bocherens and Drucker, 2003). The deer and hare in the present study are less ^{13}C-depleted than the aurochs and elk and more similar to the domestic animals, which could reflect their tendency to occupy ecotones between forests and more open areas (c.f. Stevens et al., 2006; Vidus-Rosin et al., 2012), although the isotopic differences are slight. This wild-domestic dichotomy in $\delta^{13}C$ values has been demonstrated previously by comparing similar species that occupy forested and open environment: for example, red deer vs. roe deer (Rodiere et al., 1996), aurochs vs. cow (Lynch et al., 2008; Noe-Nygaard et al., 2005), and forest vs. steppe guanaco (Barberena et al., 2011). Interestingly, Polish forests hosted Europe's final aurochs populations before their extinction, for which letters from Polish gamekeepers in the 17th c. AD provide compelling documentation (Van Vuure, 2005). More information about how this now extinct species, once-widespread in Europe, held out in Poland could be obtained with isotopic data.

The $\delta^{13}C_{coll}$ and $\delta^{13}C_{ca}$ values of the wild animals and the cows, pigs and sheep are consistent with a diet based on C_3 resources with the exception of one cow, which exhibits slightly higher values. This animal may have been foddered on the C_4 plant millet, which was common in Poland at this time. However, if this were

Table 1
Animal bone data from Kałdus.

ID #	Species		Collagen (%)	Nitrogen (%)	Carbon (%)	C:N ratio	$\delta^{15}N_{Air}$ (‰)	$\delta^{13}C_{coll}$ (‰)	$\delta^{13}C_{ca}$ (‰)
81-05	Elk	*Cervus* sp.	10.0	11.2	32.0	3.3	3.8	−22.8	−14.94
207-98	Hare	*Lepus europeaus*	5.0	12.9	36.6	3.3	5.0	−21.7	−14.82
140-050A	Aurochs	*Bos primigenius*	22.2	13.2	36.9	3.3	4.0	−22.2	−14.36
781-02	Deer	*Cervus* sp.	9.4	14.7	41.4	3.3	4.4	−21.5	−12.95
810-02	Deer	*Cervus* sp.	*nd*	11.0	31.6	3.4	4.2	−21.8	−13.61
40-05	Chicken	*Gallus gallus*	*nd*	12.9	36.0	3.3	9.1	−18.2	−11.67
639	Chicken	*Gallus gallus*	*nd*	15.3	42.7	3.2	9.1	−19.0	−12.44
816-02	Cow	*Bos taurus*	16.1	14.6	40.4	3.2	7.8	−20.7	−11.41
834-02	Cow	*Bos taurus*	12.9	13.4	38.0	3.3	7.9	−21.0	*nd*
839-02	Cow	*Bos taurus*	9.5	13.1	36.7	3.3	7.6	−21.5	*nd*
200	Cow	*Bos taurus*	*nd*	15.7	43.6	3.2	6.4	−21.0	*nd*
810-02	Cow	*Bos taurus*	11.1	14.4	40.2	3.2	6.4	−21.3	−13.80
778-02	Dog	*Canis l. familiaris*	14.3	12.9	36.5	3.3	9.6	−19.7	−13.56
100	Pig	*Sus scrofa*	*nd*	16.1	44.5	3.2	7.9	−21.6	−14.89
119-05	Pig	*Sus scrofa*	*nd*	12.9	35.6	3.2	5.9	−21.6	−14.71
816-02	Pig	*Sus scrofa*	*nd*	13.2	37.6	3.3	6.8	−19.8	−12.66
841-02	Sheep[a]	*Ovis* sp.	10.0	10.6 ± 3.2	30.9 ± 9.3	3.4 ± 0.14	7.1 ± 0.8	−21.5 ± 0.17	−13.52 ± 1.22

[a] Triplicate; %coll measured once.

Table 2
Fish bone data from Kałdus.

ID #	Species		Collagen (%)	Nitrogen (%)	Carbon (%)	C:N ratio	δ^{15}N (‰)	$\delta^{13}C_{coll}$ (‰)
75-08	Catfish	*Silurus glanis*	*nd*	5.8	16.3	3.3	11.8	−24.1
547-03	Catfish	*Silurus glanis*	5.3	6.6	19.0	3.3	12.1	−25.1
114-08A	Catfish	*Silurus glanis*	7.3	11.7	32.2	3.2	9.2	−21.6
274-03	Carp-bream	*Abramis brama*	7.7	9.4	25.8	3.2	9.4	−23.0
64-07	Carp-bream	*Abramis brama*	3.8	10.2	28.1	3.2	8.6	−27.1
408-03	Tench	*Tinca tinca*	3.1	11.4	31.2	3.2	8.9	−28.2
69-07	Tench	*Tinca tinca*	10.7	11.0	30.0	3.2	3.8	−5.6
71-04	Aspe	*Aspius aspius*	6.3	9.1	25.3	3.2	6.6	−24.0
161-05	Pike	*Esox lucius*	4.5	10.4	28.8	3.2	7.3	−23.9
50-98	Pike	*Esox lucius*	*nd*	4.6	12.9	3.3	11.4	−25.6
100-04	Pike	*Esox lucius*	5.1	11.0	30.3	3.2	8.9	−25.3
630-03	Pike-perch	*Sander lucioperca*	11.8	8.4	23.1	3.2	10.1	−22.3
4-02	Pike-perch	*Sander lucioperca*	14.3	8.7	24.3	3.3	12.0	−25.2
183-98	Sturgeon	*Acipenser* sp.	7.3	12.9	34.9	3.2	10.6	−15.6
171-05	Sturgeon	*Acipenser* sp.	3.7	4.1	11.7	3.3	9.9	−17.1
114-08	Sturgeon	*Acipenser* sp.	7.7	6.9	19.2	3.3	11.3	−16.7

the case, somewhat more ^{13}C-enriched values could be expected, such as the mean value of $-18.6 \pm 1.2‰$ ($n = 26$) of cattle from Byzantine Sagalassos, Turkey, reported by Fuller et al. (2012a) and attributed to millet foddering. Millet and/or high-^{13}C fish scraps (such as the sturgeon in the present study, discussed below) were likely consumed by the dog and chickens. $\delta^{13}C_{ca}$ values of the 13 terrestrial animals whose carbonate was analyzed in addition to collagen are shown in Fig. 5 superimposed over regression lines that illustrate three different protein diets with C_3 and C_4 energy endpoints, described in greater detail elsewhere (Kellner and Schoeninger, 2007). The animals which plot toward the midpoint or to the right of the C_3 protein are more likely to have consumed millet and/or fish.

Higher δ^{15}N values of domestic animals are not likely due to suckling as all the animals studied were adults (for a general discussion of breastfeeding and δ^{15}N variation in tissues see Fuller et al., 2006), although bone remodeling does create a problematic lag time for assessing this (Hedges et al., 2007). Rather, δ^{15}N differences likely relate to humans' land management and animal husbandry strategies. As an example of this, Müldner and Richards (2007a) found δ^{15}N values of cattle from the Roman period to be approximately 2‰ higher than cows from later historic periods (6.6–8.6‰ compared to 4.0–7.2‰) and attributed the difference to general changes in husbandry. Here, we discuss the potential for manuring and swidden agriculture over generations to increase plant and animal δ^{15}N values in the area surrounding Kałdus.

The manuring of agricultural fields can cause plants to be significantly ^{15}N-enriched relative to unfertilized plants (Bogaard et al., 2007; Choi et al., 2003; Fiorentino et al., 2012; Kanstrup et al., 2012; Szpak et al., 2012). This is because the lighter isotope (^{14}N) in manure is preferentially lost as gaseous ammonia during ammonia volatilization, a process associated with a large fractionation (Mizutani et al., 1985). Plants take up nitrogen from the remaining ^{15}N-enriched manure, resulting in higher δ^{15}N ratios throughout the food-web. Note that legumes, which can fix atmospheric nitrogen directly, may be exempt from this effect in cases where soil nitrogen is very low (Fraser et al., 2011). In an experimental study, Bogaard et al. (2007) demonstrated that plants grown on manured soils exhibit δ^{15}N values of more than 7‰, compared to non-manured plants from the same field which exhibited grain values lower than 1‰. Importantly for paleodiet reconstructions of humans, with plant values as high as 7‰, even a vegetarian diet could cause animal (including human) tissues to exhibit δ^{15}N values of over 10‰. It has been noted that numerous Roman-era and medieval human paleodiet studies report the coupling of terrestrial δ^{13}C signatures with high δ^{15}N values from human bones (Lamb et al., 2012; Müldner and Richards, 2007a,b; Prowse et al., 2004; Prowse et al., 2005; Reitsema, 2012; Reitsema

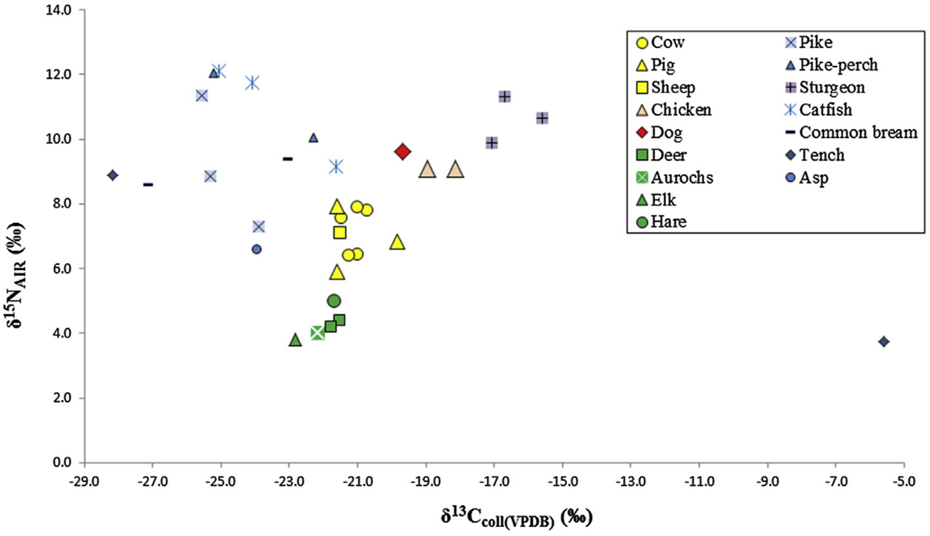

Fig. 4. Stable isotope values of animal bone collagen. Stable carbon (δ^{13}C) and nitrogen (δ^{15}N) ratios of animal bone collagen.

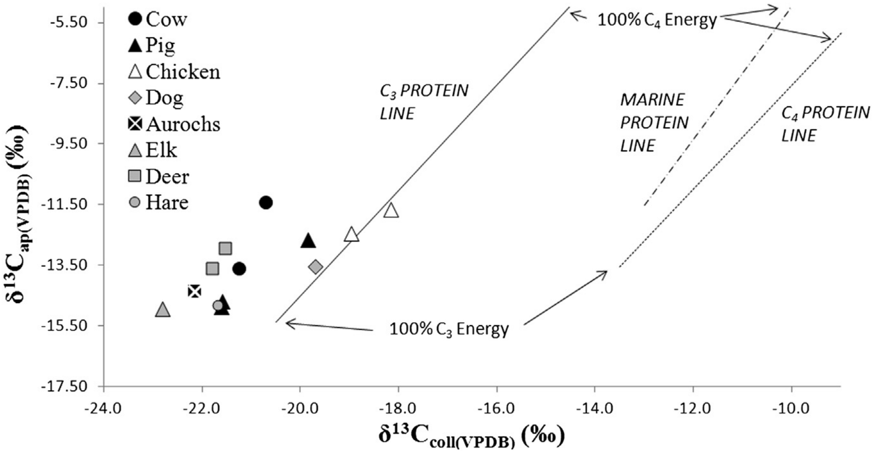

Fig. 5. Stable isotope values of carbonate from terrestrial animals. Stable carbon isotope data from apatite ($\delta^{13}C_{ap}$) and collagen ($\delta^{13}C_{coll}$) from animal bones. Based on the regression lines developed by Kellner and Schoeninger (2007) using controlled feeding experiment data from animals, this figure shows that terrestrial animals in the present study consumed primarily C$_3$ plants, with some animals (dog, chickens, pig, and possibly cow) also consuming some C$_4$ protein or C$_4$ energy. Each line represents a protein diet base and endpoints reflect dietary energy sources (C$_3$ vs. C$_4$). The original regression lines have been shifted to account for isotopic changes in atmospheric carbon dioxide (Marino and McElroy, 1991).

et al., 2010). Frequently attributed to small amounts of marine fish in the diet, a more parsimonious explanation may be soil improvement methods raising $\delta^{15}N$ values of plants (Knipper et al., 2013; Vika, 2011). The effects of anthropogenic nitrogen deposition on raising $\delta^{15}N$ values of soils and plants are even seen hundreds of years after the fact, as demonstrated by Commisso and Nelson (2006, 2007, 2008, 2010) in their studies of archaeological sites in Greenland. No archaeological plant samples were assayed for this study, but one modern sample of wheat (grain) taken in 2008 from the field of the Kałdus excavations yielded a $\delta^{15}N$ value of 7.2‰. The ^{15}N enrichment of this plant could be due to current, historic or prehistoric anthropogenic nitrogen deposition (Commisso and Nelson, 2006). Because of this, it may not be possible to exclude the possibility that manuring took place in earlier periods and not while the studied animals were alive. The $\delta^{13}C$ value of this modern wheat sample is −23.6‰, which after applying a +1.5‰ correction factor to account for modern atmospheric CO$_2$ depletion (Marino and McElroy, 1991) would equate to a pre-industrial value of approximately −22.1‰. This is rather high for C$_3$ plants, but consistent with a recent report of archaeological and modern C$_3$ cereals (Fiorentino et al., 2012).

In Europe, populations have been manuring their agricultural fields to increase productivity for thousands of years (Barker, 1985). Muck hauled from wetlands, domestic debris, ash and animal dung are all methods used since the Neolithic in Europe to increase field productivity. Cattle, sheep and goat provided dung for prehistoric farmers. Cattle require penning at night, thus their manure must be hauled to fields from stables. Sheep and goat can be left in fields overnight and provide a simpler form of fertilization (Barker, 1985). Early evidence of using animal dung to fertilize a field comes from Switzerland ca. 3880—-3480 BC (Bakels, 1997). The ancient field was identified because of its plough furrows, and fly larvae were identified after sediment analysis, suggesting manure was hauled from stables onto the field. Bakels (1997) points out that ancient fields predating the introduction of the ard will be very difficult to detect, making the earliest date of crop manuring difficult to discern. It may be possible that $\delta^{15}N$ values from animal bones will help identify manuring as an ancient agricultural technique.

Fires raise the baseline $\delta^{15}N$ in ecosystems in part because they remove topsoils which are low in ^{15}N (Grogan et al., 2000). Plants growing on land recovering from a fire take up nitrogen from the remaining high-^{15}N soils and enter the foodweb. Because deeper soils have higher $\delta^{15}N$ values, ploughing should also increase $\delta^{15}N$ of the source nitrogen available for plants (and subsequently of grazing animals) by mixing surface and deep soils. Over hundreds of years, modifications such as these were responsible for deforestation and creation of the farm and pasturelands in the Kałdus vicinity (c.f. Cyzman and Kamiński, 2004).

Even compared to other regions in Europe (Bourbou et al., 2011; Herrscher, 2003; Müldner and Richards, 2005; Privat et al., 2002; Schutkowski et al., 1999), and elsewhere in Poland (Reitsema et al., 2010), the $\delta^{15}N$ values of domestic herbivores and omnivores in the present study are relatively high, which is surprising considering manuring and swidden agriculture are widespread food production techniques. Importantly, low $\delta^{15}N$ values among domestic herbivores do not necessarily imply soil improvement strategies were *not* employed, as it could also mean the animals were grazed in areas apart from the anthropogenically modified crop fields.

Among the terrestrial domestic animals, chickens and the dog are different isotopically from the rest. Both the $\delta^{15}N$ and the $\delta^{13}C$ values of these animals indicate a higher trophic position when compared to the other domestic animals. Chickens and dogs were probably kept near households, consuming scraps of the same foods as humans once they were discarded, along with animal and/or human excrement. Domestic fowl in the medieval period helped alleviate the urban food problem in economically diverse towns where individual or family self-sufficiency is limited. Many chickens could be raised and tended on a household level in relatively cramped quarters, and eggs were a ubiquitous source of protein for humans (Żabiński, 1959). Fuller et al. (2012a) report similarly ^{15}N-enriched values from chickens (8.4 ± 1.2‰; $n = 10$) and geese (9.5 ± 1.5‰; $n = 10$) from Byzantine contexts at Sagalassos, Turkey, attributable to these animals having been fed human scraps and refuse. The high $\delta^{15}N$ values in the present study attest to this type of relationship between domestic fowl and humans in the medieval period.

It is interesting to note that pigs do not fall into this household ecological niche. Pigs may be tended in the midst of human homesteads, and along with chickens and preserved fish, are also considered a solution to the urban food problem. Indeed, pig bones at archaeological sites become relatively more prevalent in Poland between AD 500 and 1000 (Pyrgała, 1975) (Fig. 1). Evidently, pigs at Kałdus consumed foods similar to those of the larger grazing animals. A similar situation is reported for pigs from various sites in Germany leading up to the medieval period (Knipper et al., 2013). Although some of the domestic mammals reared in the early medieval period were kept in limited small spaces inside strongholds and settlements themselves (Makowiecki, 2001a), it is also reported in historical and ethnographic records that traditionally in rural settings in Poland, pigs were allowed into forests to feed on acorns and other vegetation (Van Vuure, 2005). Because they exhibit isotopic ratios comparable to the other domestic animals in this study, pigs from Kałdus appear to have been raised in this more rural manner, less dependent on humans, despite the proto-urban nature of the settlement. The isotopic values of pigs in this study vary, which is not surprising considering these animals are notorious omnivores. In the future it will be interesting to analyze bones from urban contexts, such as the nearby town of Toruń, to see how animal husbandry strategies may vary among demographic contexts.

6.2. *Fish*

Stable isotope values of fish are highly variable, even within a single species (Fig. 4). The expected trophic positions of fish summarized in Table 3 are not well-reflected by their δ^{15}N values. For example, pike do not exhibit the high δ^{15}N values expected for predatory fish. Because age influences body size of fish and the types of prey they can catch, δ^{15}N variation may be age-related. The ages/sizes of fish were not considered in the present study. Freshwater and anadromous fish are separated by δ^{13}C data, with anadromous fish (sturgeon) exhibiting higher values, as expected for fish that spend part of their lives in saline waters.

One of the *Tinca tinca* (tench) samples exhibits anomalously low δ^{15}N and high δ^{13}C values of 3.1‰ and −5.6‰, respectively, but exhibits acceptable collagen quality indicators (Table 1). It is possible that its isotopic values are biogenic, and not the product of diagenesis or contamination, because tench occupy among the lowest aquatic trophic positions, feeding on algae and macrophytes in the benthic zone of freshwater bodies (Alas et al., 2010). For comparison, δ^{15}N values around 2–3‰ have been reported for freshwater zooplankton and zoobenthos (France, 1994). Similar values have been reported for other species of fish occupying littoral zones of freshwater lakes in Africa (Hecky and Hesslein, 1995). The tench in the present study is perhaps the lowest δ^{15}N value reported for freshwater Eurasian fish (for more values, see Dufour et al., 1999; Fuller et al., 2012a; Katzenberg and Weber, 1999; Redfern et al., 2010).

Importantly, most stable isotope values of fish assayed in this study, including freshwater and anadromous varieties, are close to values from terrestrial animals. Fish "masquerading" as terrestrial animals may confound interpretations of human stable isotope ratios. Cyprinids are the most common freshwater fish species found at Polish sites (Makowiecki, 2001a,b; Makowiecki, 2003), including Kałdus site 4 (Makowiecki, 2010). Although one of the two Cyprinids studied here (common bream) exhibits an anomalously low δ^{13}C value (−27.1‰) that would stand out as a contribution to human diet if human tissues were studied, the other exhibits a δ^{13}C value (−23.0‰) similar to that of a wild animal. Both Cyprinids exhibit δ^{15}N signatures similar to chickens (8.6‰ and 9.4‰).

Fish stable isotope variability in the present study reflects isotopic variability of different niches in freshwaters, which means it may be possible to determine whether humans targeted certain areas of water bodies as part of fishing strategies, as others have done (Grupe et al., 1999; Orton et al., 2011). Even if a wide variety of taxa are represented in an assemblage, it does not necessarily imply that humans used different fishing strategies to catch them: multiple fish species may still have come from the same region of a water body, in spite of their expected habitat preferences. Stable isotope evidence shows "invisible" information about aquatic

Table 3
Ecological niches of fish. Characteristic features of fish with respect of food preference, biotope, kind of water bodies (according to Bylińska, 1986), and paleohistory and economic significance (according to Makowiecki, 2003, 2008).

Species	Preference of food	Freshwater	Migratory (Baltic Sea to river)	Preference of water bodies				Biotope	Paleohistory and economic significance
				Lake	Lake–river	River	Sea–river		
Acipenser sp. Sturgeon	Bottom fauna		×				×	Sea and migration for spawning to upper stream of big rivers	Large population in the Baltic Sea and Vistula river. Commonly fished in early medieval centers nearby. Biggest fish in the area
Esox lucius L. Pike	Predatory; fish such as Roach, other Cyprinids, Percidae	×		××	×			Water bodies with bottom growing by intensive plants	Most common predatory species in the Polish lowland lakelands. High economic significance in all settlement centers
Silurus glanis L. European catfish	Predatory, up to 80% of fish in grown up individuals	×		×	××			Slowly stream of rivers with muddy bottom, stenothermic species	Common in assemblages but not as common as pike and Cyrinidae, remarkably less significant economically than pike and cyprinids. 2nd biggest fish after sturgeon
Abramis brama L. Common bream	Larvae of insects and different kind of insects	×		×××	×	×		Stenothermic species, small requirements in oxygen	Very common species among Cyprinidae family. Very high economic significance, especially individuals of bigger sizes
Aspius aspius L. Asp	Small fish up to 8 cm, partly plants	×			×	×××		Clean water of rivers with sandy bottom	Very rare fish species and among Cyprinidae family as well. Appreciated economically for its large size among other Cyprinids.
Tinca tinca L. Tench	Larvae of insects (Ephemeroptera) and Ostracoda	×		×××	×			Lakes with muddy bottoms, depth not more than 2 m, resistant to seasonal shortage of oxygen but dislikes water with pH below 5.5; above 9.0	One of the most frequent species among cyprinids, particularly in shallow, muddy lakes

niches and fishing strategies. Only a few other species-specific stable isotope data have been reported for fish from archaeological contexts in Poland (e.g., Barrett, et al., 2008), so presently it is not possible to draw many conclusions about human fishing strategies, aside from a tentative interpretation that no single aquatic niche was targeted.

7. Conclusions

The different ecological niches of wild and domestic animals in medieval Poland are indicated by stable isotope analysis of faunal remains. The clear differences between domestic and wild animals from Kałdus point to the anthropogenic activities of humans: specifically, the possibility that fields were manured, ploughed, and/or fire-cleared in the past. The potentially high δ^{15}N values of domesticated animals must be borne in mind when interpreting human stable isotope signatures. This offers a potentially parsimonious explanation for the “problem” of high δ^{15}N values coupled to low δ^{13}C values periodically reported in paleodiet studies (c.f. Lamb et al., 2012; Müldner and Richards, 2007a,b; Prowse et al., 2004; Prowse et al., 2005; Reitsema, 2012; Reitsema et al., 2010). These issues of faunal variability underscore the need for a comprehensive faunal baseline in any paleodiet study which includes both wild and domestic taxa to capture natural and/or anthropogenic ecological variations.

Freshwater fish are isotopically variable, which reflects their different aquatic niches, even within a single species. That a variety of niches (open water, shoreline, riverine and/or lake) are represented by the fish bone assemblages at Kałdus suggests a broad spectrum of fishing strategies, and/or trade.

During the first millennium AD, “by the clearing of trees and burning of the brushwoods, human settlements cut deep swaths into the forests, and with the use of the iron ploughshares the lands around the settlements could be cultivated intensively” (Gieysztor et al., 1979, p.43). These anthropogenic changes can be studied by measuring stable isotope ratios in faunal remains, with important implications for interpreting contemporary human stable isotope values. Since farming and animal husbandry spread to Europe in the Neolithic, human activities have had substantial impacts on the environment. It will be valuable to study animal bones from more ancient periods toward pinpointing times of changing land management strategies with the adoption of animal husbandry and agriculture.

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