RESEARCH ARTICLE

Sheep Ahoy: Exploring sheep management and its role in Viking Age economy through multiproxy analyses at Löddeköpinge, Sweden

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Abstract

Sheep and their wool were paramount to Viking Age economies. The importance of wool cannot be underestimated, especially as the woollen sail was implemented on ships in general during this period. This paper investigates sheep management and landscape use in Viking Age Löddeköpinge in Scania, southern Sweden, through a multiproxy approach, integrating multi-isotope methods with zooarchaeological analysis. Using the marketplace at Löddeköpinge as a case study, 18 sheep mandibles were analyzed through zooarchaeological methods and isotope analyses of δ^{13}C, δ^{15}N, δ^{34}S, and ^{87}Sr/^{86}Sr. The results show that the sheep represent a composite deadflock, meaning they probably derive from different liveflocks. The ^{87}Sr/^{86}Sr values demonstrate likely origins north and east of Löddeköpinge. The δ^{13}C and δ^{15}N values indicate a terrestrial diet with variation in δ^{15}N, meaning that some may have grazed on manured fields. The δ^{15}N, in conjunction with δ^{34}S, values show a possible limnic influence, implying grazing on pastures close to freshwater systems; however, this requires further investigation. The results illuminate the marketplace function of Löddeköpinge, as sheep bred north and east of the site were transported and exchanged there. This shows the degree and extent of control of the re-distributional system held by the local elite. This control may be instigated by the increased textile production, especially concerning sailcloth, at the site. If so, sheep management may have been specialized towards the production of optimal wool for sailcloth, besides other essential cloth.

KEYWORDS
^{87}Sr/^{86}Sr analysis, animal mobility, multiproxy archaeology, sheep management, Viking Age Scandinavia, δ^{13}C analysis, δ^{15}N analysis, δ^{34}S analysis

1 | INTRODUCTION

Based on the similarity of material culture and burial traditions, Viking Age (AD 800–1050) peoples in southwest Scania, present-day south Sweden, had cultural affinity with those on Zealand in present-day Denmark (e.g., Svanberg, 2003:144). Although this may not be translated to power over land, it is accepted that parts of Scania were contained within the eastern Danish sphere in the Viking Age. Social upheavals, steering Denmark towards the process of state formation during the late 10th century, changed the royal power and its effect on a regional level in southwest Scania and Zealand. Land ownership became the cornerstone as the power gradually increased over land rather than over people (e.g., Schmidt Sabo & Söderberg, 2019:40–43). Animals, and the husbandry of animals, were paramount for these Viking Age societies. Macheridis (2022a) suggests that mammal husbandry in Scania was predominantly sedentary, tied to the household's impact area. This is based on several variables, one being the flat topography and short distances between different biotopes, for example, wet meadows, coastal plains, and agrarian land. Animal husbandry was, in this scenario, closely organized with agrarian production. An increasing demand for sheep wool has been suggested for the period, in response to various processes of centralization and power consolidation, especially the formation of the Danish kingdom in the Viking Age. Sheep bones and teeth are therefore a valuable source of information on animal husbandry, technology, economy, and society.

By applying a multiproxy approach, using key zooarchaeological variables, especially age, and multi-isotope analysis ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, and $^{87}Sr/^{86}Sr$) on sheep mandibles, we explore mobility and diet of sheep in Viking Age Scania, specifically at ancient Löddeköpinge, Sweden (Figure 1). The applied biomolecular techniques target sheep movement and grazing patterns in early life ($\delta^{34}S$, $^{87}Sr/^{86}Sr$, $\delta^{13}C$, $\delta^{15}N$) and in the years before slaughter ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$). This is discussed in tandem with zooarchaeological variables, mainly slaughter ages, indicating human strategies affecting herd structure.

Viking Age Löddeköpinge makes a good case study because it was a specialized trading site, and as such an important nodal point for the region (Svanberg & Söderberg, 2000). In the 9th–10th centuries AD, its marketplace area was somewhat displaced from the village (Figure 1: *Vikhögsvägen*). The trading function was probably seasonal initially and became more permanent and centralized in the later Viking Age, that is, in the 11th century AD onwards. According to Svanberg and Söderberg (2000:258), the workshops at Löddeköpinge, visible in the remains of many pit houses, were controlled by the power residing in Borgeby castle, located on the other side of the river (Figure 1). The material culture shows that Löddeköpinge was most likely important in the surrounding region, and there was a certain focus on exchange of agricultural goods and production of textiles (Andersson, 2000; Ohlsson, 1976:96).

The Löddeköpinge excavations, concentrated to the second half of the 20th century (Ohlsson, 1976, 1980; Svanberg & Söderberg, 2000), generated large faunal assemblages, which only partly have been zooarchaeologically documented (Johansson, 2000; Macheridis, 2022a:190–196; Macheridis, 2022b). The sheep remains
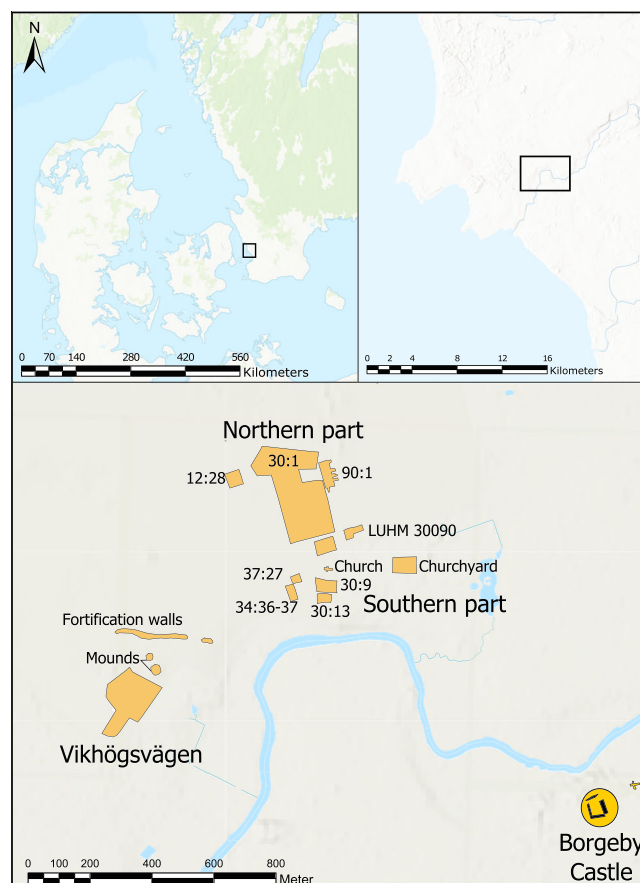
FIGURE 1 Löddeköpinge in Scania, south Sweden. Top left: South Scandinavia, with black box indicating the approximate location of the study area. Top right: Middle west coast of Scania, with black box indicating the location of Löddeköpinge along the Lödde river. Bottom half: excavated areas in Löddeköpinge, and nearby Borgeby Castle, marked in orange, redrawn after Svanberg and Söderberg (2000: 26–27, figs. 2–3) with permission, (C) Riksantikvarieämbetet. Maps made with ArcGIS pro vs. 2.9.0. © ESRI. Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]

of this study are part of the recently re-examined animal bones from the Northern part of Löddeköpinge, collected from floor layers belonging to pit houses. This material consists of 4598 fragments of bone and teeth (~30.4 kg). Being from floor layers, it represents primary refuse, although some bones may have been re-deposited as indicated by generally low inclusions of, for example, weathering (<2.5%, Macheridis, 2022b:9). Bones from all body parts from the most common animals (cattle, sheep/goat, pig) are present, indicating that the material mirrors mixed deposits of food and slaughter waste (Macheridis, 2022b). Opposing the proposed focus on textile production in the pit houses, there was no traceable large-scale production of sheep in Viking Age Löddeköpinge (Macheridis, 2022a, 2022b). The average sheep bone frequency at Löddkeöpinge is 29% of the number of identified specimens (NISP). This is similar to Scanian Viking Age-Early Medieval settlements in general (around 26%). Pig bones are more common with 40% in general (at Löddeköpinge, 38%), followed by cattle (29%, at Löddeköpinge 27%) (Macheridis, 2022a:40–41, 75).

2 | BACKGROUND TO VIKING AGE LÖDDEKÖPINGE AND THE ANIMAL BONES

2.1 | Excavations and site history

Löddeköpinge is located along the Lödde river, about 6.75 km from the coast (Figure 1). Initial excavations in 1965–1968 at the area *Vikhögsvägen* uncovered a large settlement complex. Further excavations of the village center (Northern/Southern parts) in the 1970s and 1990 indicated the large extent of the settlement area (Ohlsson, 1980; Svanberg & Söderberg, 2000). The investigations yielded a wealth of finds in terms of animal bones, ceramic sherds, and parts of or complete artifacts, such as tools of iron, stone or clay, coins, accessories, and weaponry. The pit house, a sunken-floor, often finds-rich, structure, is characteristic of the site. More than 100 pit houses were documented. The northern part of the site was permanently settled, as indicated by more permanent dwellings in the form of long houses. The *Vikhögsvägen* area constituted a possibly seasonal marketplace, as indicated by the pit houses' stratigraphy and the richness in finds. It was not a larger proto-urban marketplace similar to, for example, Åhus or Ribe (Callmer, 1994; see Sindbæk,), but rather a place for exchanging and (re)distributing products (Svanberg & Söderberg, 2000:82). The *Vikhögsvägen* area seems to have been most active around AD 700–950. Afterwards, the marketplace function relocated to the Northern part of Löddeköpinge, which was expanded around AD 950 and onwards. In AD 950–1100, Löddeköpinge grew, and around AD 1000, it functioned as part of the royal and sacred organization (Svanberg & Söderberg, 2000:314). A Christian burial ground with many graves was constructed in the Early Medieval period (Cinthio, 1980). The site's location along the river and closeness to the coast were instrumental for its development as part of the maritime networks at the time (Svanberg & Söderberg, 2000).

2.2 | The pit houses and the animal bones

The materials of the study consists of sheep bone and teeth from the pit houses. The pit house is a common architectural unit in the Late Iron Age Scandinavian area, especially in large settlement complexes, for example, central places like Old Uppsala (Macheridis & Magnell, 2020) or trading sites like Löddeköpinge. The pit house was probably multifunctional and is often discussed as workshop. The occurrence of loom weights in many of Löddeköpinge's pit houses, dated to the Viking Age in general, and the many finds of spindle whorls and other textile-related tools, is evidence of textile production (Ohlsson, 1976:96). Andersson (2000:184) argued that textile production was central to the inhabitants of Viking Age Löddeköpinge. The demand for wool in the textile production system increased in the Late Iron Age, especially since the woollen sails on ships became standard (e.g., Zagal-Mach Wolfe, 2013).

Pit houses were documented from the whole Löddeköpinge complex in different excavated areas. For example, 54 pit houses were documented in Vikhögsvägen (Ohlsson, 1976:76). In total, 34 Viking Age pit houses in Area 90:1 were documented. They belonged to two main settlement phases, AD 800–950 and 950–1100. In the earlier phase, they seem to have been connected to different households, while in the later they belonged to one larger household unit (Svanberg & Söderberg, 2000:44–47; Figure 2). In general, the pit houses contained many finds of several different categories, for example, pottery, slag, and bones. Pit houses belonging to the later phase were more find-rich than the earlier. For example, the features A260 and A261 from the later phase (AD 950–1100) contained 19% of the animal bones from all pit houses (Macheridis, 2022b:25). This seems to mirror the accumulation of refuse, which became greater when the three household units, probably wealthier farms, became integrated to one larger household complex, probably a manor, in the later phase, as suggested by Svanberg and Söderberg (2000:50).

This study focuses on the Area 90:1 in the Northern part, from which animal bones were collected from floor layers in 28 of the 35 pit houses (Figure 2, see Svanberg & Söderberg, 2000:39). These animal bones, together with bones from some other features, were chosen for osteological analysis in the 1990s (Johansson, 2000). In the frame of this research, the need for higher contextual resolution necessitated a re-examination of the bones (Macheridis, 2022b). Floor layers were prioritized for this study because of their contemporaneity with the active usage phase of the pit house. As mentioned, the bones come from primary depositions deriving from consumption and slaughter. With regards to anatomical representation, all body regions (head, axial skeleton, upper and lower extremities) are represented in the material, indicating that whole bodies were handled on site (Macheridis, 2022b: 14, figs. 3–4). The mammalian species identified at the site include cat, cattle, dog, goat, horse, pig, red deer, roe deer, and sheep (NISP: 1163). Some bird and many fish bones were also recorded, testifying to the good preservation and recovery of bone on site; taxonomic lists can be found in Macheridis (2022b:21, 23). The distribution of the three most common taxa, (cattle, pig, and sheep/goat) shows a slight increase of pig bones in the later phase, which is general for the whole Scanian region (e.g., Macheridis, 2022a). It has been connected to increased centralization and the importance of pig rearing symbolically as well as in farming, producing more fodder for pigs and less pasturage for bovids (Macheridis, 2022a:97). Sheep/goat constituted 35% of total NISP in the Viking Age. This decreased in the later Viking Age to 26% (Macheridis, 2022b:13), in favor of pig.

In conjunction to the increased importance of wool (e.g., Andersson, 2000), it is clear that sheep were more economically valuable than visible by bone frequency. The abundances indicate, however, that sheep keeping was not large-scale. Sheep/goat bones and teeth were found in 24 of the 28 pit houses with animal bones in floor layers (total NISP 316). Of these, 42 fragments were identified as sheep, and four as goat. Goat is rarely identified zooarchaeologically in Iron Age settlements, and if so, they are often very few (Macheridis, 2022a:50–52). Conclusively, most sheep/goat bones probably derive from sheep.
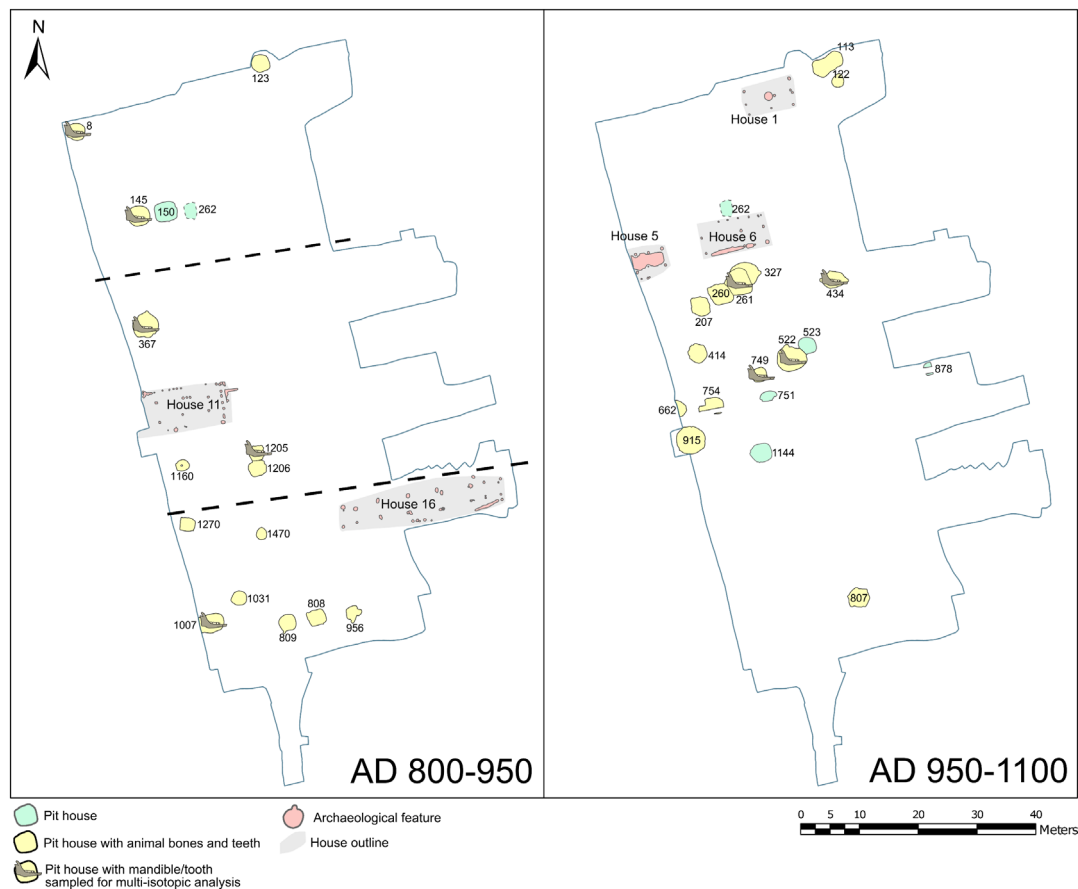
FIGURE 2 Viking age pit houses ($n = 34$) and household units in Löddeköpinge, Area 90:1, as suggested by Svanberg and Söderberg (2000:44–45). Pit houses with animal bones ($n = 28$) are marked in yellow. Nine pit houses with sheep mandibles included in this study are marked with symbolic mandibles. Left: early phase, AD 800–950, with dotted lines delineate the boundaries between household units. Outlines of houses and boundaries are based on fig. 8 by Svanberg and Söderberg (2000:44). Right: later phase, AD 950–1100, based on fig. 10 by Svanberg and Söderberg (2000:45). *Source*: Plan drawings from Svanberg and Söderberg (2000:GISDATA) (C) Riksantivarieämbetet. Maps are made with ArcGIS pro vs 2.9.0 © ESRI. Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]

3 | MATERIALS AND METHODS

From the sheep/goat bone assemblage in Area 90:1, 18 mandibles were chosen for multi-isotope analysis in this study (Table 1). The mandibles were chosen as they had been identified taxonomically by *Zooarchaeology by Mass Spectrometry* (ZooMS), a peptide-based method for taxonomic identification (e.g., Buckley et al., 2010), and because they contained enough complete tooth rows for age assessments. The 18 mandibles were almost all determined to be sheep, rather than goat, with the exceptions of SH7, SH9, and SH19, which probably belong to sheep, and SH21, which remains inconclusive (Holm Jæger, 2020; Macheridis, 2022b). Among the postcranial bones, more suitable for osteological identification, sheep dominate over goat, as mentioned above.

3.1 | Death age assessments

Most of the sheep mandibles contained tooth rows complete enough for assessing age-at-death, following Payne (1973) and Jones (2006).

We assessed slaughter ages using complete tooth rows and incomplete tooth rows (missing maximum two teeth) and certain loose teeth. Similar to Stolle and Magnell (2021), loose lower third molars (M3) and deciduous fourth premolars (dp4) were used as the basis for age assessments, although this strategy produces broader age categories. This process of assessing death ages is approximate, as scoring teeth can be problematic, even if tooth rows are complete. As mentioned, 18 mandibles were sampled for isotope analyses; however, an additional four mandibles were identified and were thus utilized in the reconstruction of mortality. Besides mandibles, the basis for reconstructing slaughter ages is postcranial fusion data, indicating the biological maturity of the skeleton attributed to age. The fusion of the postcranial elements depends also on flock sex structure, level of nutrition, and other factors, besides age of the animal (Popkin et al., 2012). This is important to consider when reconstructing mortality. Fusion data were recorded from only 51 fragments from sheep or goat. As explained above, it is assumed that most belonged to sheep (Macheridis, 2022b). Sex distribution is important for the discussion of sheep management, but very few bones have been sex assessed in the larger sheep/goat assemblage (see

TABLE 1 List of samples.

Sample ID	Pit house	Chronology	Taxon	M/L	Side	Tooth and score	Jones's age class	Estimated slaughter age (focussed ESA)	Sampled tooth
SH1	A1007	AD 800–950	Ovis aries	M	d	M1: 9A M:2 9A M3: All cusps in wear	F5/8-G	2.5–7+ yr (3–6.5 yr)	M1
SH2	A1007	AD 800–950	Ovis aries	M	s	dp4: 18L	D5-E1/2	14–30 m (17–25 m)	dp4
SH4	A1007	AD 800–950	Ovis aries	M	d	dp4: 13L M1 2A M2 C	C1/2	3–5 m (4 m)	dp4
SH5	A1205	AD 800–950	Ovis aries	M	s	P4: 9A M1: 10A M3: 7G	F	2.5–4.5 yr (3–4 yr)	M1
SH6	A1205	AD 800–950	Ovis aries	M	s	dp4: 13L M1: 2A M2: C	C1/2	3–5 m (4 m)	dp4
SH7	A145	AD 800–950	Ovis aries?	M	s	P4: 9A M1: 10A	G	4.5–7+ yr (4–6 yr)	M1
SH9	A261	AD 1000–1100	Ovis aries?	M	d	P4: 14S M1: 12A M2: 9A M3: 11G	G	4.5–7+ yr (4–6 yr)	M1
SH10	A367	AD 800–950	Ovis aries	M	s	P4 12S M1: 12A M2: 9A M3: 11G	G	4.5–7+ yr (4–6 yr)	M1
SH11	A367	AD 800–950	Ovis aries	M	s	P4: 8A M1: 9A M2: 9A M3: 7A	F9/10	3.5–4.5 yr (4 yr)	M1
SH12	A367	AD 800–950	Ovis aries	M	s	dp4: 23L P4: E	E1/2	20–30 m (23 m)	P4
SH14	A434	AD 950–1050	Ovis aries	M	s	dp4: 16L	D5-E1/2	14–30 m (17–25 m)	dp4
SH15	A1007	AD 800–950	Ovis aries	M	d	M1: 11A P4: 12S	F9/10-Ga	3.5–6.5 yr (4.5–5.5 yr)	M1
SH16	A522	AD 950–1050	Ovis aries	M	s	P4: U M1: 9A M2: 8A M3: E	E3+	22–36 m (30 m)	M1
SH17	A522	AD 950–1050	Ovis aries	M	s	P4: 12S M1: 12A M2: 9A M3: 11G	G	4.5–7+ yr (4–6 yr)	M1
SH18	A522	AD 950–1050	Ovis aries	M	s	dp4: 13L M1: E M2: C	B	1–3 m (2 m)	M1
SH19	A749	AD 950–1050	Ovis aries?	L	s	M3: 5A	E1/2	20–30 m (23 m)	M3
SH20	A8	AD 850–950	Ovis aries	M	s	dp4: 16L M1: 8A M2: 2A	D1-4	10–17 m (12–15 m)	M1
SH21	A8	AD 850–950	Ovis/ Capra	L	s	M3: 4A	E3+	22–36 m (30 m)	M3

Note: Age data from Macheridis (2022b). Ages are reported in months (m) or years (yr). Parenthetical "focussed ESA" is equivalent to Jones's "central point" (Jones, 2006:177). Samples derive from Löddeköpinge 90:1, accession no LUHM30166, Historical Museum at Lund University. M/L column refers to M = the tooth sampled was found as part of mandible, and L = the tooth was found as loose tooth. Sorted by sample ID.
Abbreviations: ESA, estimated slaughter age, based on Jones (2006). s = left side (Lat. *sinister*), d = right side (Lat. *dexter*).

Macheridis, 2022b): four iliac fragments, belonging to one female and three males, using criteria from Boessneck (1969:344–347). One may possibly be a castrate, but this remains uncertain, using the method by Hatting (1995:75).

3.2 | Isotope analyses

3.2.1 | $^{87}Sr/^{86}Sr$ isotope analysis

Strontium ($^{87}Sr/^{86}Sr$) isotope analysis is increasingly applied to archaeological studies of animal mobility (Appendix S1). To summarize, the radiogenic ^{87}Sr isotope (both primordial and produced by the decay of radioactive ^{87}Rb, present in most minerals and rocks) is measured against the stable isotope ^{86}Sr. This ratio varies according to age and formation of geological strata. The "bioavailable" strontium, that is, in water and soil, available to plants and animals, has $^{87}Sr/^{86}Sr$ ratios that principally reflects underlying geology. The $^{87}Sr/^{86}Sr$ ratio in tooth enamel, which is the most durable tissue post-depositionally, primarily reflects the period when the enamel matured during the mineralization phase; for sheep teeth, this is generally below or around 1 month (Kohn, 2004:404). The short maturation time for the enamel of small Bovidae signals that the dental development rate generally reflects mineral accumulation, although a 1-month margin of error should be applied to ensure accuracy. The timing of enamel development is different for each sheep tooth. The mineralization of the second and third molars is well mapped (see Table S1). For lower dp4 and P4, only the rate of tooth eruption is known, giving a terminus *ante quem* at best. Dp4 is often erupted in the first month after birth, in wear at 2 months, and replaced by P4 around 22–26 months (Jones, 2006). Thus, the P4 broadly reflects the first 2 years of life.

3.2.2 | $\delta^{13}C$ and $\delta^{15}N$ isotope analysis

$\delta^{13}C$ and $\delta^{15}N$ isotope values primarily reflect sources of dietary protein. Comparisons of collagen and dentine isotope values are useful for understanding potential dietary changes, as dentine does not substantially remodel after the tooth is formed (Balasse et al., 2001). $\delta^{15}N$ is closely related to trophic level, with greater consumption of animal protein generally leading to higher $\delta^{15}N$ values. Suckling animals consequently have higher $\delta^{15}N$ values than their mothers, making it a useful proxy for exploring weaning (e.g., Jenkins et al., 2001). Consumption of marine foods can also cause enriched levels of ^{15}N, due to the long nature of marine food chains (Richards, 2020). Manured soil raises the $\delta^{15}N$ value of plants, and therefore, nitrogen isotope analysis may help identify different grazing landscapes or consumption of plants grown on manured land (see Larsson et al., 2019).

In a temperate northern European context, $\delta^{13}C$ values are useful for detecting potential marine food consumption (e.g., Balasse et al., 2001). While terrestrial plants source carbon from atmospheric CO_2, marine plants rely on dissolved inorganic carbon causing them to be enriched in ^{13}C. Marine organisms, and consequently those that consume them, may therefore have increased $\delta^{13}C$ values. In addition to identifying marine/marine affected plants, $\delta^{13}C$ values show natural landscape variation and therefore are a good proxy for the use of varying pasturage (Stevens et al., 2013). Both $\delta^{15}N$ and $\delta^{13}C$ signatures can additionally be influenced by environmental and climatic factors such as altitude, aridity, the "canopy-effect" ($\delta^{13}C$), and temperature (e.g., Richards, 2020).

3.2.3 | $\delta^{34}S$ isotope analysis

Methionine in the diet is taken up and used for bone collagen synthesis and thus incorporates dietary sulfur into tissues (for a more detailed explanation, see Nehlich, 2015). Therefore, an organism's $\delta^{34}S$ values largely reflect those of the environments from which it obtained its food (Richards et al., 2001), with a limited trophic effect (Nehlich, 2015). Sulfur isotopes are useful in the identification of food sources from terrestrial versus marine or freshwater environments. Marine organisms have $\delta^{34}S$ values close to 20‰, reflecting the relatively uniform value of sea water due to constant ocean mixing (Nehlich, 2015). The so-called "sea-spray effect" can therefore affect coastal regions, whereby ocean spray and precipitation may cause elevated $\delta^{34}S$ values close to that of sea water (Richards et al., 2001). The Kattegatt has a large inflow of freshwater, and archaeological samples of seals from this region have shown low $\delta^{34}S$ values in previous studies (Craig et al., 2006; Göhring et al., 2015). Terrestrial cycling of sulfur is complex and may be affected by local geochemical conditions (Nehlich, 2015). Sulfur isotope analysis is also useful for identifying wetland grazed animals, which tend to produce very low or negative values (Lamb et al., 2023; Madgwick et al., 2023).

3.2.4 | Sampling strategy

Tooth dentine and bone collagen were sampled for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analysis (Appendix S1). Tooth enamel was sampled for $^{87}Sr/^{86}Sr$ analysis. Dentine samples were taken from the roots, except for SH12, which was taken from around the pulp chamber. Enamel samples were preferentially taken from the distobuccal cusp, though other cusps were substituted if required. Early forming teeth (dp4, M1) were sampled near the cementoenamel junction (CEJ). Later forming teeth (P4, M3) were sampled closer to the occlusal surface. A minimum of 20 mg of enamel was extracted per specimen. Where possible, bone samples were taken from the section of mandible already removed for tooth sampling. Exceptions to this were SH6, SH10, and SH 9, where samples were taken from the coronoid process to reduce risk of damage to other teeth in the mandible.

Three different plants from eight locations in and around the Löddeköpinge region were sampled and manually homogenized to provide reference values for $^{87}Sr/^{86}Sr$ and $\delta^{34}S$. Following freeze drying, the three plants from a location were weighed to equal amounts and crushed together to form one sample. Here, although trees may have more radiogenic values than grasses (Johnson et al., 2022; Maurer

et al., 2012), tree leaves were selected as samples as they are less likely to reflect modern anthropogenic contamination than shallow rooted plants (e.g., grasses) or tree cores (Maurer et al., 2012). Grasses (and other shallow rooted plants) have very ephemeral root systems, so their strontium isotope composition will derive from upper topsoil, which is the layer that is least likely to be comparable to archaeologically bioavailable strontium. The sampled trees were not large, so their root systems were not very deep (and most tree root systems spread more laterally than vertically). Therefore, this is more likely to reflect the archaeological horizons and largely avoids the risk of superficial diagenesis of topsoil to a higher degree than grasses. Although beyond the scope of this study, mapping regional strontium and sulfur isotope results in relation to species-specific root depths and geological layer depths would be beneficial to future studies in which tree leaves are sampled. Homogenization, which has become increasingly common for biosphere characterization (French et al., 2024; Holt et al., 2021; Johnson, 2018; Müldner et al., 2022; Appendix S1 for further details) and assessing bioavailability, has advantages and disadvantages and warrants further comment. It risks skewing the single homogenized values through the inclusion of substantial outliers and, without analyzing each plant separately, there is no means by which to assess whether this has had an impact. Still, omitting plants that are identified as outliers through individual analysis is, in any case, potentially flawed in assessing bioavailability; without assessing tens of plants, it is difficult to assess whether they are genuine outliers, or whether the local bioavailable range is, indeed, composed of a diverse range of values. The objective of the program of plant analysis is to provide insights into bioavailability to augment existing data. We seek to characterize the landscape through the analysis of carefully selected plants from "pristine"

landscapes with limited anthropogenic interference. All plants that we analyzed were common in the respective landscapes and therefore considered broadly representative. Any outlying plants that may be included in our analysis are representative of bioavailability and therefore worthy of inclusion. Recent mapping programs for sulfur (Lamb et al., 2023) and strontium (Evans et al., 2022) isotope bioavailability using plants have shown outliers to be rare in single locations, when carefully sampling shrubs and trees from "pristine" landscapes. It is beyond the scope of this program to produce a comprehensive biosphere map of the area, and the homogenized plant method provides a cost and time efficient approach to characterize the local biosphere, but it must be considered an initial insight only, and wider mapping work is required. Further methodological investigations of the homogenized plant approach are needed and should also consider, for example, the concentration measures of both strontium and sulfur isotope ratios.

4 | RESULTS

4.1 | Bioavailable $^{87}Sr/^{86}Sr$ and $\delta^{34}S$: plant baseline results

Crucial to isotope analysis is comparison with an isoscape—a map of the bioavailable strontium—in the region of study (Holt et al., 2021). The understanding of the distribution of $^{87}Sr/^{86}Sr$ ratios in Scania has much improved in the last decade. Here, the results are compared to the $^{87}Sr/^{86}Sr$ mapping of Scania suggested by Ladegaard-Pedersen et al. (2021) (Figure 3), which was based on plants, soil leachates and surface water $^{87}Sr/^{86}Sr$ ratios.
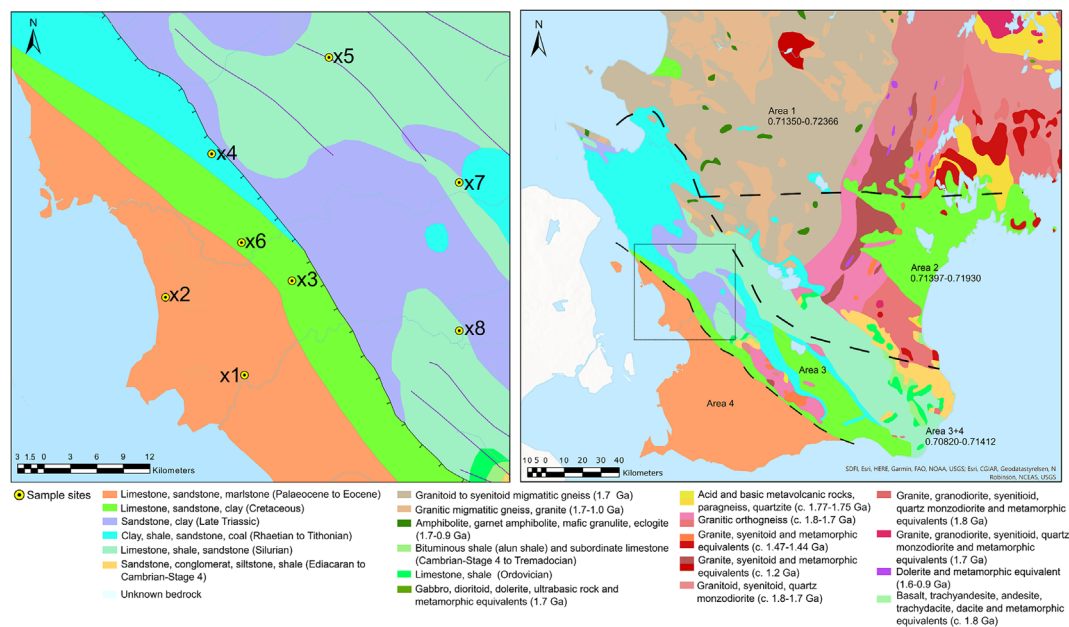
FIGURE 3 Ladegaard-Pedersen et al.'s $^{87}Sr/^{86}Sr$ division of Scania, based on distribution of values from modern plants, soil leachate, and surface waters. Minimum to maximum ranges. Map made with ArcGIS pro vs. 2.9.0. Geological map from "Berggrund 1:1 miljon" © Sveriges geologiska undersökning. Left: map of the Löddeköpinge region, with sites for reference samples. *Source*: Data from Ladegaard-Pedersen et al. (2021) and Boethius et al. (2022). Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]

Löddeköpinge is located on Paleocene to Eocene sedimentary rocks consisting of limestone, sandstone, and marlstone (Figure 3), similar to the rest of southwest Scania. Reference values from this area measured to 0.7082–0.7131 ($n = 18$). A diagonal strip of Cretaceous sedimentary rocks to the east of Löddeköpinge consists of limestone, sandstone, and clay. The $^{87}Sr/^{86}Sr$ reference values are 0.7103–0.7117 ($n = 7$). A narrow Rhaetian to Tithonian cover rock area north of Löddeköpinge, which widens along the coast, consists of clay, shale, sandstone, and coal. Reference values for this zone are 0.7093–0.7208 ($n = 19$). East of both of these narrower strips is a larger area with Late Triassic sandstone and clay, from which three reference values are reported (0.7108–0.7114). South of this is an isolated area of Silurian sedimentary rocks, consisting of limestone, shale, and sandstone, with reference values of 0.7091–0.7189 ($n = 15$). This bedrock is found north of Löddeköpinge, and elsewhere in Scania. The abovementioned values, tied to different geological zones in the Löddeköpinge region, are taken from the syntheses made by Ladegaard-Pedersen et al. (2021) and Boethius et al. (2022, Suppl. data), combined with the results from this study (Table S2).

The modern plant sample $^{87}Sr/^{86}Sr$ ratios (Table S2) showed consistency with areas 3–4 in Ladegaard-Pedersen et al. (2021). The $\delta^{34}S$ values are moderately low with seven of eight samples around 4–5‰. The range between the lowest and the highest value is high (5.2‰), with the highest (7.9‰) from the sample site closest to the coast (×2, Table S2) and the lowest (2.9‰) from ~30 km inland (×5, Table S2). The sample sites with the longest distances from the coast, ×7 (37 km distance) and ×8 (35 km distance), did not have lower values than the general (4.7 and 4.9‰, respectively). Most values are too low to indicate an explicit sea spray effect, as $\delta^{34}S$ values of modern oceanic water are much higher than our samples (Fornander, 2013; Nehlich, 2015). This provides useful insights into bioavailability but must be used cautiously given the limited sample size and the homogenized plant approach.

## 4.2 | Kill-off patterns and sheep mortality

The dental ages indicate an elevated presence of mature animals and input of young lambs throughout the Viking Age (Figure 4). This pattern is clearest in the early phase (AD 800–950). The fusion ages support that animals were kept to older ages, with some input of lambs and yearlings' slaughter. Males unfit for breeding were perhaps castrated, while many animals survived to ages above 2 years. No high lamb mortality is observed, but juvenile sheep were slaughtered occasionally. We also note an input of younger adults, probably killed for meat consumption. A kill-off strategy adapted to a mixed wool/meat/milk production, with a focus on wool, seems plausible.

4.3 | Isotope results from the sheep

The isotope results are compiled in Table 2. All samples yielded acceptable C:N, C:S, N:S ratios, except SH19, as described in more detail in Appendix S1.

4.3.1 | Preliminary provenancing through $^{87}Sr/^{86}Sr$ isotope analysis

The $^{87}Sr/^{86}Sr$ results have a relatively narrow range (0.7107–0.7125) ($n = 18$), fitting the isotope values of Area 3 (Ladegaard-Pedersen et al., 2021; Figure 3). By comparing the results directly to the
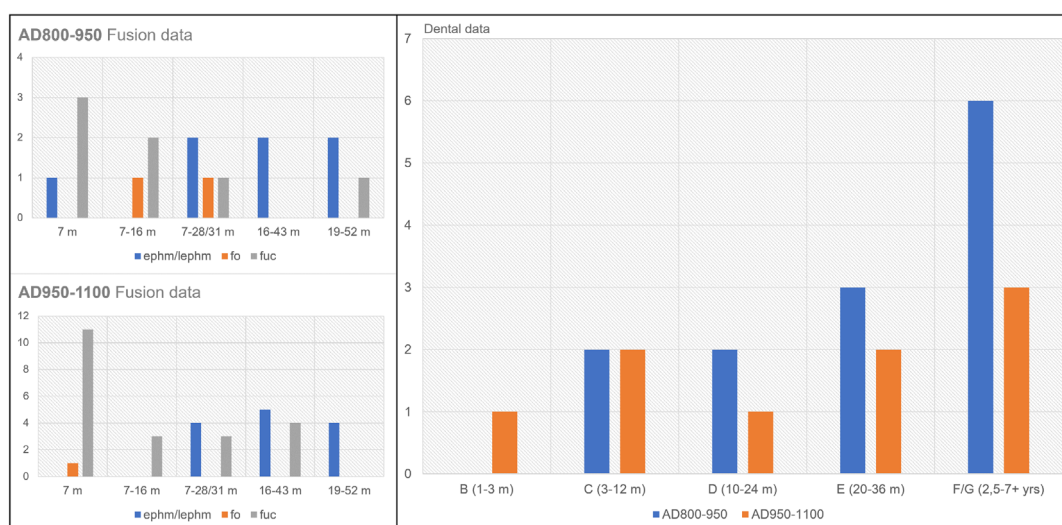
FIGURE 4 Sheep mortality at Viking Age (AD 800–950) and late Viking Age-Early Medieval (AD 950–1100) Löddeköpinge. Left: distribution of epiphysis based on fusion status related to age after Popkin et al. (2012). AD 800–950, $n = 16$. AD 950–1100, $n = 35$. Right: mandibles ($n = 22$) assigned to wear following Jones (2006) per period. Abbreviations used: ephm, epiphysis missing; fo, fusion on-going; fuc, fusion complete; lephm, loose epiphysis; m, months. Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Isotope results for the sheep mandibles from Löddeköpinge (for list of mandibles, see Table 1).

| | Lab description | | | | Dentine and enamel results | | | | | | | | | | |
Sample ID	LabID	Tooth	Side	δ15N dent	δ13C dent	δ34S dent	%N dent	%C dent	%S dent	C:N molar dent	C:S molar dent	N:S molar dent	Sr	Sr SE
SH1	SHA_01	M1	R	6.1	−21.4	11.0	16.0	43.8	0.3	3.2	399	124	0.712013	0.000020
SH2	SHA_02	dp4	L	8.9	−21.9	8.8	16.0	44.0	0.3	3.2	413	129	0.711682	0.000007
SH4	SHA_04	dp4	R	7.6	−21.5	10.0	15.6	42.8	0.3	3.2	349	109	0.711119	0.000008
SH5	SHA_05	M1	L	6.6	−21.5	10.6	15.6	43.6	0.3	3.3	458	141	0.711035	0.000006
SH6	SHA_06	dp4	L	7.6	−21.6	8.6	15.1	42.3	0.3	3.3	380	116	0.711518	0.000008
SH7	SHA_07	M1	L	8.1	−20.9	8.2	15.8	43.6	0.3	3.2	454	141	0.711321	0.000008
SH9	SHA_09	M1	R	7.1	−21.5	11.7	14.8	42.2	0.4	3.3	319	96	0.711528	0.000007
SH10	SHA_10	M1	L	7.4	−21.5	9.2	15.7	43.7	0.3	3.3	408	125	0.712257	0.000009
SH11	SHA_11	M1	L	7.8	−21.4	10.0	15.2	43.0	0.3	3.3	403	122	0.712465	0.000010
SH12	SHA_12	P4	L	7.7	−21.7	9.6	15.0	42.4	0.3	3.3	341	104	0.712258	0.000008
SH14	SHA_14	dp4	L	13.2	−22.6	6.3	14.8	43.7	0.3	3.4	391	113	0.71071	0.000009
SH15	SHA_15	M1	R	6.6	−21.6	10.6	15.6	43.5	0.3	3.3	435	134	0.711704	0.000011
SH16	SHA_16	M1	L	8.2	−21.4	9.7	15.5	43.6	0.3	3.3	450	137	0.71184	0.000010
SH17	SHA_17	M1	L	6.9	−21.4	12.1	14.8	41.8	0.3	3.3	404	123	0.711995	0.000029
SH18	SHA_18	M1	L	11.5	−22.4	9.3	15.2	42.9	0.3	3.3	454	138	0.711787	0.000023
SH19	SHA_19	M3	L	8.2	−21.6	8.2	14.4	43.0	0.6	3.5	198	57	0.712262	0.000023
SH20	SHA_20	M1	L	7.5	−21.5	10.0	15.1	43.7	0.3	3.4	420	125	0.711804	0.000029
SH21	SHA_21	M3	L	7.4	−21.5	10.3	15.3	42.4	0.3	3.2	384	118	0.711736	0.000023
Summary statistics														
			No	18	18	18								
			Minimum	6.1	−22.6	6.3								
			Maximum	13.2	−20.9	12.1								
			Mean	8.0	−21.6	9.7								
			SD	1.7	0.4	1.4								
			Median	7.6	−21.5	9.8								
			IQR	1.0	0.1	1.6								

| | Lab description | | | | Mandibular bone | | | | | | | | |
Sample ID	LabID	Tooth	Side	δ15N bone	δ13C bone	δ34S bone	%N bone	%C bone	%S bone	C:N molar bone	C:S molar bone	N:S molar bone
SH1	SHA_01	M1	R	4.8	−21.4	10.9	15.8	44.6	0.26	3.3	452	138
SH2	SHA_02	dp4	L	6.6	−21.8	9.4	16.4	45.7	0.27	3.3	452	139
SH4	SHA_04	dp4	R	6.0	−21.6	12.0	15.9	44.5	0.27	3.3	438	134
SH5	SHA_05	M1	L									
SH6	SHA_06	dp4	L	5.2	−21.4	9.5	16.3	45.1	0.25	3.2	490	151

TABLE 2 (Continued)

| Sample ID | Lab description | | | | Mandibular bone | | | | | | | | | |
	LabID	Tooth	Side	δ^{15}N bone	δ^{13}C bone	δ^{34}S bone	%N bone	%C bone	%S bone	C:N molar bone	C:S molar bone	N:S molar bone
SH7	SHA_07	M1	L	6.1	−20.8	8.0	16.3	44.7	0.24	3.2	507	159
SH9	SHA_09	M1	R	5.3	−21.2	14.3	15.6	44.3	0.24	3.3	498	150
SH10	SHA_10	M1	L	4.7	−21.3	9.9	16.3	45.7	0.24	3.3	508	156
SH11	SHA_11	M1	L	5.9	−21.2	9.8	16.1	44.7	0.25	3.2	482	149
SH12	SHA_12	P4	L	6.2	−21.4	10.2	16.2	45.1	0.24	3.3	511	157
SH14	SHA_14	dp4	L	11.2	−22.2	7.0	16.2	45.4	0.26	3.3	470	144
SH15	SHA_15	M1	R	5.5	−21.6	10.8	16.6	45.2	0.24	3.2	498	157
SH16	SHA_16	M1	L	7.5	−21.7	9.0	16.0	44.6	0.26	3.3	453	139
SH17	SHA_17	M1	L	6.3	−21.4	11.1	16.2	45.1	0.23	3.2	514	159
SH18	SHA_18	M1	L	10.5	−22.5	11.0	15.7	44.9	0.26	3.3	459	137
SH19	SHA_19	M3	L									
SH20	SHA_20	M1	L	6.4	−21.5	10.3	16	45	0	3	451	138
SH21	SHA_21	M3	L									
Summary statistics												
			No	15	15	15						
			Minimum	4.7	−22.5	7.0						
			Maximum	11.2	−20.8	14.3						
			Mean	6.5	−21.5	10.2						
			SD	1.9	0.4	1.7						
			Median	6.1	−21.4	10.2						
			IQR	1.1	0.4	1.5						

Abbreviation: IQR, interquartile range. Dent, dentine. SE, standard error.

geological zones, the picture becomes more complex (Figure 5). The isotope values from the Cretaceous (Area 3) and Paleocene to Eocene sedimentary rocks (Area 4) are, in the majority of cases, lower than those from our sheep. The $^{87}Sr/^{86}Sr$ ratios are mainly contained within the strontium isotope intervals of two zones with sedimentary rocks (Figure 5): Rhaetian-Tithonian, covering most of northwest Scania and parts in the middle, and Silurian, mainly found in a diagonal streak across Scania as well as about 20–35 km north and east of Löddeköpinge. The $^{87}Sr/^{86}Sr$ of the sheep do not appear to be especially affected by sea spray. The reported $^{87}Sr/^{86}Sr$ of modern sea water (∼0.7092, McArthur et al., 2001) do not correspond to either the strontium isotope baseline values of the areas or from the geological rock covers, except the coastal ones (Ladegaard-Pedersen et al., 2021; Figure 5).

The narrow range suggests a limited catchment, with sheep potentially deriving from the same landscape, that is, inland east or north of Löddeköpinge. The slaughter age distribution is evenly dispersed regardless of geological background, in the sense that both old and young sheep could have similar provenience, for example, SH6 and SH9 (Figure 6). Clustering of some sheep according to geological background may be observed, for example, SH4, SH5; SH10, SH12; SH16, SH18, and SH20 (Figure 6). This similarity is consistent with the animals belonging to the same flock, although contemporaneity may not be evidenced in all cases (Table 2). SH14 seems to deviate from this pattern, with the lowest observed $^{87}Sr/^{86}Sr$ ratio and $\delta^{34}S$ isotope value.

## 4.3.2 | Diet and movement through life ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$)

Differences between dentine and mandibular bone can mirror dietary changes due to the greater turnover of bone. Figure 7 shows cut-offs between $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values from dentine versus bone. Spearman's correlation tests (Spearman's rho, SPSS

vs. 29.0.0.0(241)) were conducted to evaluate the relationship between dentine and bone isotope values. The results showed statistically significant ($p < 0.01$) positive correlations for all three isotopes ($\delta^{15}N$: $r_s(13) = 0.743$; $\delta^{13}C$: $r_s(13) = 0.713$; $\delta^{34}S$: $r_s(13) = 0.785$). This suggests that, while there is a slight offset between dentine and bone, there is little change in $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values between early and later life among these individuals.

All sheep showed low $\delta^{13}C$ isotope values, indicating a terrestrial diet. The variation within the $\delta^{13}C$ data is very limited: The average interval range between dentine and bone values is 0.08‰, which is lower than the analytical error. It demonstrates that most animals experienced no identifiable shift in $\delta^{13}C$ isotope values in their lifetime (Figure 7). The $\delta^{13}C$ isotope values range from −20.8 to −22.6‰ with a mean of −21.6‰ (1σ 0.4 for both dentine and bone values). Figure 8 presents a scatter plot of the dietary isotope values in the Löddeköpinge sheep compared to sheep and other animals from other sites. It confirms that while the $\delta^{13}C$ values are consistent with previous studies, some Löddeköpinge sheep have high $\delta^{15}N$ values (Figure 8).

Higher $\delta^{34}S$ values in relation to lower "terrestrial" $\delta^{13}C$ values may indicate some degree of sea spray effect (Nehlich, 2015:9). To test this, correlation tests (Spearman's rho) were performed between $\delta^{13}C$ and $\delta^{34}S$, and $\delta^{15}N$ and $\delta^{34}S$. There is a weak positive correlation ($r_s(16) = 0.489$, $p = 0.04$), meaning that higher $\delta^{34}S$ do, albeit weakly, correspond to higher $\delta^{13}C$; this suggests that sea spray alone cannot account for the values. Terrestrial herbivores should show depleted $\delta^{34}S$ and $\delta^{15}N$ in relation to marine carnivorous animals, according to Göhring et al. (2015, but see Hamilton et al., 2019). The relationship between $\delta^{15}N$ and $\delta^{34}S$ values is strongly negatively correlated ($r_s(16) = -0.818$, $p = 0.000$), meaning that with lower $\delta^{34}S$ values, higher $\delta^{15}N$ values can be expected. Figure 9 visualizes these relationships, in relation to isotope values from relevant fauna from Haithabu and Schleswig, southwestern Baltic Sea, approximately contemporary with Löddeköpinge.
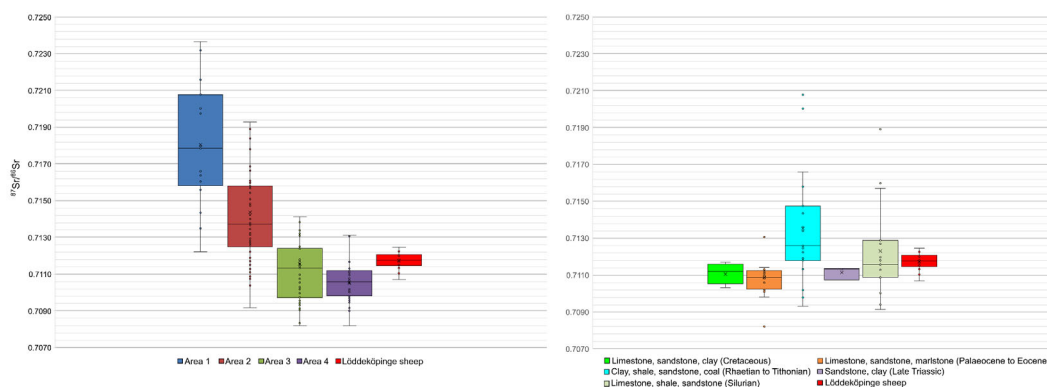
FIGURE 5 Box-and-whiskers plots of $^{87}Sr/^{86}Sr$ ratios in Scania. Left: Löddeköpinge sheep versus Ladegaard-Pedersen et al.'s areas. Right: Löddeköpinge sheep versus baseline samples from individual geological substrates. Baseline values from Ladegaard-Pedersen et al. (2021) and Boethius et al. (2022). Samples sb-22 (0.7373) from Area 2 and 4 (0.7320) from Area 3 reported by Ladegaard-Pedersen et al. (2021) are not visible on the left figure, because of the restricted scale. Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]
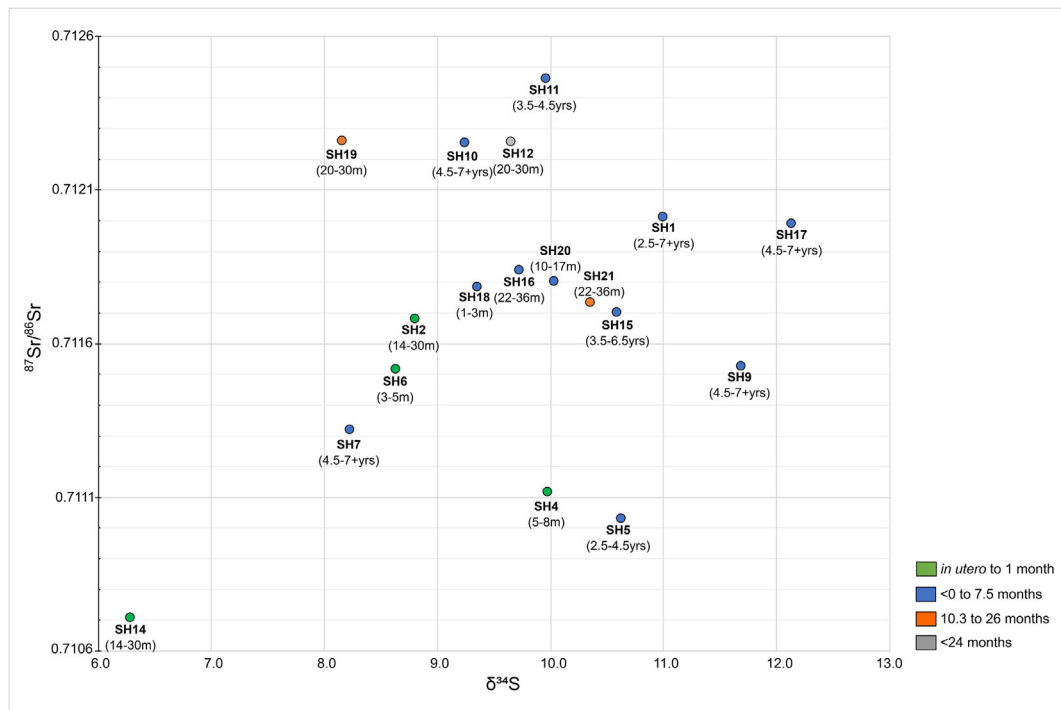
FIGURE 6 Bivariate scatter plot of $^{87}Sr/^{86}Sr$ ratios and $\delta^{34}S$ values obtained from the Löddeköpinge sheep. Estimated death ages given in parentheses (Table 1). Dental development ages from Table S1 (and references therein). Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]
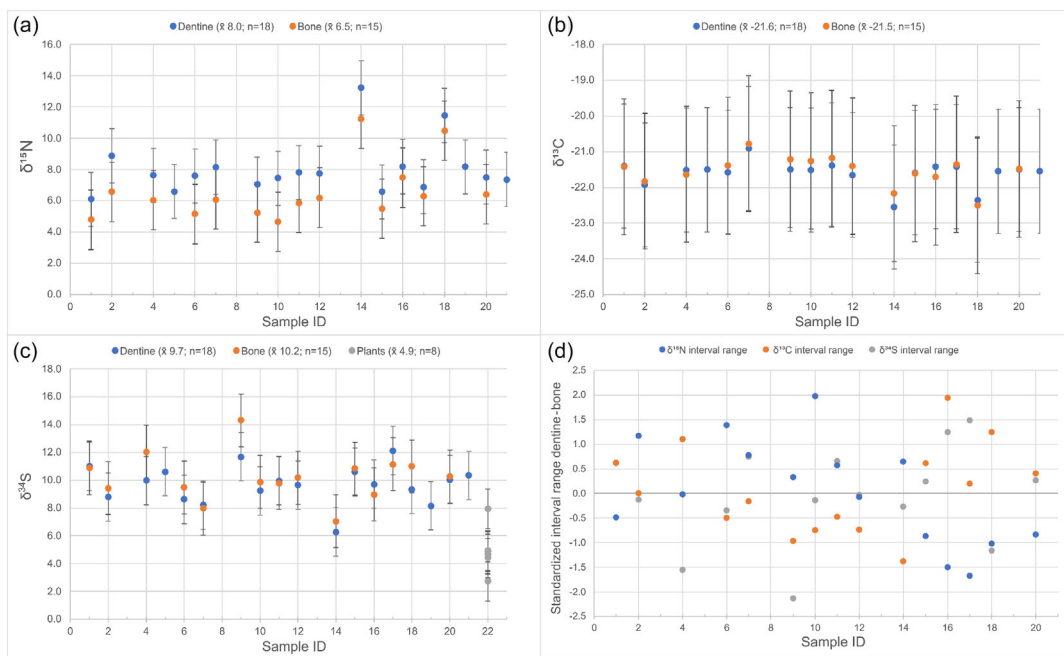
FIGURE 7 Isotope values from dentine versus bone in each sampled individual, (a) $\delta^{15}N$, (b) $\delta^{13}C$, and (c) $\delta^{34}S$ values. Plot (c) includes modern plant values, labelled as 22 (Table S2). (d) Standardized interval ranges of all applied isotope values per sample. The greater the distance from 0 (standardized mean), the wider the standardized interval range between dentine and bone values. [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 Bivariate scatter plot of dentine $\delta^{13}C$ and $\delta^{15}N$ isotope values from the Löddeköpinge, with parallels from other fauna in sites close temporally and spatially: east Denmark (Himlingøje, Skovgårde, Hågerup, Kassebjerggård in east Denmark and Bofa/Tornegård on Bornholm, Jørkov et al., 2010:526), Haithabu (Doppler et al., 2010), and Öland (Wilhelmson, 2017). Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]
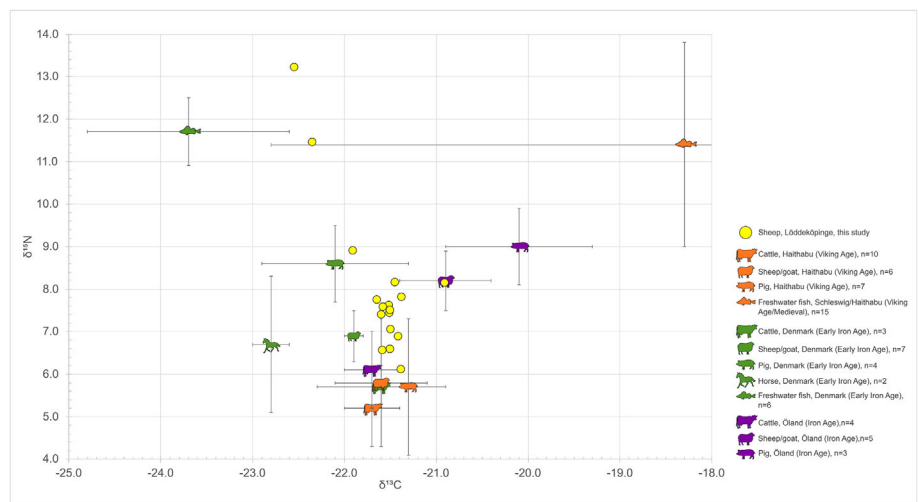
5 | DISCUSSION

5.1 | Diet, mobility, and landscape use

This paper explores sheep management in terms of landscape use and diet through kill-off patterns and multi-isotope analysis at a time when sheep husbandry was particularly important due to the increased use of wool in ships' sails. Of interest were any isotopic indications of grazing on manured fields in fallow, and/or on meadows close to freshwater systems or the coast. For this purpose, we applied $\delta^{15}N$, $\delta^{13}C$, and $\delta^{34}S$ isotope analysis on mandibular bone and dentine, and $^{87}Sr/^{86}Sr$ isotope analysis on tooth enamel. Since $\delta^{34}S$ isotope data are very scarce in a Scanian, south Swedish context, plants were sampled for investigating the local $\delta^{34}S$ variability. The results were hard to interpret. Pollution from burning fossil fuels and industry can influence environmental $\delta^{34}S$ values, and so caution must be taken when evaluating modern baselines. In addition, variation in sulfur cycling across time is poorly understood, and therefore, while environmental samples may provide a useful ordinal index of variation, the absolute values may not be a valid comparison for archaeological samples. Based on the results, modern plant $\delta^{34}S$ values are not suitable as direct evidence to support interpretations surrounding diet and mobility in this context. Instead, they have value when used in conjunction with other isotope proxies. Although the absolute values of the modern plants are problematic, the range (2.7‰ to 7.9‰) is of some use in characterizing the degree of landscape variation in the area. The $\delta^{34}S$ isotope values from the sheep collagen can therefore be interpreted relative to research on sulfur isotope systematics and our understanding of the $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{15}N$ isotope data. For example, similar geological signatures have different sulfur isotope values, indicating different diets or pasturage characteristics (Figure 6). The relatively narrow range of the $^{87}Sr/^{86}Sr$ ratios indicates that the sheep came from north and east of Löddeköpinge, and not south. Some sheep may derive from further inland, but it seems less likely. Coastal meadows were not the locus of grazing for these flocks; the values are clearly higher than the reference values from these

environments, as supported by the majority of the $\delta^{34}S$ isotope values (see below).

Isotope values from dentine and mandibular bone did not differ markedly. This could be influenced by the fact that the mandible isotope values likely show a more conservative average due to slower bone turnover rates or that the sheep were not living long enough to be affected by bone remodelling. For example, samples with higher $\delta^{15}N$ values in dentine also exhibit higher $\delta^{15}N$ values in bone. SH14 exhibited the highest $\delta^{15}N$ value for dentine and bone. Its dentine (dp4) was primarily formed in utero. It died around 1.5–2.5 years of age, post weaning. It could be argued that since the sheep died young, the mandibular $\delta^{15}N$ value likely reflects the same period as the tooth formation, and both dentine and bone are influenced by the mother. This seems to be the case for SH18, which died very young (1–3 months). However, also older sheep, such as SH10, have similar differences between dentine and bone $\delta^{15}N$ values (Figure 7). Should there be a significant weaning effect, it would likely be observed more clearly also on other lambs, as SH6 (where the interval range instead is higher than the standardized mean of interval range, Figure 7d).

The variation in isotope values between individuals mainly reflects different pastures/diets. The hypothesized cut off value for plants growing on highly manured fields was set at ~6.3‰ (Larsson et al., 2019). Using a trophic level of ≥4.6‰ (O'Connell et al., 2012), this would fit the highest $\delta^{15}N$ values of the Löddeköpinge sheep (>10‰) and could suggest moderate manuring input for the lower $\delta^{15}N$ values. High $\delta^{15}N$ values coincide with low $\delta^{13}C$ values in SH14, SH18, and SH2, and vice versa for SH1 and SH9–SH12 (Table 2).

The variation within the $\delta^{15}N$ values indicates that varied pasturage was exploited, some of which had been heavily manured, and therefore, these animals are unlikely to have come from the immediate hinterland of the site. This is supported by the sulfur isotope values that, although terrestrial, have a wide-enough range to suggest origins in areas with different landscape baselines. Both $\delta^{13}C$ and $\delta^{34}S$ isotope values, somewhat surprisingly, suggest that none of the sampled sheep derive from the coastal areas to the south. There is no evidence for saltmarsh grazing, where high $\delta^{15}N$ values would be
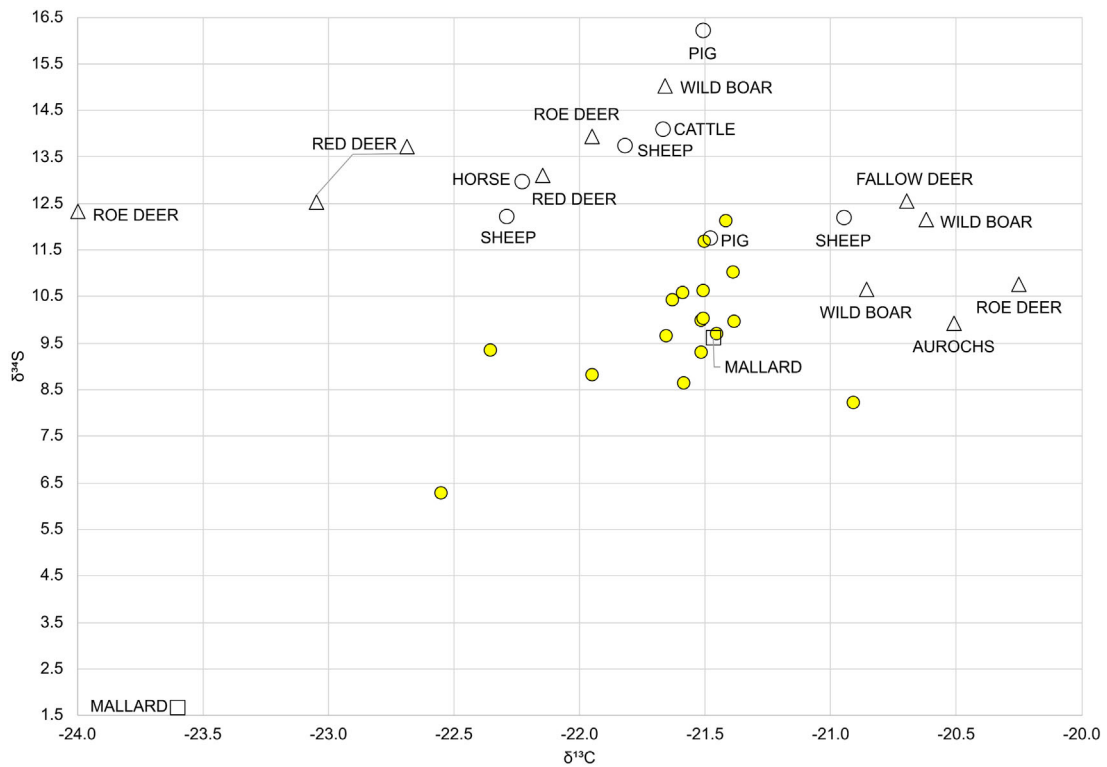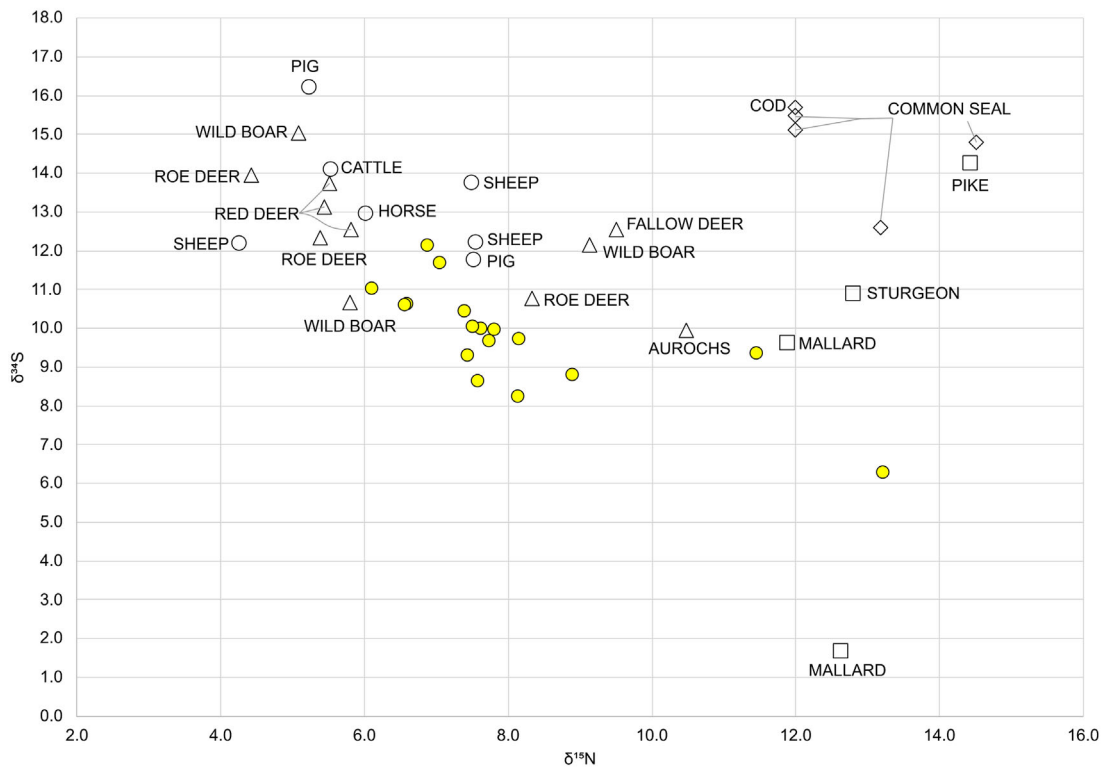
FIGURE 9 Bivariate scatterplots of dentine δ³⁴S values versus (top) dentine δ¹³C values and (bottom) dentine δ¹⁵N values. Comparative faunal data (individual isotopic values) from Haithabu/Schleswig from Göhring et al. (2015). *Freshwater diet* and *marine diet* in the legend pertain to taxa with specific dietary pathways. Brackish dietary pathways are possible for both categories, as the Baltic Sea is mixed in terms of salinity, and some of these taxa may be migratory (e.g., sturgeon). Illustration by S. Macheridis. [Colour figure can be viewed at wileyonlinelibrary.com]

expected to be coupled with moderately elevated δ^{13}C values (Britton et al., 2008). Given the degree of temporal averaging in the bone and, to a lesser extent, the dentine samples, the possibility of seasonal or short term/sporadic exploitation of coastal grazing areas cannot be discounted. However, a sea spray effect might be expected in the more temporally resolved ^{87}Sr/^{86}Sr isotope ratios. The similarities in δ^{15}N values between the freshwater fish and some of the Löddeköpinge sheep in Figure 8 may alternatively suggest a possible influence from grazing on the shores of lakes and/or rivers. The isotopic effect of grazing on sulfide-rich anaerobic wetlands in this region is not yet documented, though there is strong evidence that lower δ^{34}S values should be expected (Lamb et al., 2023).

Even so, the riverine systems and lakes of Scania might have had some effect on δ^{15}N values, as suggested for the Haithabu/Schleswig area by Göhring et al. (2015). They interpreted the enrichment of ^{15}N and depletion of ^{34}S in terrestrial herbivores as the result of a limnic effect (i.e., influenced by freshwater systems), though they do not exclude grazing on fertilized fields as a potential influence. If so, bioavailable water and plants close to riverine and lake systems would have increased δ^{15}N values. They exemplify this limnic effect foremost through the isotope values of an aurochs (δ^{15}N: 10.5‰; δ^{34}S: 9.9‰, Göhring et al., 2015:172). The Löddeköpinge sheep δ^{34}S values are similar to Haithabu/Schleswig freshwater species, especially one mallard and one sturgeon (Figure 9). They are slightly lower than several isotopic values from domestic and wild terrestrial fauna from Haithabu/Schleswig. Still, the similarities between the present study and that of Göhring et al. (2015) indicate that a limnic influence on δ^{34}S and δ^{15}N values cannot be disregarded. To test this further, a larger data set for this region is needed (see Göhring et al., 2015). This illustrates an issue of equifinality: Fertilizing the fields results in an enrichment of ^{15}N (e.g., Larsson et al., 2019), while a similar effect can be expected for a freshwater-based diet (e.g., Fornander, 2013:23).

5.2 | Sheep, wool, and sails at Viking Age Löddeköpinge

Löddeköpinge was probably a place for communication and redistribution of produced goods in a wider sense, affecting the immediate surroundings perhaps the most. The many textile-related items indicate that production, distribution, and exchange of wool and cloth were the site's most important functions (Andersson, 2000). Based on textile tools such as spindle whorls, loom weights, and awls/needles, Andersson noted an increase in textile production in the Viking Age, especially the 10th century AD (Andersson, 2003:57). She argued that the production was organized on a household level but exceeded the household's needs. In this system, a surplus was gained, which was used for exchange and trade (Andersson, 2003). Based on the vicinity to the ringfort at Borgeby in conjunction with the concentration of textile-related finds in the pit houses, she further suggested that the increase of textile production at Löddeköpinge was concentrated in these features and that it may be connected to the political dynamics of the time and the increased demand for woollen sailcloth. This

model does not contradict the production of other essential cloth, but sailcloth would probably have been an important item for trade, since the Viking Age society was to a large extent maritime-based. It is probable that the sailcloth production, including the procurement of raw material, was highly organized in the Viking Age (e.g., Andersson, 2003:57; Zagal-Mach Wolfe, 2013). This organization may be reflected in the mobility signatures of the sheep in this study. The site gathered sheep from inland northern and/or eastern Scania, and not the southwest, likely reflecting on different owners bringing their sheep in for exchange. This is indirect evidence that their human owners did not move from the southwest either. This restriction or choice in mobility of sheep and man may be connected to the dynamics of local nobility and aristocratic influence on geopolitics, as well as a precursor to the Medieval economy. This choice may also be connected to the textile crafts at Löddeköpinge and the need for specific sheep for wool of certain types.

The archaeological interpretation of the site as a local marketplace with a focus on sheep and wool is supported by the results of this study. The results point towards the practice of retaining older animals, with occasional slaughter of animals for meat. This indicates that a mixed strategy with a focus on wool is probable for the site. Though not securely evidenced and in need of confirmation, the possible presence of castrates would be a management indicator, as castration, although practiced for many reasons, especially targeted wool optimization (e.g., Ryder, 1983:448). An interesting point of departure to investigate this further would be to compare the results of this paper with sheep from other Viking Age trading sites or sites with special importance, such as Åhus and Ribe (other examples in e.g., Callmer, 1994; Sindbæk, 2007). Further, to map the sheep management on a more regional level, a future study should include sheep from surrounding villages or farms for each region. These research themes are not possible to explore further in this paper, but clearly, they need to be investigated. Hopefully, this paper may provide a springboard for such studies.

6 | CONCLUSIONS

This paper contains a multiproxy approach to the study of sheep management and landscape use in Viking Age Scania, Sweden, using mandibles from the marketplace site Löddeköpinge. We have explored mobility and diet using a range of isotope systems, namely, ^{87}Sr/^{86}Sr, δ^{13}C, δ^{15}N, and δ^{34}S values on dentine, enamel, and bone. Early life was studied through the dentine and enamel, while the longer life frame was analyzed through sampling the mandible bone. There was no evidence for substantial dietary change through life. The results presented in this paper strongly suggest that the Löddeköpinge sheep grazed on inland pastures, many on manured fields, while some may have grazed on meadows in the vicinity of rivers and lakes. The isotope data indicate intense use of wide-ranging landscapes within a moderate catchment of the site, probably to satisfy the demand for sheep products, in terms of live sheep, meat, and wool. The variation in the isotopic values indicates that the sheep from

Löddeköpinge represent a composite group, derived from different flocks in the Scanian inland, and possibly north of Löddeköpinge, with different dietary strategies, though it seems that sheep were not brought to the site from the coastal zone to the south. This reflects on the marketplace function of the site, and its influential sphere, which included mainly the northern and eastern parts of Scania. The Löddeköpinge sheep case clearly shows that the multiproxy approach allows for an improved resolution, where the individual sheep gives information of separate owner's sheep management. Certain areas, especially in the inland, right north and east of Löddeköpinge, provided suitable grazing for the optimization of meat and wool, as is indicated by the mortality patterns of these sheep. Further, the redistribution of sheep and wool was probably controlled by the local elite at Borgeby Castle, whose power did seemingly not extend to the south-southwest of the site. This may indicate the importance of these products in the political economy of the period. The role of sheep was tied to the demand for wool to textile production, especially for sailcloth, in the Viking Age economy. Considering the indications of sailcloth production at the site, sheep management in the Löddeköpinge region and to the north and east may have been directed towards producing suitable wool for such crafts.

CONFLICT OF INTEREST STATEMENT
None.

DATA AVAILABILITY STATEMENT
Data are available through this paper and its Supporting information.

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