Stable isotopic insights into crop cultivation, animal husbandry, and land use at the Linearbandkeramik site of Vráble-Velké Lehemby (Slovakia)

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Abstract
The plant and animal components of Linearbandkeramik (LBK) subsistence systems were remarkably uniform with cattle, emmer and einkorn wheat providing the primary source of sustenance for Europe’s earliest agricultural communities. This apparent homogeneity in plant and animal use has been implicitly understood to indicate corresponding similarity in the types of husbandry practices employed by LBK farmers across the entire distribution of the LBK culture. Here, we examine the results from the stable ($\delta^{13}$C/$\delta^{15}$N) isotope analysis of animal bone and cereal grains from the site of Vráble-Velké Lehemby (Slovakia), providing new information about Linearbandkeramik farming practices in the western Carpathians. Moderately high carbon isotope values from animal bone collagen show that all livestock were pastured in open areas with no evidence of forest pasturing, previously associated with LBK settlements in north-western Europe. High $\delta^{15}$N values measured from domesticated cereal grains suggest manuring took place at the site, while $^{15}$N enrichment in bone collagen suggest livestock fed on agricultural by-products and possibly grains. An integrated plant-animal management system was in use at Vráble where livestock grazed on cultivation plots post-harvest. Use of such strategy would have helped fatten animals before the lean winter months while simultaneously fertilising agricultural plots with manure. This study contributes to our growing understanding that although the building blocks of LBK subsistence strategies were remarkably similar, diversity in management strategies existed across central and north-western Europe.

Keywords Animal husbandry · Crop cultivation · Land use · Stable carbon and nitrogen isotopes · Linearbandkeramik · Slovakia

Introduction
The Linearbandkeramik (LBK) is associated with the initial spread of farming and livestock herding across central and north-western Europe during the mid-late sixth millennium cal BC, a process that ultimately incorporated indigenous hunter-gatherers through acculturation or replacement (Gronenborn 2003; Lipson et al. 2017). LBK groups emerged from the Transdanubian linear pottery (TLP) groups in the northern Carpathian region around 5600 cal BC and rapidly expanded west, reaching central and eastern Europe by 5400 cal BC, and its north-western limit in the Paris basin by the mid-sixth millennium BC (Bickle and Whittle 2013; Gronenborn 2003; Pavlú 2005). LBK groups relied primarily on cattle, although pigs, sheep and goats were also exploited at varying intensities (Gillis et al. 2017, 2019; Lüning 2000; Manning et al. 2013b; Marciniak 2013). Cattle herds were largely comprised of adult animals, probably females, and exploited for their milk and meat (Gillis et al. 2017). Dairying was an important subsistence practice, indicated by some post-lactation slaughter of male calves when they were no longer needed for milk let-down. The importance of dairy in LBK societies is further demonstrated by the predominance...
of dairy fats in pottery, replacing the exploitation of fats from bone marrow and bone grease (Johnson et al. 2018), and the processing of milk into storable products, such as cheese (Salque et al. 2013). Beef was likely consumed as part of feasting events that brought communities together (Marciniak 2005). The focus on bringing most cattle into adulthood suggests considerable investment in their animals by LBK stockherders (Russell 1998), one that required careful planning to ensure large quantities of meat and by-products were available for year round. LBK communities also farmed a reduced package of Near Eastern plant domesticates, greatly curtailed in taxonomic diversity due to cooler temperatures and wetter conditions in European temperate environments (Ivanova et al. 2018; Kreuz 2007; Kreuz and Schäfer 2011). The cultivation of hulled wheats, such as emmer (Triticum monococcum) and einkorn (Triticum dicoccum), may have been exploited by LBK farmers because the glume protected the grain from freezing and wet growing conditions as well as damp storage conditions (Colledge and Conolly 2007) and therefore better suited for temperate continental climates. Overall, einkorn and emmer wheats were raised on permanent garden plots and were the primary cultivars exploited by LBK groups (Bogaard 2004), while barley (Hordeum vulgare) and legumes (pea (Pisum sativum) and lentil (Lens culinaris)) were rarely farmed (Bogaard 2004; Kreuz 2007; Saqalli et al. 2014). Livestock herds also produce a key ingredient for crop cultivation: manure, which may have been deliberately collected and spread on fields or introduced through animals being penned on cultivation plots to graze on harvest residues. Although limited in number, stable isotopic analyses of carbonised seed remains are revealing that plant management strategies practised by LBK farmers were concerned with the fertilisation of crops in order to ensure production and possibly to increase yields (Fraser et al. 2013; Styring et al. 2017).

The plant and animal building blocks of LBK subsistence systems and the productive outcomes of those systems appear at first glance to have been remarkably homogenous across Europe (Manning et al. 2013b). Although recent studies have highlighted some difference between sexes, with males apparently consuming more protein than females, within the LBK sphere (Bickle and Whittle 2013), ancient DNA analysis has reinforced the traditional image of the LBK as the outcome of monolithic demic and cultural diffusion with little inherent diversity (Bramanti et al. 2009; Lazaridis et al. 2016). The apparent uniformity of LBK subsistence practices is surprising given that LBK groups inhabited assorted habitats ranging from riverine valleys with sparse woodland stands to dense mixed deciduous or alpine forests that bristled with swamps. Furthermore, these landscapes were set across a variety of climatic zones, which follow a general gradient of increased precipitation from east to west and decreased summer temperatures (Bogucki 1988; Kreuz 2007). It is likely that animal husbandry and agricultural practices, including pasturing and foddering, timing of animal breeding and crop planting, were shaped to local environments across the LBK cultural zone, but, to date, these key practices remain largely unexplored for LBK societies. Stable isotope analysis of animal and plants provides an important tool for characterising animal husbandry and agricultural practices and identifying potential articulation points between livestock herding and plant cultivation (Bogaard et al. 2013; Fraser et al. 2013; Styring et al. 2017). The data produced from stable isotope analysis can help us understand about how these practices were influenced by the size of farming population, their subsistence needs and the resource availability, including arable land as well as animal pasture (Ebersbach 2013) across time and space.

Here, we examine LBK animal pasturing and foddering strategies and their impact on agricultural activities at Vráble–Veľké Lehemby (Slovakia; 5250–4950 cal BC) through stable carbon and nitrogen isotope analyses of animal bone and cereal grain remains. Specifically, we examine the degree to which LBK agriculturalists grazed their animals in open and/or forested environments and whether cultivation and herding practices are detectable in bone collagen carbon and nitrogen isotopes of herbivorous species (Ambrose and Norr 1993; Jim et al. 2004). The results of this study will help build a picture about pasturing and foddering practices and its articulation with agricultural activities in the Western Carpathians, which will further our understanding of human–environment interactions during the LBK.

Background to the study

LBK subsistence practices and environment interactions

Mixed deciduous forests covered much of the central and northern European region during the sixth millennium BC (Kalb et al. 2003; Nielsen et al. 2012). These forested environments varied in density and composition depending on local topography, hydrology and soil conditions, making some areas, such as river valleys and floodplains, more attractive to settlement than thickly forested hills sides (Kalb et al. 2003; Kreuz 2007; Zanon et al. 2018). Openings within the canopy may have been caused by natural processes, such as lightning strikes, browsing by wild herbivores and rooting by wild boar (Vera 2000), and hunter-gatherer groups, who may have practised woodland management to encourage the proliferation of game and nut- and fruit-bearing plants (Caseldine and Hatton 1993; Innes and Blackford 2003; Simmons 1996). The earliest LBK communities were established in forest clearings as indicated by changes in woodland composition and weed seed assemblages recorded in pollen and
archaeobotanical archives (Bogaard 2002, 2005; Kalis et al. 2003). Openings within the forests were exploited to establish LBK settlements, small-scale garden plots and animal herds (Bogaard et al. 2013; Kreuz 2007; Saqalli et al. 2014), and, eventually, farmers expanded these areas with selective harvesting of trees for fuel, construction material and tools. Small-scale garden plots and animal husbandry required high labour and resource inputs per unit of land to ensure success, which is a typical mode of production for family groups with a resilient subsistence base (Bogaard 2005; Ebersbach 2013). In addition to domesticated animals and plants, local environments were exploited for hunting and collection of wild foods during the LBK. In general, deer, wild pigs and aurochs were the most commonly exploited wild species with their frequencies in faunal assemblages usually no greater than 10% (Lüning 2000). There are exceptions, for example during early phases of the LBK in Austria and Hungary, and throughout the LBK period in Southern Germany and Alsace, wild fauna can account for as much as 50% (Döhle 1993; Tresset and Vigne 2001). Intensive hunting of wild prey may reflect both LBK settlers opening up and exploiting dense forested environments.

The introduction of domesticated livestock into forested environments would have further shaped their density and composition, and this, in turn, together with open pasture availability, likely influenced the range and characteristics of animal management strategies used by LBK herders. Historically, European forests have been important resources for animal pasture, pannage and fodder (Austad 1988; Read 2003) with the earliest direct botanical remains from trees found in animal dung from Swiss lake village contexts dating to the fifth millennium BC (Rasmussen 1993). To maintain herds and flocks throughout the winter, fodder would have likely been stockpiled throughout the year and collected from several sources including the forest and agricultural by-products (Gregg 1988; Saqalli et al. 2014). Detailed stable isotopic analysis of LBK faunal assemblages from Vaihingen an der Enz and Bischoffsheim, located in southern Germany and eastern France, respectively, has shown that cattle were pastured in forests and/or foddered on tree fodder or ‘leafy hay’ while small stock including pigs were kept within the settlement (Fraser et al. 2013; Gillis et al. submitted). Stable isotope analysis of carbonised cereals from Vaihingen and Viesenhäuser Hof (southern Germany) indicates that crops received a high input of manure (Fraser et al. 2013; Styring et al. 2017), which suggests use of penning strategy where animals are either allowed access to cultivation plots during fallow periods allowing for easy application of manure to fields or carolled facilitating the collection of animal dung. Penning animals on cultivation plots would have simultaneously provided animals with graze from the stubble of crops while ensuring the manuring of plots for the following growing season. Crop stubble or cereal by-products could be used as a source of fodder or post-harvest graze to cover shortages in open pasture due to over-grazing or snow cover (Saqalli et al. 2014).

We would expect LBK farmers to have adapted pasturing/foddering practices in response to local landscapes. The nature and extent of this interaction between LBK farmers and their animals with their surrounding environment would vary across central and north-western Europe given the variety of habitats encompassed by within the cultural zone. However, our present understanding of LBK crop cultivation and animal husbandry practices is one where there is homogeneity in management practices between communities (Kreuz et al. 2005; Manning et al. 2013a). Domesticated species, such as cattle, sheep and pigs, are often considered as a single group when in reality these species have different productive lifecycles and physiologies, which can result in diverse husbandry strategies. Coupled stable isotope analysis of botanical and faunal remains can help us understand the articulation between animal husbandry and plant cultivation. Furthermore, it can help generate detailed information about LBK land use and help us understand adaption of farming practices to forested environments.

The LBK settlement of Vráble and its paleoenvironmental context (Fig. 1)

Vráble is one of the largest LBK settlements so far identified in central Europe, with over 313 house structures in an area of ca. 50 ha (Fürholt et al. 2014, 2020; Müller-Scheeßel et al. 2020). It is located in Nitra region and lies on the northern edge of the Danube plain in south-western Slovakia (Fig. 1). The site is partitioned by a small brook, Kováčovský potok, which flows into Žitava. This is one of several rivers connecting the mineral and stone raw material-rich northern Carpathians with the Danube, an important axis of communication in central Europe. The site consists of three spatially distinct neighbourhoods of similar size (named after their cardinal direction: North (N), South-east (SE) and South-west (SW)), separated from each other by the brook and a ditch-system that encircles the SW neighbourhood of the settlement. Radiocarbon determinations (n = 99) date the site from 5250 to 4950 cal BC, spanning the entire late LBK-Želiezovce phase, and indicate that the three neighbourhoods were more or less contemporaneous with each other (Meadows et al. 2019). The neighbourhoods consisted of the typical LBK-style post-built longhouses, which are grouped into individual yards, which measure an average of 0.5 ha and consist of several, non-contemporary houses and pits of different functions. The most important ones are the so-called lateral long pits, which usually flank both sides of each longhouse. These yards are interpreted as individual households, with a trans-generational transfer of the yard-space. The
majority of material culture was obtained from the lateral long pits, which appear to have served as middens, and included pottery and burnt clay, chipped stone and bone artefacts as well as ground stone artefacts, such as millstones, rubbing stones or adzes.

The landscape of the Nitra region at present is characterised by plains, undulations and low foothills of the Western Carpathians and is dissected by the northern Danube tributaries (Fehér 2019: 2–3). These low-lying areas are characterised by thermophilous oak (Quercus pubescens) and maple (Acer tataricum) forests, locally with ash (Fraxinus ornus) or hornbeam (Carpinus) and sporadic patches of grassland. Alluvial zones are covered by elm (Ulmus) woodland and willow-poplar (Salix-Poplar) floodplain forests along the watercourses. Higher elevations and sub-mountain areas are occupied by beech forests, with meadows in forest clearances. Oak forests support rich understorey composed of shrubs and herbs, whereas riparian vegetation also includes herbaceous flora, such as sedges (Carex sp.), grasses and floating-leaf plants (Fehér 2019; https://geo.enviroportal.sk/atlassr/). Nowadays, much of the area is deforested, open field landscape, with grain and root crops grown in the plains and vineyards in the foothills (Fehér 2019: 5, 9). Today, the overall climate is predominantly warm and dry with annual precipitation averaging 500–600 mm with mild winters (3 to −2 °C), especially in the lowlands.

The anthracological archive retrieved from the three Vráble neighbourhoods (Schroedter in press) was composed mostly of the remains of halophilic oak (Quercus) and ash (Fraxinus), pointing to the presence of mixed deciduous forests with a more-or-less open canopy in the vicinity of Vráble. There were traces of light-demanding trees, such as hazel (Corylus), pine (Pinus) and cherry (Prunus), and also taxa that grow in moist areas, including alder (Alnus), poplar (Populus) and elm (Ulmus). The range of represented arboreal taxa at Vráble fits well into the picture of the vegetation of central Europe during the Atlantic period, which has been suggested to be a combination of relatively open mixed oak woodland and riparian vegetation (Magyari et al. 2010; Moskal-del Hoyo 2013). The landscape surrounding Vráble may have also consisted of dry grasslands as indicated by the continuous presence of non-arboreal pollen dating to around 7150 cal BP in the core taken near Santovka, 35 km east of Vráble (Šolcová et al. 2018) as well as by the evidence of persistent non-forest vegetation elsewhere in the Carpathian Basin (Magyari et al. 2010; Pokorný et al. 2015).

Sediment samples were floated from all features for paleobotanical remains. Botanical density (i.e. number of items per litre of soil) was extremely low, even from midden deposits from long pits. The low recovery of plant remains may be due to post-depositional disturbance and/or taphonomy (Filipović et al. in press). However, it is likely, based on their ubiquity in midden deposits, that the inhabitants of Vráble farmed cereal and pulse crops, primarily einkorn (Triticum monococcum) and emmer (T. dicoccum), with barley (Hordeum vulgare), free-threshing wheat (T. aestivum/durum/turgidum), lentil (Lens culinaris) and pea (Pisum sativum) were also cultivated albeit possibly
in smaller quantities. Wild edible nuts and fruit, such as hazelnut (Corylus avellana), wild strawberry (Fragaria vesca) and Chinese lantern (Physalis alkekengi), were also exploited. The weed flora indicate that crop fields were intensively managed, as suggested from previous analysis of botanical remains from LBK sites (Bogaard 2004). The most common arable weeds in the assemblage, fat-hen (Chenopodium album), black bindweed (Fallopia convolvulus) and false cleavers (Galium spurium), indicate high soil disturbance as well as fertile conditions characteristic of intensively managed small permanent arable plots where the cultivation regime would have included tillage (probably by hand), weeding and manuring (Bogaard 2004, 2005). Previous analysis of botanical remains together from Vaihingen an der Enz demonstrated differences between ‘clans’ or neighbourhoods in terms of crop cultivation and to a lesser extent animal husbandry (Bogaard et al. 2016). However, no difference in terms of domesticated crops and weed seed frequencies has been detected between neighbourhoods at Vráble.

A total of 1741 animal bone specimens were recovered from pits associated with 22 separate LBK longhouses located in different areas of the site. Domesticated livestock formed the foundation of the animal-based subsistence economy at Vráble. Pigs were the most commonly identified species (NISP = 180), followed by sheep/goat (NISP = 154) and cattle (NISP = 149) (Table 1). This contrasts with other LBK settlements in Slovakia where cattle overwhelmingly dominate faunal assemblages, followed by sheep/goat and pigs (Bickle and Whittle 2013). Meat production appears to have been the primary focus of stockherders, with all domestic species slaughtered within the first and third year of life (Eckelmann et al. in press). The evidence for dairying is not conclusive, although some cattle survived past 6 years, which may represent slaughter of non-productive females. Overall, the material was poorly preserved and fragmented (Table 1).

### Materials and methods

#### Carbon and nitrogen isotope mechanics

##### Carbon isotopes

The carbon isotopic compositions of flora ingested by livestock are influenced by photosynthetic pathway, water availability and forest canopy cover (Ambrose and Nør 1993; Jim et al. 2004). C3 plants exhibit a global δ13C mean of −26.5 ± 2.0‰ (range −38 to −22‰; O’Leary 1988; Smith and Epstein 1971; Tieszen 1991; Vogel 1978) while C4 globally average −12.5 ± 1.0‰ (range −6 to −19‰; O’Leary 1988; Smith and Epstein 1971; Tieszen 1991). The western Carpathian region was at the time of the site’s occupation characterised by a range of environments supporting primarily C3 biomes, including pine and mixed broad-leaf forests, while open forest-steppe conditions consisting of scattered woodland stands in areas covered by grasses and forbs may have also contained C4 plants, such as those from the grasses family (Poaceae sp.) (Collins and Jones 1986).

In C3 plants, the isotope fractionation of carbon isotopes largely takes place during the carboxylation process, which is directly affected by light intensity which impacts stomata conductance (Arens et al. 2000; Farquhar et al. 1989b; Van der Merwe and Medina 1991). In European forested temperate environments, canopy density substantially influences the stable carbon isotope composition of understory floral growth (Van der Merwe and Medina 1991; Vogel 1978), with understory plants exhibiting δ13C values of ca. −31.5‰. This is due to a combination of 13C depletion of atmospheric CO2 under the canopy caused by CO2 respired by decaying organic matter (Tieszen 1991) and low light intensity at the forest floor decreasing photosynthesis efficiency (Farquhar et al. 1989b; Van der Merwe and Medina 1991). The carbon isotope ratios of C3 floral growth increases, between 1 and 6‰, with an opening up of the forest canopy depending on canopy density (Arens et al. 2000). Consequently, animals browsing and grazing under heavy forest canopies will exhibit low carbon isotope values in their skeletal tissues. Contemporary wild herbivores feeding in minimally managed mixed deciduous forest in temperate environments in both Poland and France exhibit bone collagen δ13C values ranging between −26 and −23‰ (Drucker et al. 2008). Forest type also appears to impact floral δ13C values. For example, red deer (Cervus elaphus) feeding in mixed deciduous English woodlands exhibit dietary values of −23.9‰ ± 2.2‰ in comparison to a mean value of −22.8‰ ± 1.3‰ for animals gazing in a coniferous plantation where undergrowth browse was likely limited.

### Table 1

| Species                     | SW | SE | N  | Total |
|-----------------------------|----|----|----|-------|
| Bos sp.                     | 55 | 61 | 35 | 151   |
| Sus sp.                     | 38 | 70 | 73 | 181   |
| Ovis aries/Capra hircus     | 39 | 73 | 42 | 154   |
| Canis sp.                   | 0  | 1  | 10 | 11    |
| Capreolus capreolus         | 2  | 1  | 4  | 7     |
| Cervus elaphus              | 2  | 1  | 1  | 4     |
| Lepus europeus             | 4  | 0  | 4  |       |
| Valpes vulpes               | 0  | 1  | 1  | 2     |
| Perditis perdix             | 0  | 1  | 0  | 1     |
| Total NISP                  | 140| 209| 166| 515   |
| Unidentified                | 612| 308| 308| 1229  |
| Total                       | 752| 517| 474| 1743  |
and graze on the edge of the plantation was more readily available (Stevens et al. 2006).

The stable carbon isotope composition of plants is also influenced by water availability. During periods of water stress, low humidity and soil moisture, plants reduce stomatal conductance in order to conserve water resulting in lower discrimination against $^{13}$C (Arens et al. 2000; Farquhar et al. 1989a; Tieszen 1991). In temperate environments, seasonal variation in soil moisture conditions imparts a 1% enrichment in $^{13}$C hair values of herbivores from winter to summer (cattle pastured in Germany, $-26$ to $-25\%$) (Schnyder et al. 2006). In water-inundated areas, such as swamps and river flood plains as well as riverbanks, the variable hydrological conditions can have different effects on the $^{13}$C values of plant communities (Cloern 2002; Fan et al. 2018; Tieszen 1991). The foliar $^{13}$C values in seasonally inundated areas will exhibit low values in comparison to dry areas. However, in frequently waterlogged areas, values have been observed to increase because of stomatal closure and less discrimination against $^{13}$C. During periods of prolonged flooding events, the $^{13}$C values may decrease due to a combination of decreased photosynthetic ability as well as stomatal closure (Fan et al. 2018).

**Nitrogen isotopes**

Stable nitrogen isotope composition of livestock bones and teeth can provide insights into management strategies, such as weaning (Balasse and Tresset 2002; Gillis et al. 2013) and winter pasturing (Makarewicz 2014, 2015), while $^{15}$N of cereal grains and pulses has been used to investigate prehistoric manuring practices (Bogaard et al. 2013; Fraser et al. 2013; Styring et al. 2014). Nitrogen isotope values in producers and consumers exhibit a c. $3\%$ stepwise enrichment between diet and herbivore consumers (Sponeimher et al. 2003b; Vanderklift and Ponsard 2003) but this can vary between 1 and $6\%$ in other organisms (DeNiro and Epstein 1981; Minagawa and Wada 1984; Schoeninger and DeNiro 1984; Sealy et al. 1987). This variation is in part due to the studied species trophic position, i.e. carnivore, omnivore or herbivore, as well as related to ecosystem (marine/terrestrial), (Schoeninger and DeNiro 1984), local climate and water availability (Heaton et al. 1986).

Soil nitrogen isotope ratios are influenced by physical and biological processing of organic and inorganic N compounds that take place in soils (Knoepp et al. 2015). Compounds containing $^{14}$N are lost through leaching, denitrification and volatilisation resulting in $^{15}$N enrichment in remaining organic matter (Knoepp et al. 2015). Environmental factors have the greatest influence on soil $^{15}$N values, such as mean annual rainfall and temperature, which are intrinsically linked to geography and topology. European temperate forest soils undisturbed by deforestation or farming activity, such as grazing and tillage, yield low $^{15}$N soil values ($-6$ to $0.6\%$) reflecting wet and cool conditions where little $^{14}$N is lost through leaching and denitrification (Handley et al. 1999; Martinelli et al. 1999).

Nitrogen is fixed in plants from the atmosphere directly or indirectly. $N_2$ fixing plants, such as legumes, convert atmospheric $N_2$ to ammonia and in general exhibit $^{15}$N values of around $0\%$ reflecting atmospheric $N_2$ (Ambrose and DeNiro 1989). In contrast, non-fixing plants, which include cereals and most tree species, rely solely on sources of fixed N derived from decomposed plant and animal matter, and activity of nitrogen-fixing microorganisms (Handley et al. 1999). Within these plants, $^{15}$N values vary widely between and within species, reflecting physiological differences that impact the degree of N assimilation by plant roots and shoots and subsequent translocation and reduction processes, local differences in soil N and abiotic factors including aridity and salinity (Amundson et al. 2003; Liu et al. 2014). The latter factors can lead to $^{15}$N-enrichment due to increased denitrification favouring the loss of $^{14}$N (Ambrose and DeNiro 1989; Handley et al. 1999). The incorporation of manure into the soil N cycle can lead to an increase in plant $^{15}$N values by 4 to $9\%$. This is because manure is enriched with $^{15}$N due to the loss of $^{14}$N by the animal during digestion and excretion (Robbins et al. 2005). Therefore, the nitrogen isotopes of cultivated plant remains can indicate quality of agricultural soils and manuring practices (Bogaard et al. 2013; Fiorentino et al. 2014; Fraser et al. 2011). There is a clear link between manure and high $^{15}$N values in cereals, with the magnitude of this effect relative to the quantity of manure applied to fields (Bogaard et al. 2007; Fraser et al. 2011). For example, previous experimental work has demonstrated that crops grown without manure yield low values averaging $2.5\%$ compared to crops subjected to under long-term manuring regimes receiving c. $35$ to $37$ t per hectare (t/ha) per annum of dung, yielding nitrogen isotope ratios averaging $6\%$. Crops grown under low levels of manuring regimes (20 to 30 t/ha) produced $^{15}$N values of between $2.5$ and $6\%$ (Fraser et al. 2011).

**Sample selection and preparation for stable carbon and nitrogen isotope analysis**

**Faunal remains**

To investigate animal dietary intake at Vráble, bone samples were taken from 45 domesticated animal bones (Bos taurus, $n = 20$; Ovis aries/Capra hircus, $n = 13$; Sus sp., $n = 12$ (SDATA 1)) from each of the three settlement areas. Only specimens exhibiting fused epiphyseal ends typical for older juvenile and mature animals were analysed in order to ensure suckling did not impact isotope values. Suckling can increase stable nitrogen isotope values and, to a lesser extent, stable carbon isotope values due to infants consuming a protein-rich
diet via the mother’s milk, resulting in a trophic level positioned one step higher than that of the mother (Balasse and Tresset 2002; Gillis et al. 2013).

Bone collagen was extracted from the bone samples following Tuross et al. (1988) using EDTA (0.5 M; pH 7.5) solution. Small bone samples were soaked in 10 ml EDTA until complete decalcification, then the samples were rinsed in ultra-pure distilled water several times then rinsed in 0.1 M NaOH. Extracted collagen was left to soak overnight at 10 °C in distilled water and rinsed again five times in ultra-pure distilled water and then freeze dried. Bone collagen samples (800–1200 µg) were analysed for carbon and nitrogen isotopes on GVI IsoPrime and a Eurovector elemental analyser (Flash 2000) interfaced with a mass spectrometer (DeltaV Advantage). The mean analytical precision estimated based on 3 alanine standards for δ15N analyses was ±0.8‰, and for 13C analyses, 0.02‰. Cereal grain samples were analysed at the Service de Spectrométrie de Masse isotopique du MNHN (SSMIM, Paris) using an elemental analyser (Flash 2000) interfaced with a mass spectrometer (DeltaV Advantage). The mean analytical precision estimated based on 13 alanine standards for δ15N analyses was 0.06‰ and for δ13C analyses was 0.07‰. The offset between diet and animal/human δ13C values depends on the tissue under study such as bone collagen, bioapatite (Jim et al. 2004; Sponheimer et al. 2003a), digestion physiology, the ratio between C4 and C3 plants in the diet (Codron et al. 2011), and the ratio of marine versus terrestrial protein in the diet (Schoeninger and DeNiro 1984). The enrichment between diet δ13C values and herbivore bone δ13C values collagen has been proposed to between 5.1 and 5.3‰ (Ambrose and Norr 1993; Jim et al. 2004; Sponheimer et al. 2003a). We will use 5.1‰ to be comparable to previous stable isotope studies of LBK faunal material (Berthon et al. 2018). The trophic enrichment factor between diet δ15N and animal δ15N values is 3‰ following (Schoeninger and DeNiro 1984; Sponheimer et al. 2003b; Vanderkift and Ponsard 2003).

### Cereals

Cereal grains of emmer (T. dicoccum) and einkorn (T. monococcum) wheat selected for stable carbon and nitrogen isotope analysis were recovered from five houses: Houses 102 and 131 in the SE neighbourhood, houses 258 and 262 in the N neighbourhood and house 39 from the SW neighbourhood (SDATA 2). Grains δ15N values vary up to 3‰ within a single ear (Nitsch et al. 2015). Therefore, five or more grains for each species were selected from the houses and aggregated into a single bulk sample for each house. This was to reduce the potential over- or under-representation by single grains (Nitsch et al. 2015).

Pre-treatment of carbonised seeds using an acid–base–acid sequence or acid alone at applied at a variety of temperatures do not significantly impact stable isotope results, although acid–base–acid protocols lead to considerable sample loss (Brink kemper et al. 2018; Vaiglova et al. 2014b). We chose a gentle acid protocol to remove exogenous carbonates as samples grains exhibited no observable sediment contaminants under a microscope. Bulk samples were prepared by first soaking carbonised seeds in aqueous 0.5 M HCl for 30 min or until effervescence ceased at room temperature. Samples were then rinsed three times in ultra-pure distilled water and homogenised using a pestle.

Carbonisation causes loss and breakdown of proteins, lipids and carbohydrates (cellulose and starch) and shift in vivo δ15N and δ13C values in carbonised seeds. Charring experiments have proposed several offset values for δ15N values from 1.1‰ (± 0.4) (Fraser et al. 2011) to 0.3‰ (± 0.5) (Nitsch et al. 2015). This discrepancy is due to the variation in temperature and charring time applied to seeds in each of these experiments. We will use the most recent calculated offset value of 0.3‰ as it considers different possible variations in temperature and time and its impact on δ15N values. The offset between grain δ15N values and rachis values is 2.4‰ (± 0.8) (Fraser et al. 2011). An offset value of 0.1‰ (± 0.1) will be used for δ13C values (Nitsch et al. 2015).

Statistical analyses were carried out using PAST (Hammer et al. 2001), and where the total sample sizes were less than 30, we used non-parametric tests (Dytham 2003).

### Results

#### Faunal isotopic results (Fig. 2)

Collagen yields from bone specimens ranged between 12.0 and 2.0% (Table 2). All samples with the exception of one sample (7154) yielded well-preserved collagen (20 to 0.5%), with CN ratio (3.1 to 3.5), %C (26 to 40%) and %N (11 to 16%) that fall within the ranges established by van Klinken (1999) for well-preserved collagen.

The δ13C values for all sampled animals range from −21.8 to −16.0‰. Bos sp. exhibit an average δ13C of −20.1 ± 0.4‰ (range, −20.7 to −18.9‰, n = 18) while the average for Ovis/Capra was −20.3 ± 0.5‰ (range, −21.3 to −19.3‰, n = 13) and for Sus sp. −20.7 ± 0.5‰ (range, −21.6 to −19.8‰, n = 12). Bos was enriched on average −0.6‰ in δ13C relative to Sus (Mann–Whitney, = 0.002). There was no significant difference in the isotopic composition of livestock species between different neighbourhoods, probably due to the small sample size. Welsh’s t-test returned non-significant results.
### Cereal stable isotope results

The C to N ratios (24.1 to 18.2) and %C (59.7 to 52.6) and %N (3.6 to 2.8) values were consistent with previous reported values from carbonised archaeological cereal grains (Fraser et al. 2013; Vaiglova et al. 2014a) (Table 3). For the emmer samples, δ\(^{13}\)C values averaged −23.5 ± 0.5‰, and for the einkorn samples, −23.6 ± 0.3‰. There is little carbon isotopic difference observed in charred seed remains recovered from different neighbourhoods nor are there isotopic differences between crop species.

The average δ\(^{15}\)N values overall, adjusted for the charring effect, for emmer samples was 6.6 ± 1‰ and for einkorn samples was 6.9 ± 1‰ (Table 3). Einkorn grains from the northern neighbourhood have the highest δ\(^{15}\)N values (7.9 ± 0.1‰ (n = 2)), which were between 1.5 and 2.1‰ higher than those from the SE and SW neighbourhoods. While emmer grains from the south-eastern neighbourhood, on the other hand, had the highest δ\(^{15}\)N values (7 ± 1.2‰ (n = 2)). These are between 0.3 and 1.3‰ higher than those from the N and SW neighbourhoods. The estimated δ\(^{13}\)N average for chaff for emmer, using the 2.4‰ offset, was on average 4.3 ± 1.0‰ and for einkorn was 4.6 ± 0.9‰.

### Discussion

**Vráble livestock foddering/pasturing from the perspective of carbon isotopes**

The striking lack of difference in the carbon isotope ratios within and between sheep/goat, pigs and cattle at Vráble suggests all livestock ingested broadly plants growing in similar environments. This strongly suggests a highly generalised husbandry system was employed that did not apply species-
specific pasturing or foddering regimes. Species-specific foddering regimes may have been practiced by LBK farmers in north-western Europe, with cattle pastured in forests while small stock remained within the settlement. This strategy was possibly developed to provide for large herds of cattle and/or the lack of available open pasture. In this area, there is strong stable isotopic evidence for forest pasturing and leafy hay based on cattle bone collagen $\delta^{13}C$ values lower than $-22\%$ (Gillis et al. submitted), based on a study of Scandinavian Aurochs browsing with forested environments (Noe-Nygaard et al. 2005). Using this baseline, Vráble livestock $\delta^{13}C$ values ($-21.8$ to $-16.0\%$) do not appear to support closed canopy forest pasturing at the site. It is possible that livestock from Vráble were pastured within an open forested landscape or foddered with fodder resources from open forests. However, further compound-specific analysis of amino

![Fig. 2 Stable isotope results for Vráble: a Mean values for Bos with outlier 7158 removed, Ovis/Capra and Sus sp.; Bos results for each settlement with outlier 7158 removed; b Ovis/Capra results for each settlement; c Sus sp. results for each settlement.](image)
acids, which can directly demonstrate woody plant consumption (Kendall et al. 2018, 2019), is needed to confirm leafy hay foddering. Thus, we cannot confirm or rule out the use of forests as pasture or their resources for foddering at Vráble.

Comparison of stable carbon isotope results from Vráble with a dataset containing 17 roughly contemporaneous sites from across the LBK cultural zone (Fig. 1; SDATA 3) reveals little diversity in small stock diet in terms of δ13C values across these different regions. For example, sheep/goat from Vráble exhibit similar δ13C values with those reported from proto-LBK in the Carpathian Basin (TLP and Alföld linear pottery (ALP), −19.9 ± 0.4‰, N = 3) and LBK settlements in other regions of central Europe (−20.2 ± 0.6‰, N = 8) and north-western Europe (−20.6 ± 0.4‰, N = 5) (Fraser et al. 2013; Gillis et al. submitted; Hedges et al. 2013; Oelze et al. 2011). This is also seen to a lesser extent in pigs (Carpathian Basin, −20.3 ± 0.5‰; central Europe, −20.5 ± 0.3‰), except Vráble pigs had values an average 0.4‰ higher than those from north-western Europe (−21.1 ± 0.5‰; ANOVA p < 0.005; Vráble ~ north-western Europe: Tukey pairwise, p = 0.01). This may be a reflection of forests being used for pannage in this region.

Statistical analysis shows Vráble cattle δ13C values were significantly different than cattle from central and north-western Europe (ANOVA p < 0.005; Tukey test: central Europe ~ Vráble, p = 0.001; north-western Europe ~ Vráble, p < 0.005) whereas there was no difference when compared with proto-LBK (ALP/TLP) sites south of Vráble in the Carpathian Basin. This suggests Vráble cattle and those from the Carpathian Basin (average, −19.9; range, −21.6 to −17.0‰) were pastured and foddered on plants within similar open environments. There is a clear 2.3‰ decrease in δ13C bone collagen values visible in LBK cattle from the riverine environments of Carpathian Basin to the more densely forested environments of eastern France and southern Germany. We propose that this clear environmental imprint is a direct reflection of the cattle pastures and resources used for fodder. Here, and in a large-scale regional analysis, the stable isotopic evidence suggests that there are variations in terms of cattle pasturing/foddering practices across the LBK cultural zone (Gillis et al. submitted), although it remains to be seen whether this is the result of local adaptive response to environment and availability of pasture or diversity within LBK cultural subsistence practices.

Evidence for manuring: Perspectives from the cereals

Cereal grains from Vráble exhibited high δ15N values suggesting fields were manured. In comparison to previous stable isotopic studies, cereal grains from Vaihingen (Fraser et al. 2013) were c. 2.3‰ (einkorn) and 2.4‰ (emmer) lower in δ15N than those from Vráble while those from at Viesenhäuser Hof (Styring et al. 2017) were 1 to 0.2‰ lower. Grains from long-term experiments (>100 years) where manured plots received c. 20 t/ha of animal manure biennially, yielded δ15N values ranging between 2.7 and 5.7‰, whereas cereals under long-term or intensive manuring regimes yielded δ15N values greater than 6‰ (Bogaard et al. 2013). Consequently, at Vaihingen, cereal δ15N values were interpreted to be the result of low level manuring of about 10–15 t cattle manure per hectare using a conservative estimate of 5 t per animal (Fraser et al. 2013). In the case of Viesenhäuser Hof, it was proposed that cultivation plots were under a more intensive manuring regime, for example, 35 t/ha per annum (Styring et al. 2017). The considerable 15N enrichment in Vráble cereals suggests cultivation plots received high levels of manure. This may have been the result of manure being collected from pastures or by penning animals directly on cultivation plots. Penning animals on agricultural plots to feed upon crop stubble or by-products would have led to animal dung being contained within an area and reduced the need for collection. Small-scale garden plots requires high labour so penning animals on cultivation areas would have potentially reduced the labour output needed for collecting manure. Combined archaeobotanical and stable isotopic analysis at Vaihingen has indicated that some clans/households had access to manured fields (Bogaard et al. 2013) perhaps fertilised by animals kept within the settlement. While this differentiation between neighbourhoods is not evident at Vráble, future excavation and stable isotopic analysis of cereals may elucidate differences and similarities in animal-crop husbandry systems between communities.

Articulation between herding and cultivation practices

Livestock δ15N values ranged from 6.8 to 11.7‰ with ruminants exhibiting the highest values. When these results are examined within the regional context, Vráble cattle δ15N values were found to be statistically different than those from sites in other regions (ANOVA, p < 0.05). Furthermore, this is also seen for sheep/goat (ANOVA, p < 0.05) and pigs (ANOVA, p < 0.05). All livestock had higher δ15N values than those from other regions (Tukey tests between all regions and Vráble, p < 0.0001). High δ15N values in pigs reflect in part their omnivore diet, and access to food sources enriched with 15N, such as protein-rich food and human waste (Balasse et al. 2016). However, high δ15N values in herbivores are a direct reflection of the nitrogen isotopic composition of ingested plants. Soil and therefore plants can become enriched in 15N as a result of areas being used for long-term pasture (Makarewicz 2014, 2015). Moderately high δ15N values shared by all Vráble livestock species indicate animals consistently ingested 15N enriched plants within pastures. This may be the result of animals grazing long-term pastures but also may be caused by livestock feeding on crop stubble or by-
products grown within manured fields. The $\delta^{15}$N values for animal fodder were estimated using the offset between diet and herbivores of 3‰. These were compared with the species-specific $\delta^{15}$N values from cereal grains and estimated for chaff (using an offset of 2.4‰ (Fiorentino et al. 2014)) (Fig. 3). The fodder estimates for individual species were not significantly different from the $\delta^{15}$N values from cereal grains (Kruskal–Wallis, $p = 0.35$). However, there was a significant difference between sheep/goat and pig fodder and estimated $\delta^{15}$N values for chaff (Kruskal–Wallis $p < 0.001$). Cattle fodder estimates were not significantly different than values estimated for emmer and einkorn chaff. These results suggest that spent grain or logged cereals were used as animal fodder. A previous analysis at Vaihingen indicated that the animals were mainly fed on wild browse and graze (Fraser et al. 2013) while at Viesenhäuser Hof, animals were fed on cereal chaff/spent grain (Styring et al. 2017). In these studies, the offset between diet and bone collagen was 4‰ in comparison to 3‰ used in this study. If we use the 4‰ offset, there is no difference between the chaff and animal fodder $\delta^{15}$N estimated values (Kruskal–Wallis, $p = 0.1$). There was a significant difference between $\delta^{15}$N values for cereals and animal fodder (Kruskal–Wallis, $p = 0.002$), with pig fodder estimates significantly different from $\delta^{15}$N values for emmer and einkorn grains (Mann–Whitney: ~ emmer, $p = 0.05$; ~ einkorn, $p = 0.05$). Further analysis is needed to determine which offset is the most accurate to use. However, what is clear is that cereal crops and possible by-products were used as animal fodder at the site.

The intensive manuring regimes interpreted from cereal grain $\delta^{15}$N values suggest that Vráble livestock were penned on cultivation plots. The close articulation between crop cultivation and animal husbandry potentially to reduce labour demands is associated with manure collection as well as facilitating collection of other animal products, such as milk. Intensive articulated cultivation-herding strategy may be an indication that the availability of arable land for cultivation was low (Bogaard 2005; Ebersbach 2013), possibly due to geology, such as heavy soils, or differential access for individual clans or neighbourhoods as seen previously at Vaihingen (Bogaard et al. 2016). Over-specialisation may also have exposed LBK farmers to crop failure due to unseasonable weather during the crop cycle. Small herds may not have provided populations within the three neighbourhoods with sufficient resources to cope with subsistence crisis caused by crop failure, potentially leading to inequality and strife between communities (Furholt et al. 2020). Trauma pathologies found within populations in later phases of the LBK has been proposed to be evidence of violent conflict over resources (Golitko and Keeley 2006), and diminished food supplies may have contributed to the eventual ‘collapse’ of LBK societies (Shennan et al. 2013).

**Conclusions**

The use of stable carbon and nitrogen isotope analysis in the investigation of prehistoric animal husbandry and agricultural practices is broadening our understanding of Neolithic subsistence strategies and how these evolved and adapted to different ecological niches and by cultural groups. The analysis of the Vráble faunal and cereal remains makes a significant contribution to enhancing our understanding of LBK crop cultivation and animal husbandry practices. The clear indication that agricultural plots at Vráble were likely supplied with manure demonstrates an articulation between plant cultivation and animal husbandry practices. It appears that all livestock species were pastured in open forest/open areas near the settlement, with cultivation plots used as pasture reducing labour needs for manure collection. The data presented here highlight the importance of stable isotope analysis of cereal grains to gain a nuanced picture of their growing conditions and to provide another dimension to archaeobotanical investigations. Our stable isotopic analysis of domesticated fauna was based on bone collagen, and the attenuation of stable isotope ratios in adult bone means that seasonal variation in foddering and pasture practices is lost. Further incremental analysis of livestock dentine and bioapatite is required to investigate whether plants with high $\delta^{15}$N values was a seasonal fodder suggesting a fodder source connected to crop cultivation or whether...
animals grazed on plants with high δ¹⁵N values all year round thus from long-term pasture use. In addition, detail analysis of livestock teeth from individual neighbourhoods would highlight similarities and variations between communities in terms of seasonality of husbandry practices.

The study contributes to the growing evidence for the existence of diversity as well as flexibility within LBK crop cultivation and stock herding practices. It is clear that Neolithic herding practices have been adapted since their introduction from the Near East into Europe; however, what is not clear is whether this was the result of adaptive response by farmers to local environments or cultural subsistence choices, or a combination of both. Future holistic stable isotopic analysis of plants and faunal from a single culture, such as the LBK, can help determine the important factors underlining this adaptive processes as well as build a more comprehensive picture of early Neolithic subsistence practices. This can be investigated by cross-correlation between detailed datasets of cultural attributes, such as frequencies of lithic technology and pottery styles, with environmental proxies and stable isotopic results from multiple sources including bone collagen, bioapatite and organic residues from ceramics. Together with a detailed chronological framework, this will generate the deep data sets required to trace the evolution of crop and animal husbandry systems, land use and subsistence practices over time and space, increasing our understanding of role played by domesticated plants and animals in shaping Neolithic societies.

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