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Integrated approaches to understanding animal exploitation and dairying in the Central European Early Neolithic: a case study from Ludwinowo 7 (Kuyavia, Poland; c. 5250–5000 cal BC)

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Recent genetic studies point towards 6th millennium BC central Europe as the core region for the emergence of the lactase persistence (LP) gene mutation -13,910*T, making it important to understand the intensity of milk production and consumption among Linearbandkeramik (or LBK) farming groups. However, it is not known if milking was part of the LBK Neolithic "package" from the start, or if it displayed a discontinuous pattern in time and space. Documenting the changing nature of prehistoric animal exploitation requires integrating multiple strands of evidence and here we detail multi-proxy research into animal management strategies and the intensification of dairying in Neolithic Europe, using the LBK site of Ludwinowo 7 in central Poland as a case study. Lipid biomarker and stable isotope compositions of food residues from vessels provide qualitative and quantitative assessments of the major animal products acquired and processed, while zooarchaeological analyses identify slaughter and butchery practices, revealing the nature of meat, milk and fat exploitation. Stable carbon and oxygen isotope analyses on cattle teeth are also undertaken to define seasonal herd management. This combined approach offers an integrated picture of animal exploitation and milk use at the central European LBK site of Ludwinowo.

KEYWORDS

Neolithic Europe, animal exploitation, zooarchaeology, stable isotope analysis, organic residue analysis, multi-proxy

1. Introduction

As archaeological studies increasingly show, early agriculture in Europe was not transmitted as a fixed package; plant and animal management strategies developed in different ways in different areas in response to different environmental conditions and cultural choices. Take, for example, the evolving relationship with milk products: whether one assumes milk to be a secondary product of animal domestication (e.g., Bökönyi, 1974; Sherratt, 1981), or part of multi-resource exploitation by early pastoralists (e.g., Helmer et al., 2007), the route to the intensification of dairying was complex and not necessarily linear. Anatolian evidence from the 7th to 5th millennium BC suggests a pattern of regional variation in the importance of milk use rather than of general change with time (Evershed et al., 2008; Debono Spiteri et al., 2016). Hints of similar variation have been observed in late 6th to mid-5th millennium BC central Europe, with dairy fat residues recovered from vessels on some settlement sites but not others (Salque et al., 2012), while in the Western Baltic in the 4th millennium BC, milk consumption occurs alongside continued exploitation of traditional hunter-gatherer aquatic resources (Craig et al., 2011). To better apprehend the complex nature of these human-animal-environment interactions, a multi-proxy approach is essential-each analytical technique either supports or flags inconsistencies within other datasets or reflects different aspects of management strategies. For example, dairying is commonly identified in the archaeological record via mortality profiles based on domesticated ruminant teeth. At sites where such faunal remains are absent, lipid residue analysis of ceramics can provide conclusive proof of this practice; at other sites, where milk has been processed in stone, wooden or woven containers and not in ceramic vessels, milk exploitation may only be visible through the system of exploitation of the ruminants. A multi-proxy approach also becomes increasingly important in large-scale sampling programmes, where taphonomic conditions and preservation levels can vary greatly from site to site and region to region, with the effectiveness of certain methods sometimes curtailed.

We focus in this paper on animal exploitation strategies within the Linearbandkeramik (LBK), the first farming communities that spread across central, temperate Europe in the mid-6th millennium BC. Past study of LBK animal husbandry has been hampered by uneven preservation of faunal remains, especially poor on the loess soils normally favoured by these early farmers (Bogucki, 1988; Bartosiewicz, 2005). However, an increase in projects dedicated to collecting and assessing zooarchaeological data both within the LBK and beyond provides a new, more substantial foundation for debate (e.g., Larson et al., 2005, 2007; Knipper, 2011; Colledge et al., 2013; Saqqali et al., 2014; Manning et al., 2015; Gillis et al., 2017). Technological advances, particularly in the areas of ancient DNA, geometric morphometrics, and stable isotope analyses of faunal remains have also provided new insights into animal management strategies (e.g., Balasse and Tresset, 2002; Bollongino and Burger, 2010; Balasse et al., 2012a; Evin et al., 2013; Gillis et al., 2013). Complementing this are molecular and isotopic analyses of absorbed lipid residues from archaeological ceramics, which retain information on the sources of commodities processed in the vessels, often found to be from animals (e.g., Salque et al., 2012, 2013; Matlova et al., 2017; Casanova et al., 2020a). Further advances in ^{14}C dating now allow us to directly date lipid residues extracted from archaeological pottery vessels (Casanova et al., 2020b), with ^{14}C dates recently obtained on milk residues from LBK vessels (Casanova et al., 2022). The appearance of the LBK also seems to coincide with the Lactase Persistence (LP) gene mutation−13,910*T, modelled as increasing in frequency between the Balkans and central Europe around 5,500 BC (Itan et al., 2009). While ancient DNA analysis has so far failed to detect the mutation in LBK skeletons (e.g., Burger et al., 2007; Gamba et al., 2014; Mathieson et al., 2015; Witas et al., 2015; Evershed et al., 2022), this is not inconsistent with a scenario of late 6th millennium BC farmers beginning to use milk as a sustainable dietary staple; the LP gene mutation would initially have been at a very low frequency in the population.

2. Materials and methods

The LBK settlement of Ludwinowo 7 lies on the edge of a small plateau overlooking the Vistula valley on a heavy but fertile gley soil in the Kuyavia region of the central Polish lowlands. Excavated in 2000-1 and 2008-10 ahead of motorway construction, features uncovered included postholes, long pits (*Längsgruben*) and other pits. These features were interpreted as the remains of ∼33 "households" including 14 reconstructible longhouses (Pyzel et al., 2019; Figure 1). Activity at Ludwinowo 7 is dated to the late 6th millennium BC (Marciniak et al., 2022), with the first traces of occupation appearing early in the regional sequence (Kuyavian phase I, corresponding to late *Älteste* LBK). However, the main period of site occupation spans ∼250 years, from c. 5250 to 5000 cal. BC (Kuyavian phases IIA to III, or early *Notenkopf* to *Jüngere* LBK). Correspondence analysis of the pottery motifs has further identified 6 site sub-phases, each thought to relate to a single house generation, although correspondence between the Kuyavian LBK phases and these sub-phases is not straightforward (Pyzel, 2019a). Preliminary zooarchaeological analysis (Osypińska, 2011) revealed an animal bone assemblage dominated by cattle (4,860 bone specimens from a total of 6,115 specimens identifiable to species, or 79%), with pigs (*Sus scrofa domesticus*), caprines (*Ovis aries/Capra hircus*) and wild animals playing seemingly only a small part in the site's economy. These proportions were largely confirmed by later in-depth analysis (Osypińska and Abłamowicz, 2019). The total number of reported fragments from LBK contexts (18,258; Osypińska and Abłamowicz, 2019) was large enough to probe in more depth-examining, for example, age-at-death profiles and fracture and fragmentation patterns by site phase and context type. In addition, organic residue analysis carried out on a selection of pottery vessels from the site had identified the processing of ruminant milk products and, by extension, evidence for dairying within this farming community (Salque et al., 2013; see below). Ludwinowo thus provided an ideal opportunity to investigate in more detail, and with a suite of complementary analyses, the development of sophisticated animal management practices among early farming groups.

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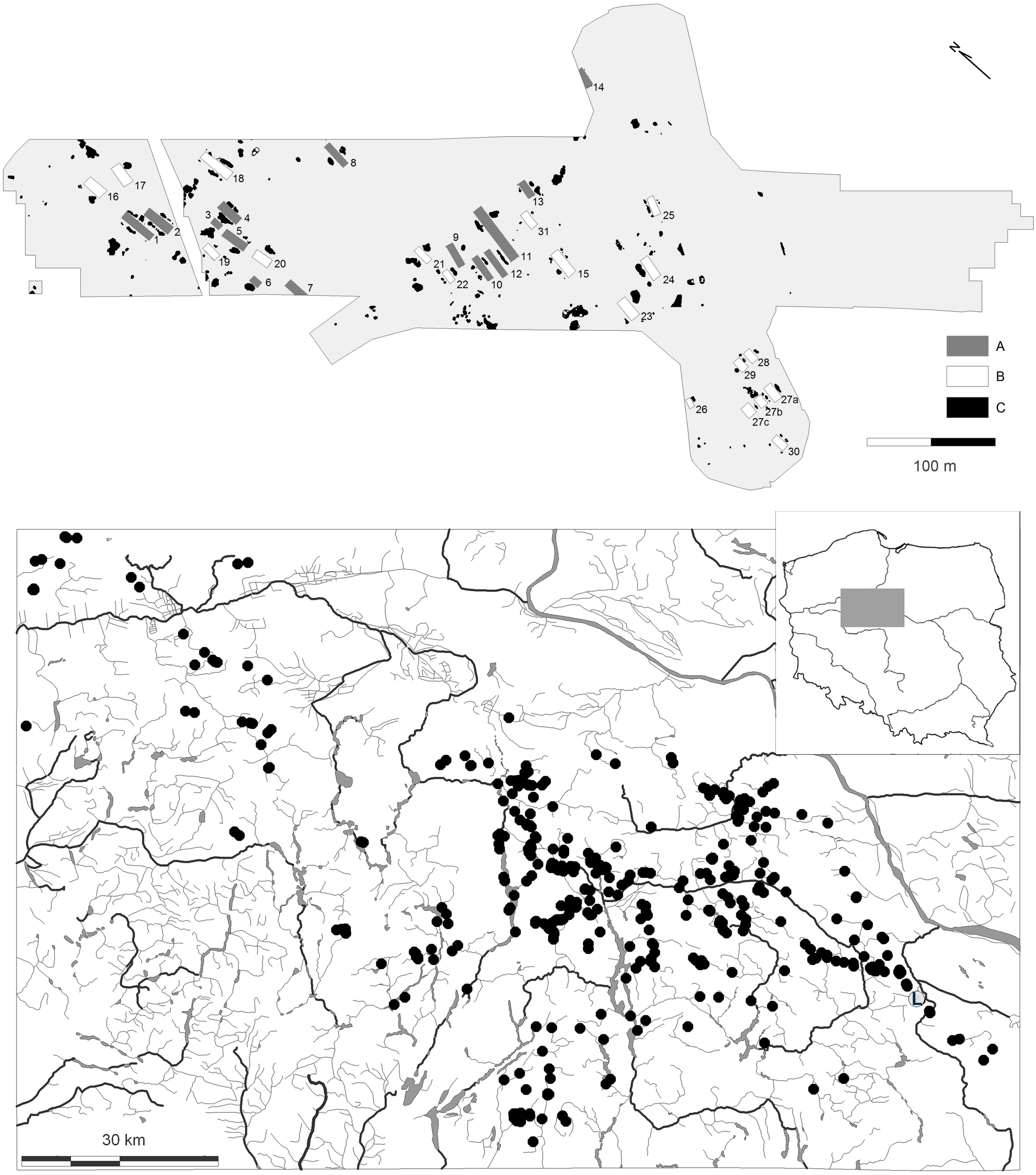

FIGURE 1
(Top) Ludwinowo 7 site plan (after Pyzel et al., 2019, fig. 2.10; A-LBK houses; B–hypothetical LBK houses; C–other LBK features); **(bottom)** Ludwinowo 7 (light grey polygon marked with letter L) in its regional setting, other LBK sites shown in black (after Pyzel, 2019b, fig. 12.1).

2.1. Organic residue analysis

A selection of pottery vessels from Ludwinowo were previously analysed as part of an exploratory study tracing milk use across mainland Europe (Salque, 2012), with 87 pots sampled across four categories: the ubiquitous LBK *Kumpf* or globular pot (the vessel type most likely to have been used for cooking), collared flasks or bottles, bowls, and perforated vessels (interpreted as sieves; Bogucki, 1984). Compound-specific carbon stable isotope analysis of the absorbed residues from these vessels revealed that extracts from the sieves were dominated by ruminant dairy fats, strongly suggesting they had been used in cheese production. By contrast, the *Kümpfe* yielded residues dominated by ruminant adipose fats, while several collared flasks showed traces of beeswax, possibly used as a sealant (Salque et al., 2013). These earlier results indicated a strong degree of vessel specialisation at Ludwinowo. More recently, more than 400 additional sherds from different houses and phases were analysed using the method highlighted by Correa-Ascencio and Evershed (2014) to investigate patterning across the site and through time (Roffet-Salque et al., 2019).

2.2. Butchery, fracture and fragmentation analyses

A sub-set of 13,428 bone specimens were selected for additional analysis with the aim of highlighting general consumption practices, as well as meat and fat exploitation (see also Parmenter et al., 2015; Johnson et al., 2016, 2022). Selection was based on the number of bones from different contexts, aiming to analyse a representative sample of context types from different site phases. Features associated with Houses 2, 6, 8, 15, 18 and 22 and four pit contexts (isolated pits B156, G64 and clay pits K66, K82) were completely or comprehensively analysed. Material from these contexts comprised 91% of the sub-set. As noted above, there was a paucity of large contexts from the earliest phases of the regional Kuyavian sequence, with the majority of the sub-sampled bone recovered from contexts assigned to later phases. Just under 39% of bone came from phase IIB (5230/5185-5120/5080 cal. BC, 68% probability; Marciniak et al., 2022), while 56% came from phase III (5105/5070-5060/5025 cal. BC, 68% probability; *ibid.*). Less than 1% of bone came from Kuyavian phase I, with a further 4% of the sample set coming from unknown phases. As new analysis was targeting the evidence for fracture and fragmentation in the faunal assemblage, there was accordingly lower resolution in species identification, with material classified as follows: 887 specimens identified to both species and element; 1,681 specimens partially identified as large/medium mammal or bird, and as bone shaft, vertebra etc.; 10,861 specimens classed as indeterminate. Butchery analysis followed Outram and Knight (2007) and Outram et al. (2005). Identification of fracture types on animal bone from Ludwinowo was primarily based on three fracture characteristics: outline of the fracture, angle of the fracture surface to the bone's cortical surface, and texture of the fracture surface (Johnson, 1985; Outram, 2001, 2002; Outram et al., 2005; Johnson et al., 2016).

2.3. Herd mortality and husbandry practices

Mortality data based on dental eruption, wear and replacement has been shown to provide an insight into slaughter management and therefore the potential orientation of husbandry practices (Payne, 1973; Helmer, 1995). These data can be displayed as a histogram or mortality profile with fixed age classes. New statistical approaches have improved the reliability of mortality profiles by using Bayesian statistics to generate credible intervals for each age class (Gerbault et al., 2016). These profiles can be interpreted using hypothetical husbandry models for dairy and meat subsistence practices (Payne, 1973; Peske, 1994; Helmer and Vigne, 2004). For cattle, the post-lactation slaughter model proposed by Peske (1994) is where calves are retained to stimulate milk let-down but killed at the end of the lactation period. This is a practice common amongst stock herders within traditional systems exploiting both meat and milk and as a consequence the milk is shared between the calf and community (Bonal et al., 1985). Archaeologically, this practise has been identified at the early 4th millennium BC site of Bercy in northern central France (Balasse and Tresset, 2002). At Ludwinowo, the dental remains for both cattle and caprines came from phases IIb and III, since there was poor preservation of phase IIA remains and limited material in Phase I. The age-at-death profile for cattle from phase IIB is based on 40 mandibular teeth and from phase III is based on 83 mandibular teeth, using Legge (1992) to determine age-at-death. There were very few identifiable remains of caprines (787 bone specimens, representing just under 13% of identifiable animal bone specimens from the site). Only 11 mandibular teeth were recovered from phases IIB and III together.

2.4. Investigating birth seasonality from oxygen isotopes in cattle teeth

The $\delta^{18}O$ values of ingested water is recorded in the developing tooth enamel of young animals and reflects the seasonal variations in the temperature of ingested water, where the values, in temperate regions, reflect the transition between the cold season (lowest values) and warm season (highest values). This record is not remodelled once enamel mineralisation is completed and reconstruction of a seasonal cycle is therefore possible by performing a sequential $\delta^{18}O$ analysis along the tooth growth axis (Bryant et al., 1996a,b; Fricke and O'Neil, 1996). Because the timing of tooth development is fixed within a species, seasonality of birth can be investigated through quantification of the inter-individual variability in the sequential series of $\delta^{18}O$ values along the tooth crown (Balasse et al., 2003, 2012a,b). As the Ludwinowo assemblage contained mainly isolated teeth, making it difficult to distinguish between first and second molars (M1 and M2), 10 third molars (M3) were selected for analysis: 4 individuals from phase IIB (LUD Bos 2–4, 10) and 6 from phase III (LUD Bos 1, 5–9). Selected teeth were between Grant (1982) stages d to g (age range of 26–48 months), to ensure sequential sampling produced a complete annual signal, part of which could be lost to abrasion. Details of sampling methodology and analysis can be found in Kendall et al. (2019a).

2.5. Investigating environment and foddering regimes from carbon and nitrogen isotopes in cattle teeth

Sequential sampling along the tooth growth axis allows any seasonal shift in $\delta^{13}C$ values to be detected, providing evidence for changes in management regimes such as periods of foddering or mobility (e.g., Balasse et al., 2006, 2012a, 2014; Britton et al., 2008). The lower third molar forms over the second year of the cow's life, so incremental stable isotope analysis will record the diet during its second year. Compound-specific nitrogen isotope analysis of dentine amino acids provides a method independent of the $\delta^{13}C$ value canopy effect to determine whether animals were pastured within, and/or fodder was collected from, forests. This method takes advantage of the differences in biosynthesis and metabolism of different amino acids and has the potential to directly examine animal dietary sources (Lynch et al., 2016; Kendall et al., 2017) as it enables the consumption of woody plants, due to browsing or foddering, to be detected due to amino acid nitrogen isotopic differences between woody and herbaceous plant types (Kendall et al., 2019b). In order to determine the diet of cattle from amino acid $\delta^{15}N$ values, β values (the difference between glutamate and phenylalanine $\delta^{15}N$ values, $\Delta^{15}N_{Glx-Phe}$, at the base of the food web; Kendall et al., 2017) were calculated for all dentine samples and compared to the values expected from herbaceous and woody plants. Details of sampling methodology and analysis can be found in Kendall et al. (2019a).

3. Results

3.1. Organic residue analysis

Of the 400 additional Ludwinowo sherds analysed, after Salque et al. (2013), 47% (n = 190) contained appreciable quantities of lipids (concentration > 5 µg per gramme of potsherd) with characteristically high amount of $C_{16:0}$ and $C_{18:0}$ fatty acids—indicative of animal fats—frequently observed (Figure 2). In both studies, compound-specific carbon stable isotope analysis of the $C_{16:0}$ and $C_{18:0}$ fatty acids (n = 144 + 46 samples from Salque et al., 2013) confirmed the presence of dairy fats. However, the increased sample size revealed less vessel specialisation than initially thought: absorbed residues from *Kümpfe* were still dominated by ruminant adipose fats, but a sizeable proportion were found to contain dairy fats (Figure 3). For the site as a whole, ruminant adipose fats comprised 67.9% of lipid residues identified in pottery vessels, with ruminant dairy fats comprising 32.1% (Figure 3). There was insufficient data in pottery from the earliest contexts (Kuyavian phase I, $n = 3$ sherds with identifiable animal fats) to infer meaningful patterns. However, there was a slight increase (although not statistically significant, χ^2 test, $p < 0.05$) in the proportion of dairy: adipose fats from phase IIA to III (with 20% and $n = 15$ for Phase IIA; 32% and $n = 72$ for Phase IIB; 43% and $n = 98$ for Phase III; Figure 3).

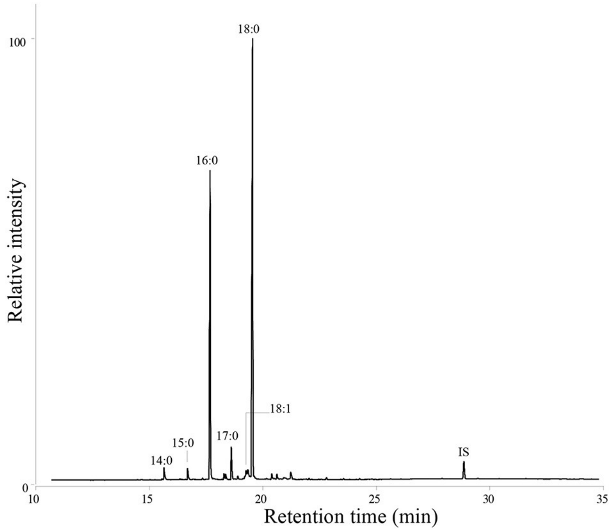

FIGURE 2
Gas chromatogram showing typical distribution of degraded animal fat residues in pottery from Ludwinowo 7 with characteristically high abundance of $C_{16:0}$ and $C_{18:0}$ fatty acids, indicative of fully hydrolysed triacylglycerols originating from animal fats. Key: n:i, fatty acid with n acyl carbon number and i degree of unsaturation.

3.2. Butchery, fracture and fragmentation analyses

Butchery was found to be visible on 13.2% (n = 114/862) of bones identifiable to species from the sub-sampled Ludwinowo 7 assemblage (Figure 4). Evidence of butchery was particularly abundant at the elbow (distal humerus, proximal radius and ulna) and ankle (astragalus, calcaneum, navicular-cuboid), reflecting the disarticulation of the meat-rich upper limbs from the extremities. Butchery indicating defleshing was present on many meat-rich elements, especially the upper forelimb, and marks consistent with skinning were noted on the metapodia and phalanges. The abundance of butchered bones per species suggests that large wild mammal bones were more often marked during butchery than those of domestic animals, although due to small sample sizes differences were not often significant at 95% confidence. Aurochs (*Bos primigenius*, 23.3%, n = 7/30) and red deer (*Cervus elaphus*, 30.0%, n = 6/20) bones were some of the most commonly butchered in the assemblage. Red deer specimens had significantly more butchery evidence than domestic cattle (13.0%, n = 84/645; p = 0.029). This could be explained by intensive kill-site disarticulation of wild carcasses for transport back to the settlement, which would not have been as necessary on smaller wild animals such as roe deer (*Capreolus capreolus*) or on the domestic animals, which were likely butchered locally. However, wild horses (*Equus ferus*) do not seem to fit this pattern.

In the sub-sampled assemblage from Ludwinowo, 44.8% (n = 821/1,831) of all fractured mandibular and long bone fragments larger than 29 mm in maximum dimensions displayed evidence of fresh fracture. Fractured bones known to yield high quantities of marrow (humerus, radius, femur and tibia) had significantly higher proportion of fresh fracture than the overall assemblage at 64.4% (n = 103/160; $p < 0.001$) of instances, and on high-yield cattle bones the percentage of fresh fracture was further elevated compared to the overall assemblage, at 68.7% (n = 57/83; $p < 0.001$). These figures indicate an established tradition of intentional breakage of bones for marrow at the site, which was particularly intensive in the clay pits where the percentage of fresh fractures on all fractured bone was significantly higher at 68.2% (176/258; $p < 0.001$) than proportions of fresh fracture in house pits (46.6%, n = 543/1,164).

Despite these proportions of freshly fractured bone, the subsampled assemblage from Ludwinowo does not reflect

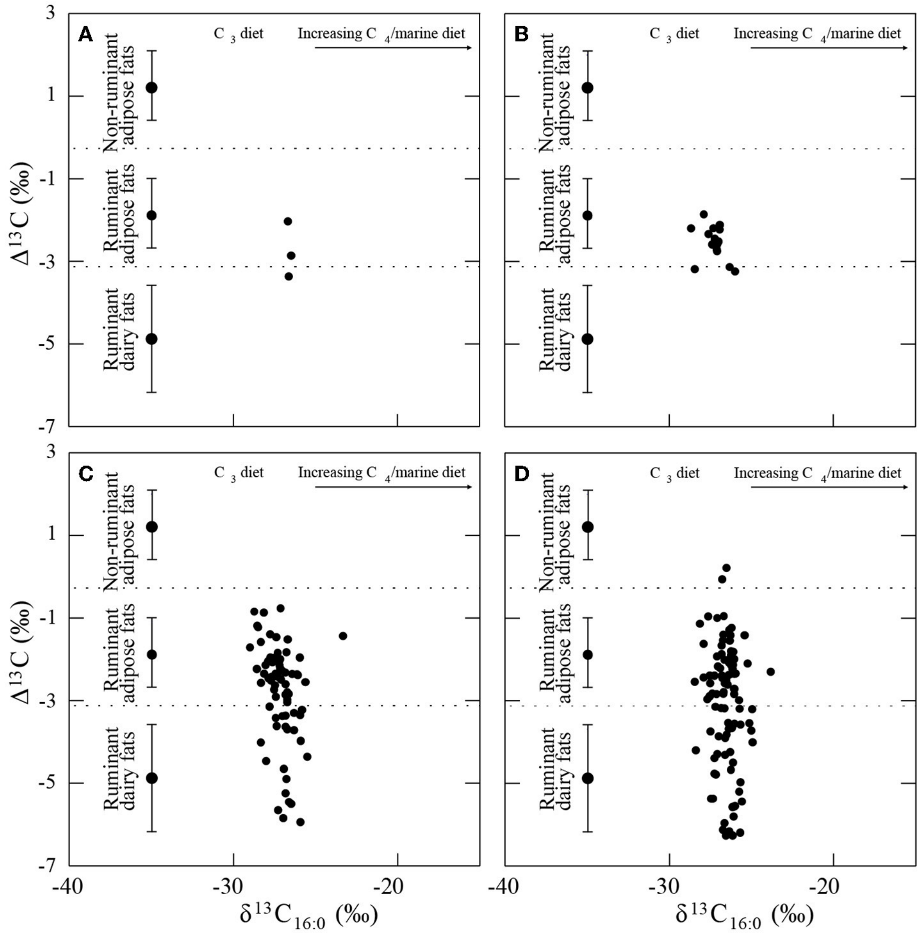

FIGURE 3
Difference in the $\delta^{13}C$ values of the $C_{18:0}$ and $C_{16:0}$ fatty acids ($\Delta^{13}C = \delta^{13}C_{18:0}$-$\delta^{13}C_{16:0}$) obtained for archaeological fats extracted from sherds attributed to **(A)** phase I (n = 3), **(B)** phase IIA (n = 15), **(C)** phase IIB (n = 72) and phase III (n = 98) of the Kuyavian LBK. The ranges represent the mean ± 1 standard deviation of the $\Delta^{13}C$ values for the global database comprising modern animal fats from Kazakhstan (Outram et al., 2009), Britain (pure C_3 environment; Copley et al., 2003), Switzerland (Spangenberg et al., 2006), the Levant (Gregg et al., 2009), Turkey (Pitter, *unpublished*), Kenya and Libya (Dunne et al., 2012). Analytical precision is ±0.3‰.

an intensive bone fat processing regime. Similar studies of archaeological sites where intensive bone fat utilisation have been suggested have reported far higher levels of fresh fracture, such as the Initial Middle Missouri site of Mitchell, South Dakota [87.4% (n = 198) fresh or above in certain contexts; Karr et al., 2015], and Mediaeval Norse under subsistence stress in Sandes, Greenland (Outram, 1999, 2003). Fragmentation analysis at Ludwinowo also shows little evidence for intensive bone grease processing, identified in the archaeological record by highly comminuted cancellous bone and high levels of fresh fracture on diaphysis bone (Outram, 2001; see Karr et al., 2015 for an example). The bone assemblage was fairly fragmented, but this was probably due to poor preservation as the weight by size class chart does not show a large enough mass of small fragments (<30 mm) to indicate intensive comminution of cancellous material, and many articular epiphyses were unfragmented (Figure 5). Combined with the fracture analysis, this would suggest that animal carcasses were not being exploited to their maximum nutritional effect at Ludwinowo.

3.3. Herd mortality and husbandry practices

Among the phase IIb cattle, the largest peak at 15–26 months (Figure 6A) reflects the slaughter of animals who have survived into their second year, probably young males at optimal weight. The peaks in the younger age classes, particularly those 3–6 months and 6–15 months, could be the result of a post-lactation slaughter management, where milk is shared between the Ludwinowo community and the growing calves. The strong frequency of adult slaughter could be from the removal of females, and a possible indication that the herd mainly consisted of lactating females. Overall, the profile suggests low intensity milk exploitation with the majority of animals being slaughtered between 15 and 26 months for meat. The age-at-death profile for cattle from phase III is strikingly different from phase IIb (Figure 6B). In contrast to the previous phase, there is stronger evidence for dairy exploitation with continued slaughter of animals at optimal weight for meat. The high frequency of older animals (>26 months in age) likely reflects the keeping of females for milking. Furthermore, strong

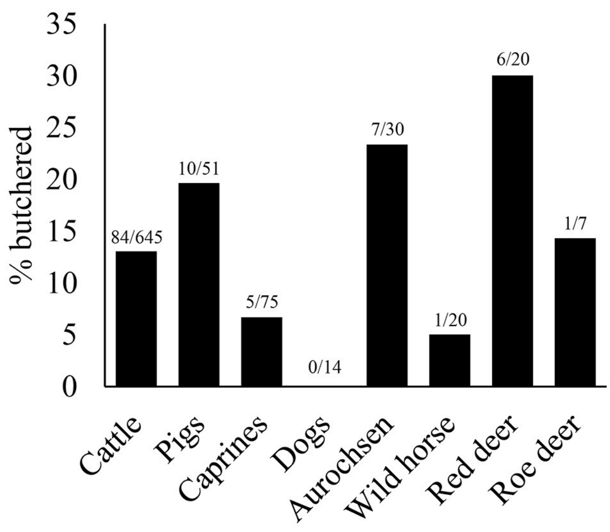

FIGURE 4
Evidence of butchery on animal bone identified to different taxa at Ludwinowo 7 (selected contexts). The number of butchered bones and the number of identifiable specimens per taxon is displayed above each bar.

peaks in the 0–15 month age classes suggests that calves were being kept alive up to the end of their first year, perhaps for the purpose of stimulating milk let-down. The high frequency of animals in age class 15–26 months and 26–36 months suggests that the Ludwinowo community were keeping animals to reach optimal weight for meat production. Recent correspondence analysis using simulated data suggests that there was little difference between the phases when compared with 15 other LBK sites (Gillis et al., 2017). Due to the low number of caprine mandibular teeth recovered from phases IIb and III, there is very little that can be extrapolated from the caprine age-at-death profile (Figure 6C). Age-at-death analysis of cattle remains from different context types i.e., household pits (*Längsgruben*), clay pits and unassociated pits found that mature adults, perhaps males, were concentrated in clay pits while infants and juveniles were found in household pits (Johnson et al., 2022). Together with the fracture and fragmentation analysis results, this would suggest the clay pits were short-lived rubbish pits used perhaps after communal feasting events, while household pits were used over longer periods of time.

3.4. Oxygen isotope composition in cattle teeth

Mean δ^{18}O values of the Ludwinowo cattle molars ranged between −8.4 and −2.5‰ with an amplitude of 2.3 to 4.8‰ for individual teeth. The sequences of δ^{18}O values measured show an undulating pattern close to a sinusoidal variation except for Bos 10 (Figure 7A). Individuals Bos 1, Bos 5 and Bos 10 were excluded as the curves produced did not represent a complete annual signal so only seven of the 10 molars could be modelled following the cosine function proposed by Balasse et al. (2012a; Figure 7B). The normalisation plot indicates that the length of the birthing period at Ludwinowo was 4–5 months, with Bos 4 as an outlier and possibly born outside the main birth period. This is similar to previous analysis of birth seasonality for cattle at the 5th millennium BC site of Cheia, Romania (Balasse et al., 2014; Figure 7C) although shorter than the approximate 6-month calving period observed at 4th millennium BC Bercy, northern France (Balasse et al., 2012a). With birth seasonality in cattle mainly driven by food availability and cattle mating season strongly related to the annual cycle of vegetation development (Balasse et al., 2021), a relatively short period of calving at Ludwinowo suggests strong environmental constraints and/or minimal intervention (in the form of foddering) by stock herders.

3.5. Carbon and nitrogen isotope composition in cattle teeth

The δ^{13}C values from the Ludwinowo teeth ranged between −12.1 and −9.7‰ and, with an amplitude of 0.3 to 1.7‰ for individual teeth (Figure 8). Considering a 14.1‰ enrichment factor between enamel bioapatite and diet δ^{13}C values (Cerling and Harris, 1999), the Ludwinowo teeth values would correspond to dietary δ^{13}C values ranging between −25.8 and −23.5‰, which fall within the global range of variation for C_3 plants from open areas (−31.5 to −23‰ in modern plants: Kohn, 2010; corrected by +1.5‰ for pre-industrial plants using Friedli et al., 1986; Marino and McElroy, 1991). C_3 plants include most trees, woody shrubs, herbs, temperate/shade loving grasses and domesticated cereals such as barley and wheat, and in temperate regions such as central Poland are the most commonly represented (Pyankov et al., 2010). In addition to the apparent open area grazing of the Ludwinowo cattle, the low amplitude between maximum and minimum δ^{13}C values suggests that there was little seasonal variability in their diet. There was no significant difference between the dietary δ^{13}C values based on bioapatite samples with those based on dairy $C_{16:0}$ fatty acid (Student *T*-test: $t = 1.02$ $p = 0.3$), which suggests cattle were the primary source of milk and there was no change in diet during lactation.

With regard to the amino acid δ^{15}N values, the β values fall within the range of expected values for herbaceous plants (−7.9 to −3.7‰; Kendall et al., 2019b) for each of the teeth analysed (Figure 9), indicating that the cattle from Ludwinowo had a year-round herbaceous, graze-based diet, with no seasonal movement between forested and open landscapes, or use of leafy fodder evident (Kendall et al., 2019a).

4. Discussion

Organic residue analysis of absorbed pottery residues has unequivocally determined that LBK farmers settled at Ludwinowo were milking their animals and processing that milk for consumption, not only in the ubiquitous LBK *Kümpfe*, but in specialised processing equipment, namely ceramic sieves. With faunal analysis showing that these farmers mostly reared cattle—pigs, sheep, goats and wild animals playing only a small part in subsistence strategies—it is reasonable to conclude that cow's milk was primarily exploited. This is supported by mortality profiles for

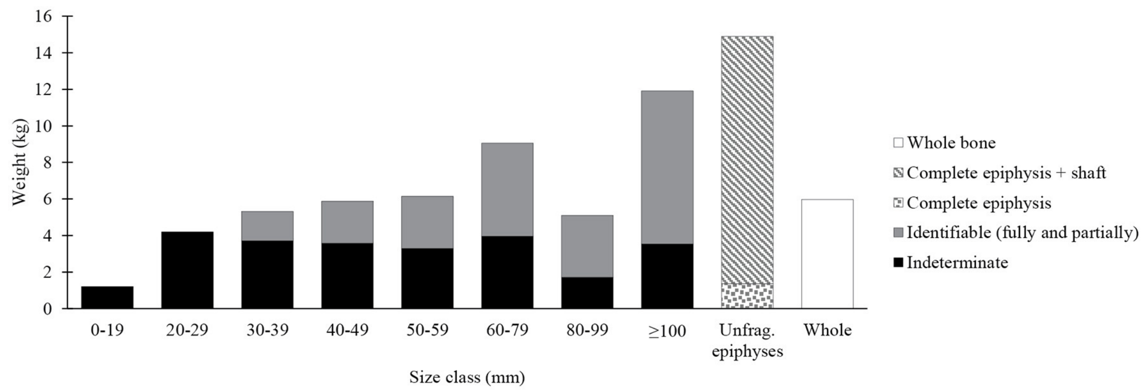

FIGURE 5
Weight by size class for both identified (full and partial) and indeterminate bones (n = 13,428), from Ludwinowo 7 (selected contexts).

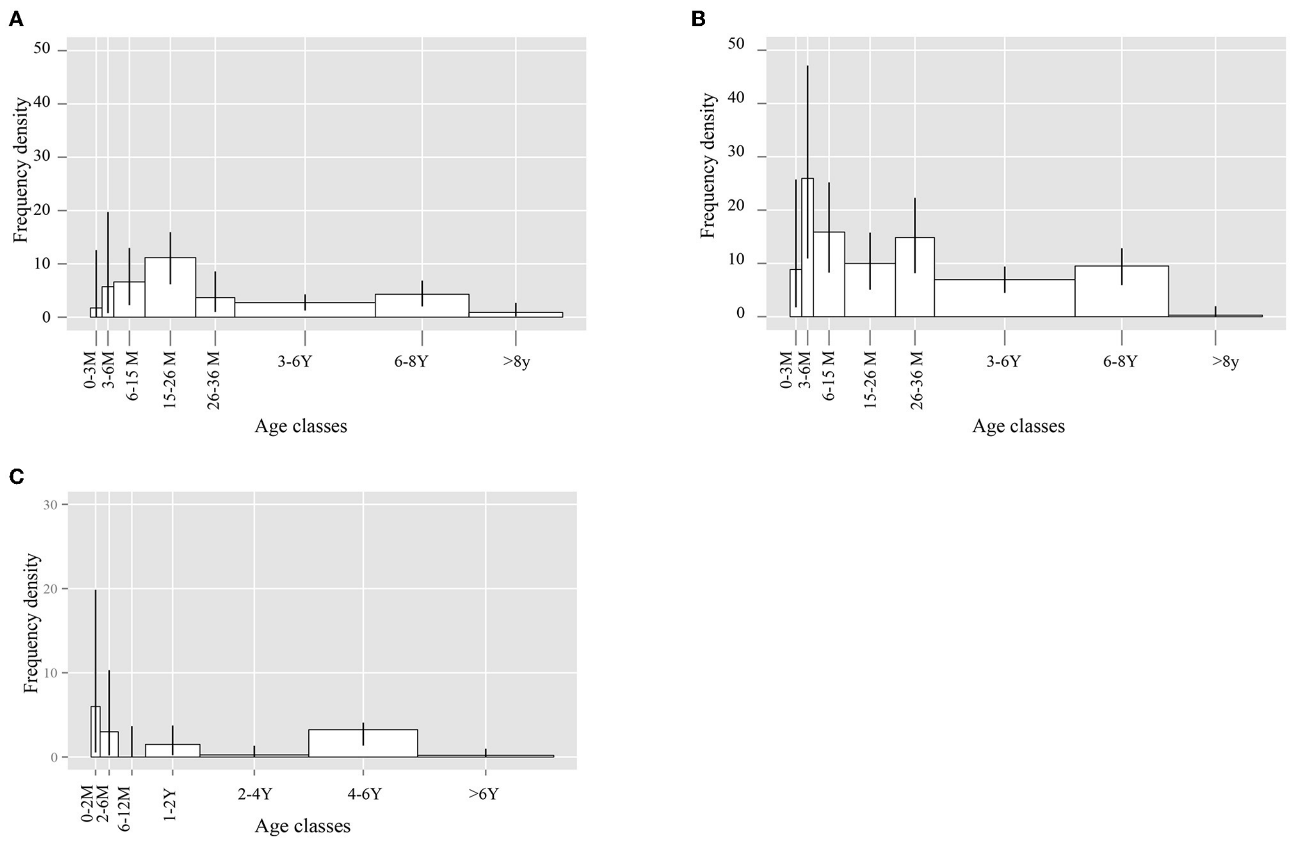

FIGURE 6
Mortality profiles for cattle from **(A)** Phase IIB (number of teeth = 39) and **(B)** Phase III (number of teeth = 83), using Legge (1992) age classes; **(C)** ovicaprids (all phases, number of teeth = 11), using Payne (1973) age classes. Gerbault et al. (2016) methodology was used to generate credible intervals for each age class using the Dirichlet function.

the Ludwinowo cattle, which feature older animals past the optimal age for meat production likely representing females slaughtered at the end of their productive life. Our combined analyses also tease out the likely intensity of dairying, with mortality profiles suggesting that (some) calves are being kept alive to stimulate lactation in the adult herd, with male calves perhaps fattened for communal feasting events. The $\delta^{18}O$ values in the cattle tooth enamel identify a calving period of ∼4–5 months duration, making milk available for up to 9 months of the year (if 6 months is taken to be the average lactation length of a cow; Gillis, 2017). If dairying was a specialised seasonal activity at Ludwinowo, how else were occupants of the site exploiting their animals? Slaughtered and jointed carcasses of cattle and other domesticated ruminants were both processed in pottery vessels and roasted over fires–activities

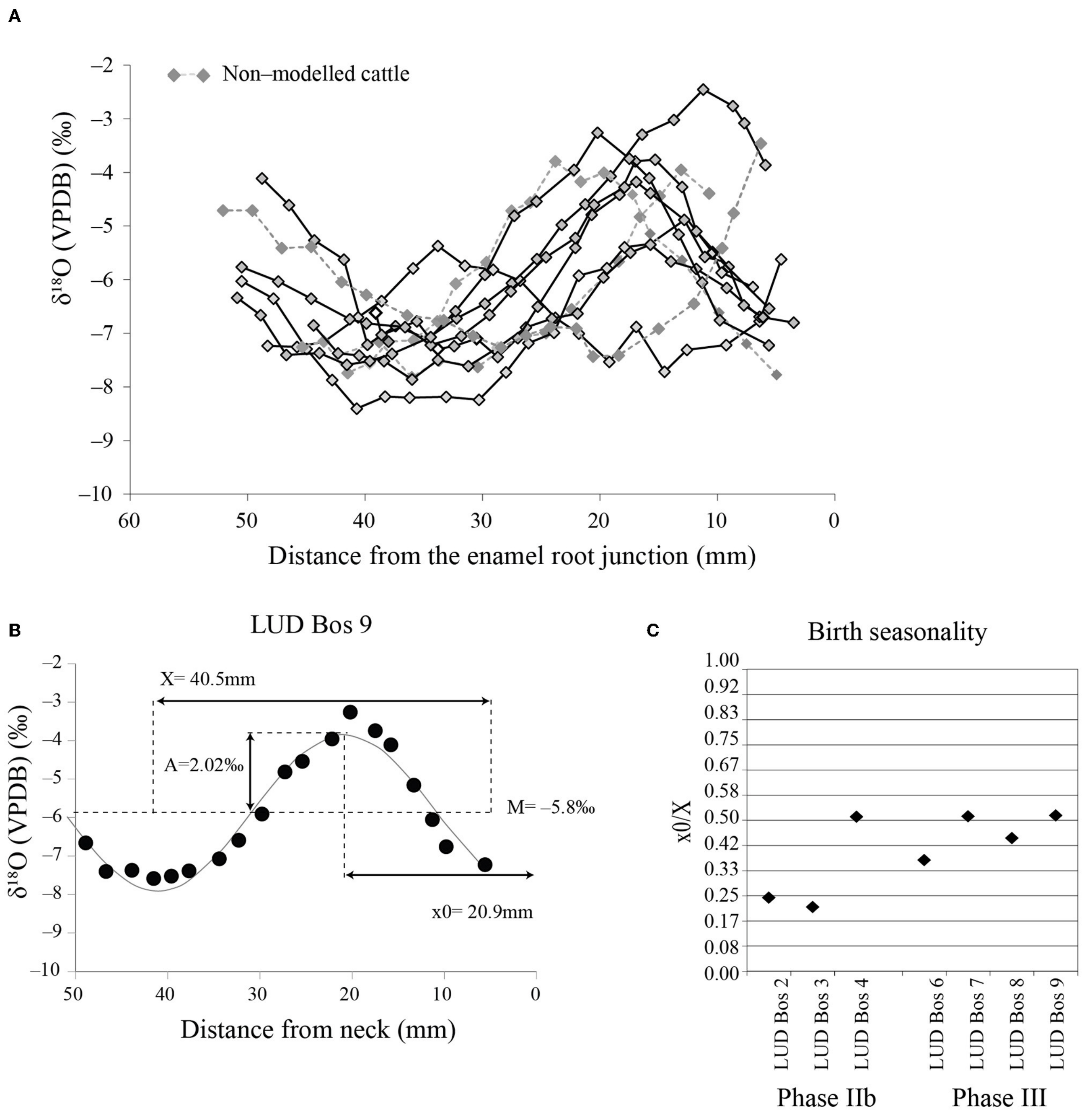

FIGURE 7
(A) Inter-variability of $\delta^{18}O$ values shown from 10 cattle teeth from Ludwinowo 7 (Individuals Bos 1, Bos 5 and Bos 10 were excluded from modelling as the curves produced did not represent a complete annual signal); **(B)** Application of the model to the results from Bos 9 (M = mean, A = amplitude, X = the potential length of the crown formed over an annual cycle, x0 = when the $\delta^{18}O$ values reach its maximum); **(C)** the birth seasonality prediction for Ludwinowo 7 based on seven samples. The y-axis is divided in 12 areas representing the 12 months of the year.

leaving their trace in pottery organic residues and on the animal bones themselves. Marrow was also extracted but not exhaustively, and there was no evidence for intensive exploitation of bone grease, an indicator of food stress or shortage. Indeed, some of these consumption practices, like dairying, may have had a temporal dimension; periodic feasting events are suggested by the large quantities of marrow-extraction waste recovered from the clay pits at Ludwinowo. Bone fracture is freshest in these pits, compared to house pits and other pit contexts, indicating refuse was deposited and covered over soon after consumption (Johnson et al., 2016, 2022).

How do the results from Ludwinowo fit with the archaeology of the wider Kuyavia region in the 6th millennium BC? Situated beyond the fertile loess belt more commonly associated with the LBK, early farming communities of the North European Plain nevertheless sought out similar "energy-subsidized" habitats,

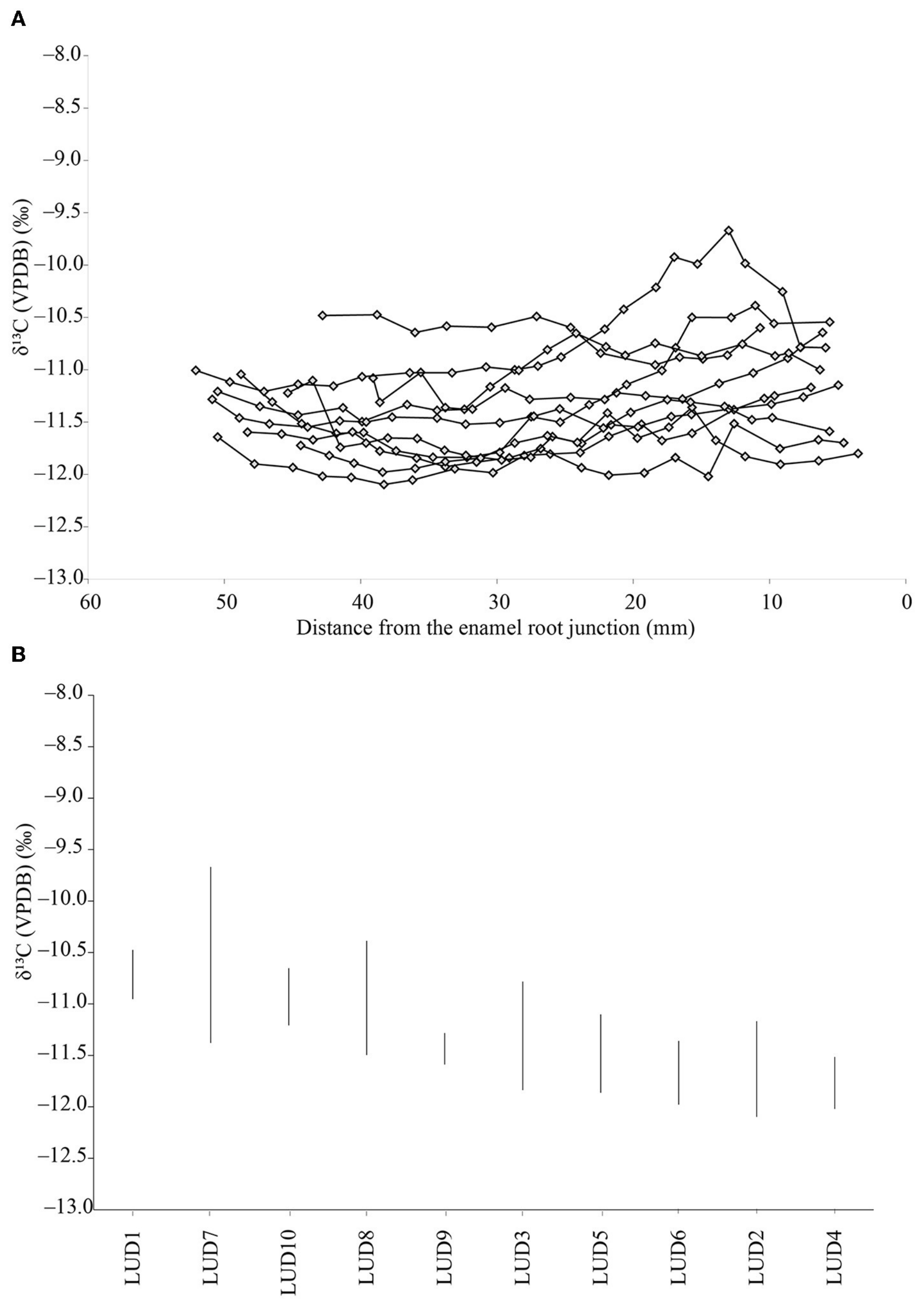

FIGURE 8
$\delta^{13}C$ values from the sampled cattle teeth from Ludwinowo 7: **(A)** values plotted against the distance from the enamel root junction; **(B)** intratooth minimum and maximum values.

exploiting fertile lake shorelines of the North European Plain for both tillage and pasture (Bogucki, 2000, 205). While LBK sites did not cover the whole region evenly, recent research has overturned the idea that this was an area of ephemeral, frontier farming (e.g., Bogucki, 1988; Grygiel, 2004), with settlement now known to be of a similar density and duration to other LBK regions. By c. 5300 BC, when the main period of occupation at Ludwinowo begins, the entire region of historical Kuyavia is settled; the relatively high number of sites lasting three phases (IIA, IIB, III)—Ludwinowo included—point towards a stable settlement system (Pyzel, 2009, 2010).

In terms of animal husbandry, species representation and ratios at Ludwinowo mirror that of the wider Kuyavian region, with domestic cattle dominating (e.g., Bogucki, 2000). These cattle may also have been exploited for their milk, as ruminant dairy fats have been detected in additional Kuyavian LBK sieve fragments (Salque et al., 2013; Roffet-Salque and Evershed, 2016). This could indicate a wider Kuyavian specialisation, although sieves from other regions of the LBK (e.g., Bogucki, 1984, 18) are currently being investigated and may alter this picture. The phenomenon of marrow-extracted cattle bone from clay pits has also been observed on other Kuyavian

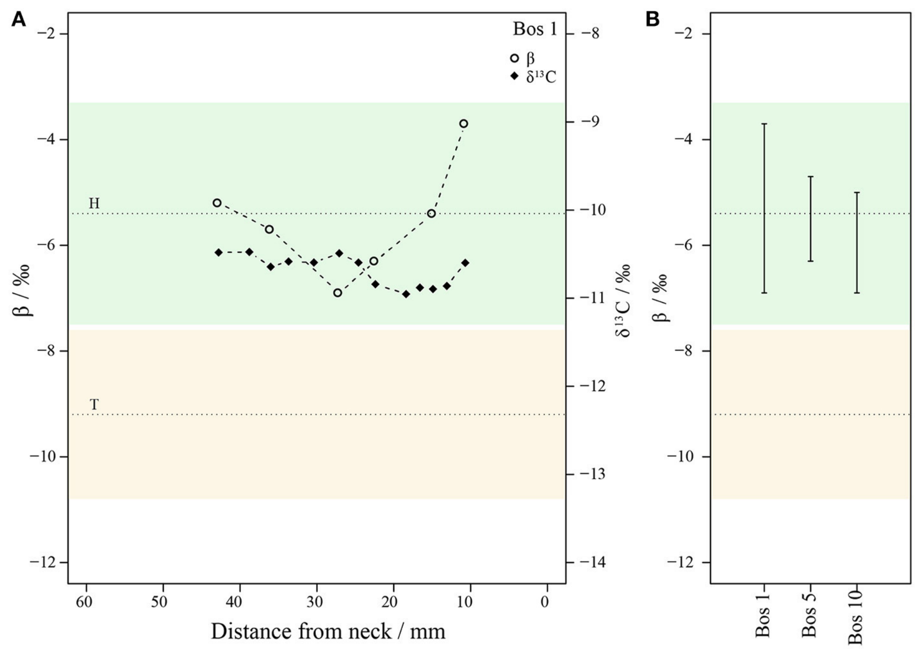

FIGURE 9
(A) β values (dots) and bioapatite $\delta^{13}C$ values (diamonds) from incremental sampling of Bos 1. The β values for herbs (H) and trees (T), determined by Kendall et al. (2019b), are displayed as dotted lines with their standard deviations shaded; **(B)** ranges of β values M3 teeth sampled for dentine amino acid stable nitrogen isotope analysis for 3 Bos individuals.

LBK sites (e.g., Marciniak, 2004, 2005, 188). If indeed the remains of episodic feasting events, this activity may have had a role in maintaining social ties across the region, even sustaining a specific Kuyavian group identity (Marciniak, 2005; Pyzel, 2009, 77).

Wider stable isotope analyses on LBK human and animal bone collagen (Bickle and Whittle, 2013) provides additional context for activity at Ludwinowo, sampling some 617 humans and 366 animals from LBK cemeteries and settlements across a 1,200 km range. From this data there emerges a human-faunal trophic level difference that varies in magnitude across the LBK territory: while the overall impression remains one of dietary consistency, human–fauna $\Delta^{15}N$ values for eastern sites (within the Danube catchment) are smaller than those for western sites (within the Rhine catchment) and when modelled offer the possibility that western LBK communities were consuming a greater proportion of animal-based dietary protein (c. 50%) than eastern LBK communities (at c. 25%; Hedges et al., 2013). No human remains were analysed as part of the Ludwinowo study and the human-faunal trophic level difference cannot be reconstructed, but it provides a useful reminder that both meat and milk may have been in consumed in relatively low quantities by the site's occupants. Across the wider LBK, there was also an isotopic difference observed between the adult males and females analysed, with higher $\delta^{15}N$ values recorded for males (Hedges et al., 2013, 348) and it remains a possibility that foodstuffs, such as milk products or bone marrow, were not consumed in equal quantities by men and women at Ludwinowo.

In terms of animal management practices, the wider LBK data displays some additional east-west trends, with bone collagen $\delta^{13}C$ values (and, less clearly, $\delta^{15}N$ values) from the fauna sampled (cattle, caprines, and pigs) tending to decrease to the west across the extent of the LBK. This east-west trend is especially pronounced for cattle, about twice that of caprines and pigs, and is thought to reflect some specific aspect of the isotopic composition of plants eaten by cattle (Hedges et al., 2013, 360). Cattle pastured and foddered using forest resources may exhibit depleted values due to the canopy effect, suggesting that human-cattle relationships—for example foddering regimes—change as the LBK extends westwards (Gillis and Zanon, 2021). According to feeding experiments on herbivores, $\delta^{13}C$ values of bone collagen are c. 6.6 ‰ more enriched than lipids from the same individual (Tieszen and Fagre, 1993). Average $\delta^{13}C$ values (of the $C_{16:0}$ fatty acid) of Ludwinowo animal lipid residues is −27.1‰, giving an expected value of around −20.5‰ on collagen from animals exploited at the site. This fits well within the range of cattle bone collagen values recorded on other eastern LBK sites (Bickle and Whittle, 2013, Appendix A). Enamel bioapatite $\delta^{13}C$ values from the Ludwinowo cattle teeth reinforce the above, suggesting that the farming regime was being undertaken with little seasonal variation in the cattle fodder. There is no evidence of leaf fodder from closed forests being given to the cattle at Ludwinowo based on the $\delta^{13}C$ values, although foddering would not be detected if leafy material was collected in open forests (Balasse et al., 2012a). However, the compound-specific amino acid nitrogen isotope proxy, which distinguishes between woody and herbaceous plant types independently of the canopy effect, confirms that leaf fodder was not used, even from trees in open-canopy woodland or forest margins (Kendall et al., 2019a).

Insight obtained at Ludwinowo into dairying and other forms of Early Neolithic animal management continues to be enhanced by programmes of organic residue analysis, undertaken both across the LBK and into later periods (e.g., Roffet-Salque and Evershed, 2016; Casanova et al., 2020a; Evershed et al., 2022). This is being complemented by more robust methods of statistical analysis of faunal remains (e.g., Gerbault et al., 2016; Gillis et al., 2017). The food and farming webs connecting the earliest farmers of central Europe are being revealed at an ever-increasing rate, and integrated studies such as the above are key to capturing the complexity of these relationships.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Pottery sherds were collected by MR-S, MK, and JP, and lipid data analysis and interpretation were performed by MR-S. EJ performed the butchery, fracture and fragmentation zooarchaeological analysis. RG collected, analysed the dental material zooarchaeologically and isotopically. IK performed the compound-specific amino acid analysis and data interpretation. The paper was conceived and written by JS with contributions from MR-S, RG, EJ, IK and with edits and approval from all co-authors. All authors contributed to the article and approved the submitted version.

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Conflict of interest

RG, JP, and AO declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer AS declared a past co-authorship with the authors IK and RPE to the handling editor.

Publisher's note

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