

Auli Bläuer, Laura Arppe, Marianna Niemi, Markku Oinonen,
Kerstin Lidén, Jussi-Pekka Taavitsainen & Juha Kantanen
INFERRING PREHISTORICAL AND HISTORICAL FEEDING PRACTICES FROM
 $\delta^{15}\text{N}$ AND $\delta^{13}\text{C}$ ISOTOPE ANALYSIS ON FINNISH ARCHAEOLOGICAL DOMESTICATED RUMINANT BONES AND TEETH

Abstract

Written historical sources describe different feeding practices for cattle and sheep during the 16th–18th century in Finland. In this study, we analysed carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope values in 43 bones and teeth from archaeological cattle and sheep (or goat) dating from the Bronze Age to the modern times (c 1700 BC to AD 1980). The results indicated small differences in the isotope values among species and periods. Our results suggested a temporal trend in $\delta^{13}\text{C}$ values likely reflecting an increasing importance of forest-based fodder in the animal feeding. Seaweed was not a major component in the diet of domestic Finnish animals, but could have contributed to the diet of the sheep from Pasvik, Norway. The variation in the isotopic values cannot be explained by the feeding regimes described in written sources alone, but other factors, such as metabolic differences between cattle and sheep, starvation and sampling variation can have contributed.

Keywords: Bone, carbon isotope, cattle, feeding, nitrogen isotope, sheep, teeth

Auli Bläuer*, Green Technology, Natural Resources Institute Finland (Luke), FI-31600 Jokioinen, Finland and Department of Archaeology, University of Turku, FI-20014 Turun yliopisto, Finland; Laura Arppe*, Laboratory of Chronology, Finnish Museum of Natural History, P.O. Box 64, FI-00014 Helsingin yliopisto, Finland; Marianna Niemi*, Green Technology, Natural Resources Institute Finland (Luke), FI-31600 Jokioinen, Finland and Department of Forensic Medicine, University of Helsinki, FI-00014 Helsingin yliopisto, Finland; Markku Oinonen, Laboratory of Chronology, Finnish Museum of Natural History, P.O. Box 64, FI-00014 Helsingin yliopisto, Finland and University of Turku, FI-20014 Turun yliopisto, Finland; Kerstin Lidén, Archaeological Research Laboratory, Stockholm University, SE-106-91, Stockholm, Sweden; Jussi-Pekka Taavitsainen, Department of Archaeology, University of Turku, FI-20014 Turun yliopisto, Finland; Juha Kantanen**, Green Technology, Natural Resources Institute Finland (Luke), FI-31600 Jokioinen, Finland and Department of Environmental and Biological Sciences, University of Eastern Finland, P.O. Box 1627, FI-70211 Kuopio, Finland: juha.kantanen@luke.fi.

* – Authors contributed equally to this work; ** – Corresponding author.

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INTRODUCTION

The long winter feeding period has been one of the major challenges for Finnish animal husbandry in the past. In Finland the survival of domesticated herbivores (cattle, sheep, goats

and horses) over winter requires intensive feeding and thus a significant amount of work. Written historical records reveal that during the 16th century cattle and other livestock were kept inside and fed with winter fodder (hay, straw and leaves) for 31–34 weeks every year (Ström 1932:

12; Sähke 1963: 48). Wild plants collected from natural meadows and forests represented an important source of winter fodder for domesticated herbivores before hay or other animal fodder was cultivated, that was not until the late 19th century. Only straw and small amounts of grain, that were available for animals, derived from cultivated soil (Soininen 1974; Bläuer 2015).

Collecting enough fodder for the indoor season, which lasted c 7 months, was a struggle. Documents indicate that even during normal years fodder had to be carefully rationed in order to last until spring. During cold and late springs, or after a bad harvest, animals were left starving, sometimes even to death (Sähke 1963; Lappalainen 1970: 762; Heino 1987: 246).

Due to the limited amount of hay available its use was strictly regulated during the late medieval and post-medieval periods. Farm animals formed a hierarchy, where the most valuable animals were prioritized: this practice is described in several written sources dating from the 16th century onward (e.g. Sähke 1963; Soininen 1974: 225; Talve 1997: 69). Most of the hay was reserved for horses. Pregnant dairy cows also got some hay, but they were mostly fed straw, chaff and dry leaves, and draught oxen, which were not worked during the winter period, were fed almost exclusively straw. Even horse dung was sometimes used as cattle fodder (Soininen 1974: 226). Sheep, on the other hand, were usually fed dry leaves and branches of deciduous trees (Fi. kerppu) (Soininen 1974: 224). There were also differences in the summer pastures of these animals. Sheep, where possible, grazed on islands further away from the settlement, while cows were pastured in the forest around the farm or village, returning for milking every evening (Mattila 1960: 427; Papunen 1996: 306).

However, in Finland, written historical sources describing animal feeding are only available from the 16th century onwards (Bläuer 2015: 24–5). It remains uncertain whether similar practices were in place already during the early medieval and prehistoric periods. It could be assumed that some of the post-medieval winter feeding difficulties were due to the growing human and domesticated animal populations and increasing colonization. Consequently, the diminishing size of sheep from the medieval period to the post-medieval period in the town of Turku has been

interpreted as reflecting increasing competition over fodder resources (Tourunen 2008: 139). A period of cool climate (the so called ‘Little Ice Age’) that lasted from the 13th or 14th century to the mid-19th century had negative effects on the crop yields in Finland (Holopainen & Helama 2009; Huhtamaa & Helama in press) and may also have affected the availability of animal fodder. Thus, during the earlier periods there could have been better resources for animal feeding and more hay available per animal.

As bulk bone collagen carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope values of herbivores reflect the average isotope composition of the consumed vegetation during the last few years of an animal’s life, their values can be used to study diet of animals (e.g. Ambrose & Norr 1993; Tieszen & Fagre 1993; Noe-Nygaard et al. 2005; Zazzo et al. 2015). Several factors operating on different levels – regional, local and individual – can cause variability in herbivore $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values.

As regards to $\delta^{13}\text{C}$ values, regional climatic and environmental factors such as temperature, precipitation and altitude have been observed to influence the isotopic levels of animals (van Klinken et al. 1994; 2000; Hobson et al. 2003; Männel et al. 2007). In coastal areas, ingestion of marine biomass can result in elevated $\delta^{13}\text{C}$ values of consumers (Balasse et al. 2005). On a more local scale, $\delta^{13}\text{C}$ values can be used to distinguish between animals feeding in open areas, such as meadows, or animals feeding in closed environments (Tieszen 1991; Noe-Nygaard et al. 2005; Bonafini et al. 2013; Zazzo et al. 2015). As $\delta^{13}\text{C}$ values in a closed forest environment tend to be lower than those in open environments, browsers (such as roe deer and red deer) tend to have $\delta^{13}\text{C}$ values lower than grazing herbivores (Eriksson et al. 2008; Zazzo et al. 2015). In the case of $\delta^{15}\text{N}$ values, variation could be due to regional-scale environmental factors, such as precipitation (Heaton et al. 1986; Gröcke et al. 1997; Schnyder et al. 2006) and altitude (Männel et al. 2007), farm-level factors like manuring and pasture management (Bogaard et al. 2007; Zazzo et al. 2015), or use of browse, and factors operating at the individual level like nutritional or drought stress (Sealy et al. 1987; Hobson et al. 1993; Schwarcz et al. 1999; Fuller et al. 2005), gestation and weaning (Balasse & Tresset

2002; Fuller et al. 2004). However, previous studies have shown that specimens of the same species excavated from the same site typically display similar $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ patterns and that these values usually differ from values of the same species from different sites (Männel et al. 2007). This suggests that microhabitats – with subtle differences in light, moisture and temperature – affect the isotopic values at specific sites providing variation in values of the same species (Krigbaum 2003; Eriksson et al. 2008; Eriksson 2013).

Here we used $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from archaeological cattle and sheep skeletal remains in order to study the diet of these two domesticated herbivores, and to compare the diet inferred from the isotopic records with written records. This is the first study that investigates collagen $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ isotope values in Finnish prehistorical and historical animal bones and teeth. Moreover, it is typical to use published isotope data from ruminants as baseline information for human dietary studies, but less studies have been conducted to explore the diet of sheep and cattle (but see Noe-Nygaard et al. 2005).

Our assumption is that the different feeding practices described in the Finnish written records would also be visible in the bone collagen isotope data, as seen in differences between cattle and sheep. If cattle were fed straw and husk during the winter, that were derived from farmlands fertilized with organic supplements, we would expect higher $\delta^{15}\text{N}$ values in cattle than sheep that were almost exclusively fed wild plants. Further, differences in the $\delta^{13}\text{C}$ values could reveal temporal changes in the use of forests for pasture or a winter fodder source. Moreover, the change in the feeding practices over the centuries inferred from the historical sources and the increasing proportion of straw in fodder would turn up as increasing $\delta^{15}\text{N}$ values in the later periods.

MATERIALS AND METHODS

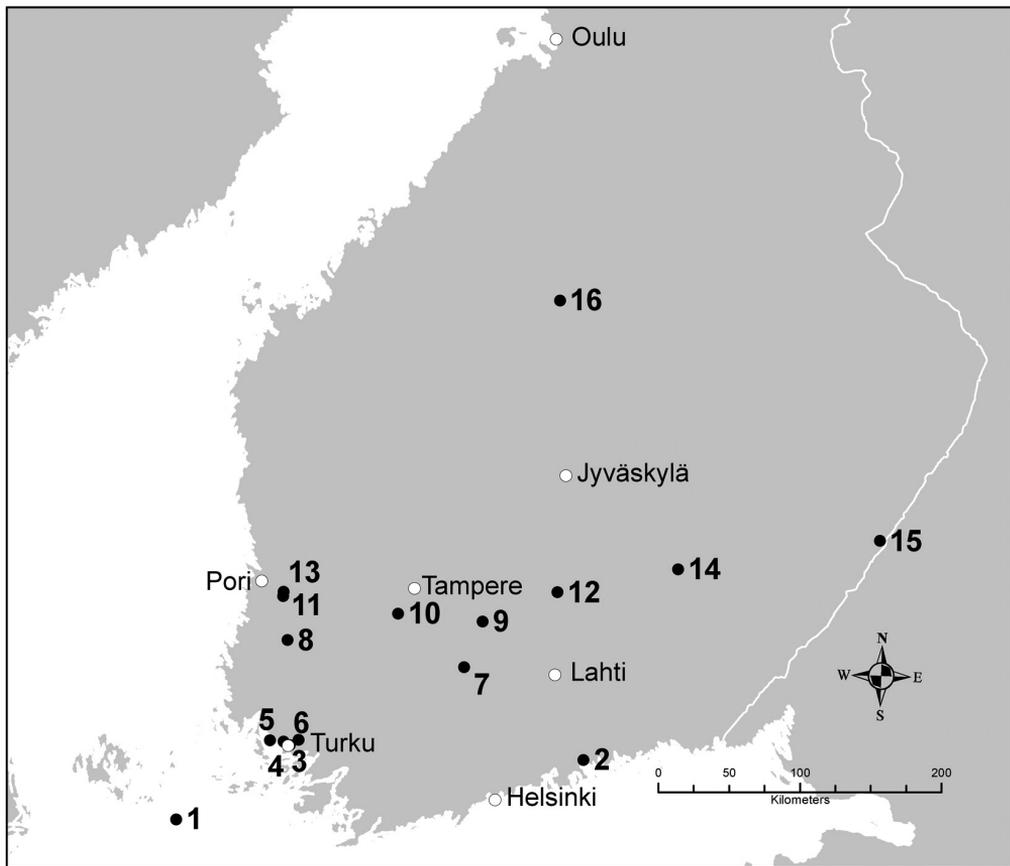
Materials

Finland suffers from a relative scarcity of archaeological bone finds due their dissolution in the acidic soils common throughout the Boreal forest zone. The isotopic preservation of our

study material in the challenging soil conditions of Finland are examined using well-established quality criteria based on elemental concentrations and molecular ratios. In total, we studied 43 samples of bone or teeth from cattle (*Bos taurus*, 23 samples), sheep (*Ovis aries*, 20 samples) and sheep or goat (*Ovis aries/Capra hircus*) dating from the Bronze Age to the modern times (from 1700 BC to AD 1980) (Table 1). The selected bones and teeth were also sampled for aDNA and radiocarbon dated (Niemi et al. 2013; 2015). The paucity of well-preserved and securely dated animal bones limited the possibilities to acquire temporally and geographically representative material, as prehistoric unburnt bone rarely survives in the acidic Finnish soil (Tourunen 2011; Bläuer & Kantanen 2013). All bones used in this study were radiocarbon dated to ascertain their connection to a particular chronological period, as in thin archaeological layers some bones may be later intrusions (Table 1; also Bläuer & Kantanen 2013).

The material was divided into three chronological categories: the prehistoric period (1700 BC to 1200/1300 AD), the medieval period (from AD 1200/1300 to AD 1550) and to the post-medieval period (from AD 1550 to AD 1800). In the prehistoric sample only one bone dates to the Bronze Age (Nakkila), and rest of the available samples date to the Iron Age. Even if found in an Iron Age cemetery or burial context (see Table 1), the bones from Luistari in Eura and Hinsala in Vesilahti proved to date to modern times (the 19th–20th century) (Tourunen 2011). However, they were included for comparative purposes.

Out of 20 sheep samples, three (Sysmä and Mikkeli: mandibular molars; and Turku: axis) were identified osteologically as sheep or goat. As goats are rare in the Finnish osteological samples (Bläuer & Kantanen 2013; Bläuer 2015: 54), these bones are more likely to derive from sheep than from goat and are thus here referred to as sheep. Most of the sampled bones were metacarpals or metatarsals. We preferred bones with closed epiphyses in order to exclude infants, possibly still suckling animals, from the sample set. If the epiphysis was missing, care was taken to sample only bones from adult-sized individuals with a compact bone structure, indicating maturity.



Nr	Country	Location	N	E
			ETRS89-TM35Fin	
1	Finland	Kökar	6658262	159806
2	Finland	Loviisa	6700237	447451
3	Finland	Turku	6710848	240120
4	Finland	Raisio	6713450	235819
5	Finland	Naantali	6714300	226091
6	Finland	Lieto	6714649	246325
7	Finland	Hämeenlinna	6765903	363151
8	Finland	Eura	6785034	238596
9	Finland	Pälkäne	6798282	376325
10	Finland	Vesilahti	6803832	316656
11	Finland	Nakkila	6816161	235274
12	Finland	Sysmä	6819039	429268
13	Finland	Nakkila	6819393	235753
14	Finland	Mikkeli	6835312	514494
15	Finland	Parikkala	6855364	656764
16	Finland	Pihtipudas	7025656	430877
17	Norway	Pasvik	7749515	638553

Fig. 1. Map of sampled sites and their coordinates. Map: H. Ojanen, Natural Resources Institute Finland (Luke).

No on Fig. 1	Site	Dating of the sample	Site type	Reference
1	Kökar Klostret	Medieval/post-medieval	Monastery/rectory	Gustavsson 1994
2	Loviisa Pernajan Pappila	Medieval/post-medieval	Monastery/rectory	Pellinen 2007
3	Turku Åbo Akademi, Aboa Vetus	Medieval/post-medieval	Settlement site	Pihlman 2003; Sartes 2003; Tourunen 2008; Seppänen 2012; Uotila & Korhonen 2012
4	Raisio Mulli	Iron Age–medieval	Settlement site	Tupala 1999; Vuorinen 2009
5	Naantali Luostari	Medieval	Monastery/rectory	Uotila 2011
6	Lieto Aittämäki	Iron Age	Cemetery/burial	Fisher 1994; Hautio 1994; Tourunen 2011
7	Hämeenlinna Varikkoniemi	Iron Age	Settlement site	Schultz & Schultz 1992
8	Eura Luistari	Modern	Iron Age cemetery/burial	Lehtosalo-Hilander 1982
9	Pälkäne Isosaari	Stone Age–post-medieval	Settlement site	Kankkunen 2005
10	Vesilahti Hinsala Tonttimäki	Modern	Iron Age cemetery/burial	Antikainen 1987
11, 13	Nakkila Selkäkangas	Bronze Age	Cemetery/burial	Kuokkanen & Korkeakoski-Väisänen 1985; Bläuer et al. 2013
12	Sysmä Ihananiemi	Iron Age–medieval	Settlement site	Mannermaa 2002; Poutiainen 2000
14	Mikkeli Moisio Latokartano	Iron Age	Settlement site	Schultz 1993
15	Parikkala Uukuniemi Papinniemi	Medieval/post-medieval	Settlement site	Laakso 2014
16	Pihtipudas Hämeensaari	Iron Age–post-medieval	Settlement site	Miettinen 1993
17	Pasvik Brodtkorbneset	Iron Age	Settlement site	Hedman & Olsen 2009

Table 1. Sampled sites.

The samples used in this study all derived from different archaeological excavations in Finland, except one that was from northern Norway (Fig. 1; Table 1). The bones derived from different types of sites, including burial sites, monasteries and both urban and rural settlement sites. The Norwegian sheep sample from Pasvik originated from a different biogeographic environment (costal and Arctic) and was considered as a reference sample for the Finnish specimens.

Methods

The sample pre-treatment and measurements were performed at the Laboratory of Chronology, Finnish Museum of Natural History – LUOMUS at the University of Helsinki, unless otherwise stated. The bone samples were pre-treated using the Longin method (Longin 1971) modified for the present study to extract bone collagen for radiocarbon and isotopic analyses. They were first mechanically and ultrasonically cleaned in distilled water. They were then dried

at 100°C overnight, ground to 0.5–1 mm grains on which hydrolysis and removal of carbonate contaminants were performed with 10% HCl at 5°C. After neutralization, humic acids were removed from the samples by leaching the insoluble residue at room temperature with 0.5% NaOH for 18–20 hours. The solution was again neutralized and the sample placed in distilled water with pH adjusted to 2–3 by adding HCl. This was left at 90°C for 24 hours with continuous mixing. This process formed soluble gelatin from which insoluble humic acids were separated in a centrifuge. The remaining soluble gelatin samples were then dried for packing and combustion.

For radiocarbon analyses, the pre-treated samples were mixed with a stoichiometric excess of CuO and packed into glass ampoules, which were pumped to vacuum and torch-sealed. The packed samples were combusted at 520°C overnight. The released CO₂ was collected and purified with liquid N₂ and ethanol traps at -196°C and -85°C, respectively. The purified

Site and No on Fig. 1	Lab. ID	BP	Period	Species	Element	Collection number	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	N%	C%	C/N	Radiocarbon date/reference
Pihtipudas (16)	Helia-2322	342±30	Post-medieval	Sheep	Tibia	KM 2658:4:4	-21.6*	3.1	13.4	39.3	3.4	Tourunen 2011
Pariikkala (15)	Helia-2323	410±30	Medieval	Sheep	Metatarsal	KM 98040:326	-21.9*	5.1	14.5	40.8	3.3	Niemi et al. 2013
Pasvik (17)	Helia-2324	984±31	Prehistorical (Iron Age)	Sheep	Metatarsal	Bone 330	-20.3*	8.6	14.0	40.9	3.4	Niemi et al. 2013
Raisio (4)	Helia-2325	965±30	Prehistorical (Iron Age)	Sheep	Metacarpal	TYA 642:2316a	-21.4*	4.6	15.8	40.3	3.0	Niemi et al. 2013
Raisio (4)	Helia-2326	1040±31	Prehistorical (Iron Age)	Sheep	Metacarpal	TYA 642:371a	-21.2	4.1	14.3	41.1	3.4	Niemi et al. 2013
Raisio (4)	Helia-2328	995±30	Prehistorical (Iron Age)	Sheep	Metacarpal	TYA 642:767a	-21.3*	5.0	14.5	39.4	3.2	Niemi et al. 2013
Raisio (4)	Helia-2329	1081±32	Prehistorical (Iron Age)	Sheep	Metacarpal	TYA 619:771a	-21.2*	4.8	N/A	N/A	N/A	Niemi et al. 2013
Sysmä (12)	Helia-2350	1093±31	Prehistorical (Iron Age)	Sheep/goat	Mandibular first molar	KM 32291:552	-21.6*	N/A	N/A	N/A	N/A	Tourunen 2011
Mikkeli (14)	Helia-2351	865±33	Prehistorical (Iron Age)	Sheep/goat	Mandibular molar	KM 28014:38	-21.7*	7.6	14.8	41.8	3.3	Niemi et al. 2013
Naantali (5)	Helia-2352	452±30	Medieval	Sheep	Talus	KM 2005034:185	-21.6*	6.6	14.4	41.4	3.4	Niemi et al. 2013
Turku (3)	Helia-2353	506±32	Medieval	Sheep	Metacarpal	TMM 21816:104	-21.6*	6.8	14.7	41.3	3.3	Niemi et al. 2013
Turku (3)	Helia-2354	581±31	Medieval	Sheep	Metacarpal	TMM 21816:104	-21.7*	5.5	14.7	41.3	3.3	Niemi et al. 2013
Turku (3)	Helia-2355	722±32	Medieval	Sheep	Metacarpal	TMM 21816:513B	-21.9*	7.0	14.9	42.2	3.3	Niemi et al. 2013
Turku (3)	Helia-2356	737±32	Medieval	Sheep	Metacarpal	TMM 21816:513B	-21.7*	5.7	14.8	41.9	3.3	Niemi et al. 2013
Turku (3)	Helia-2552	550±30	Medieval	Sheep/goat	Axis	KM 2010001:706	-21.2	7.5	13.7	39.0	3.3	Niemi et al. 2013
Turku (3)	Helia-2553	487±30	Medieval	Sheep	Horn core	KM 95032:11487	-21.8	7.0	14.7	42.2	3.3	Niemi et al. 2013
Lovisa (2)	Helia-2584	473±30	Medieval	Sheep	Mandible	KM 2006051:9	-21.4	5.8	12.7	34.8	3.2	Niemi et al. 2013
Kökar (1)	Helia-2593	489±30	Medieval	Sheep	Metacarpal	ÄM 553:33	-22.1	7.3	15.0	41.5	3.2	Niemi et al. 2013
Kökar (1)	Helia-2594	305±30	Post-medieval	Sheep	Metacarpal	ÄM 640	-20.8	5.2	14.8	40.1	3.2	Niemi et al. 2013
Nakkila (11)	Helia-2496	3086±30	Prehistorical (Bronze Age)	Cattle	Maxillary second molar	TYA 169:7	-21.7*	6.8	N/A	N/A	N/A	Bläuer & Kantanen 2013
Päikäne (9)	Helia-2528	408±30	Post-medieval	Cattle	Mandibular molar	KM 13407:67	-21.8	4.0	14.1	39.9	3.3	Tourunen 2011
Raisio (4)	Helia-2545	990±30	Prehistorical (Iron Age)	Cattle	Metatarsal	TYA 619:903a	-21.1	3.8	15.6	40.9	3.1	Niemi et al. 2015
Raisio (4)	Helia-2546	984±30	Prehistorical (Iron Age)	Cattle	Metatarsal	TYA 631:410a	-21.7	4.8	15.4	42.7	3.2	Niemi et al. 2015
Raisio (4)	Helia-2547	953±30	Prehistorical (Iron Age)	Cattle	Metatarsal	TYA 619:950a	-21.3	2.2	9.9	26.5	3.1	Niemi et al. 2015
Raisio (4)	Helia-2548	990±30	Prehistorical (Iron Age)	Cattle	Metatarsal	TYA 619:864d	-21.1	4.4	10.6	30.4	3.3	Niemi et al. 2015
Sysmä (12)	Helia-2549	637±30	Medieval	Cattle	Talus	KM 32291:552	-21.8	6.1	14.5	41.3	3.3	Tourunen 2011
Mikkeli (14)	Helia-2550	567±30	Medieval	Cattle	Cranium	KM 28014:38	-21.7	7.2	14.1	39.7	3.3	Niemi et al. 2015
Turku (3)	Helia-2551	599±30	Medieval	Cattle	Metatarsal	KM 2010001:703	-21.7	4.0	15.1	41.8	3.2	Niemi et al. 2015
Vesilhti (10)	Helia-2578	81±30	Modern	Cattle	Phalanx 2	TYA 335:330	-22.4	4.9	13.3	38.6	3.4	Tourunen 2011
Pihtipudas (16)	Helia-2579	323±30	Post-medieval	Cattle	Tibia	KM 27198:39	-21.6	4.2	15.2	41.9	3.2	Tourunen 2011
Naantali (5)	Helia-2580	431±30	Medieval	Cattle	Metacarpal	KM 2005034:196	-21.8	4.2	14.5	41.2	3.3	Niemi et al. 2015

Parikkala (15)	Heia-2581	350±30	Post-medieval	Cattle	Metacarpal	KM 98040:413	-22.0	3.3	15.2	42.4	3.3	Niemi et al. 2015
Parikkala (15)	Heia-2583	238±30	Post-medieval	Cattle	Metacarpal	KM 2001058:187	-21.7	2.9	14.6	42.2	3.4	Niemi et al. 2015
Loviisa (2)	Heia-2585	322±30	Post-medieval	Cattle	Pelvis	KM 2006051:9	-22.1	4.6	15.3	43.1	3.3	This publication
Eura (8)	Heia-2586	-21	Modern	Cattle	Mandibular M3	KM 25480:646	-21.2	5.0	11.2	30.1	3.1	Tourunen 2011
Lieto (6)	Heia-2587	1814±44	Prehistorical (Iron Age)	Cattle	Metatarsal	TYA 597:102	N/A	N/A	N/A	N/A	N/A	Tourunen 2011
Turku (3)	Heia-2589	740±30	Medieval	Cattle	Metacarpal	TMM 21816:513B	-22.2	5.2	15.6	43.4	3.2	Niemi et al. 2015
Turku (3)	Heia-2590	606±30	Medieval	Cattle	Metacarpal	TMM 21816:513B	-22.2	3.2	14.5	40.1	3.2	Niemi et al. 2015
Kökar (1)	Heia-2592	324±30	Post-medieval	Cattle	Metatarsal	ÄM 640	-21.6	5.1	15.4	43.0	3.3	Niemi et al. 2015
Hämeenlinna (7)	Heia-2690	984±24	Prehistorical (Iron Age)	Cattle	Maxillary deciduous PM 4	KM 27424:1291	-21.3	7.0	14.7	40.8	3.3	Niemi et al. 2015
Nakkila (11)	Heia-2691	187±23	Post-medieval	Cattle	Phalanx 2	SatM 17102:78	-22.5	5.9	14.9	42.9	3.4	Bläuer & Kantanen 2013

Table 2. List of samples. Lab. ID – Radiocarbon dating code; Collection number: KM – National Museum of Finland; TYA – University of Turku collection; TMM – Turku Museum Centre; ÄM – Åland Museum; SatM – Provincial Museum of Satakunta. $\delta^{13}\text{C}$ values were determined by using EA-IRMS or IRMS (latter denoted with an asterisk, *). Crossed-out samples were rejected based on C/N results.

CO_2 samples were then converted to graphite targets in the presence of a zinc powder and an iron catalyst (Slota et al. 1986). AMS (Accelerator Mass Spectrometer) radiocarbon measurements were eventually performed at the Uppsala Tandem Laboratory on the graphite targets.

Every radiocarbon analysis requires a fractionation correction, i.e. normalization of the ^{14}C content of different sample materials to correspond to the fractionation in wood, which has an average stable carbon isotopic ratio of $\delta^{13}\text{C}_{\text{wood}} = -25\text{‰}$ (see e.g. Stuiver & Polach 1977). Thus one needs a $\delta^{13}\text{C}$ measurement of each sample, which was performed after combustion from the purified CO_2 with IRMS (Isotope Ratio Mass Spectrometer; Finnigan MAT Delta-E). Several stable carbon isotopic values were obtained with this offline IRMS method (see Table 2). Typical analytical uncertainties were below 0.1‰ based on reference measurements for the Oxalic Acid II standard (NIST SRM 4990C).

For the majority of the stable carbon isotopic ratio measurements, and for all the stable nitrogen isotopic ratio measurements, analyses were performed with the EA-IRMS (Elemental Analyzer-IRMS; NC 2500 + Thermo Finnigan Delta Plus Advantage) method. Fractions of the pre-treated samples were weighed (typically 0.5 mg), packed into tin cups (Elemental Microanalysis D4019) and run on the EA-IRMS. Two measurements were performed for each sample and the results are given as averages of these. Average analytical uncertainties were below 0.1‰ for $\delta^{13}\text{C}$ and 0.2‰ for $\delta^{15}\text{N}$ deduced from the double measurements of samples as $(\delta_{\text{max}} - \delta_{\text{min}})/2$. Results are reported as δ values (‰) against the international standards VPDB (Vienna Pee Dee Belemnite) for carbon and AIR for nitrogen.

In order to probe the possible $\delta^{13}\text{C}$ differences between the offline IRMS and EA-IRMS measurements a comparison was performed in 19 animal bone collagen samples. The average deviation between the results was $<0.1\text{‰}$ (range 0–0.3‰). Therefore, we concluded that the above-described offline IRMS measurements provided consistently similar results compared with the EA-IRMS technique. To monitor the quality of the extracted collagen, the carbon and nitrogen contents (weight-%) were determined using a ThermoScientific Flash2000 elemen-

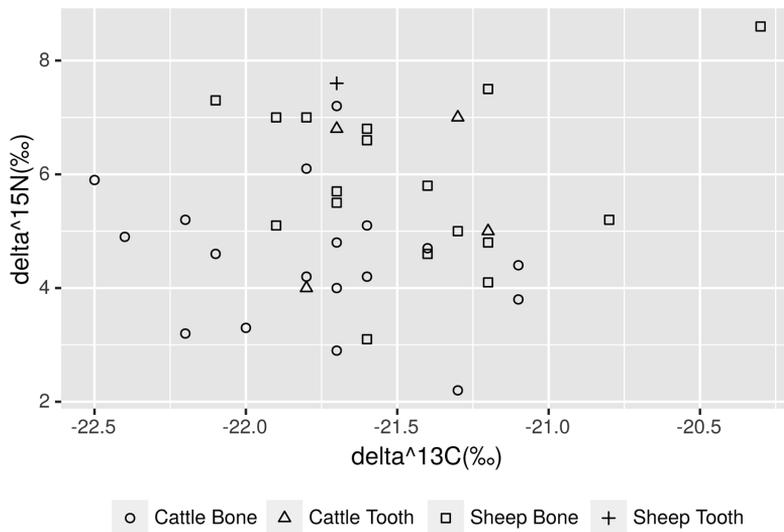


Fig. 2. Scatterplot of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for cattle and sheep bones and teeth. Species and bone type are indicated separately (see key). One sample analysed only for $\delta^{13}\text{C}$ (see Table 2) is omitted from the figure.

tal analyzer at the Laboratory of Chronology, University of Helsinki. The obtained C% and N% values were used to calculate collagen C/N ratios.

Only bone samples were considered in the statistical analysis because teeth and bones represent different time periods in an individual's life and the isotopes found in teeth might reflect suckling (e.g. Hedges et al. 2006). In addition, the two modern samples and the Iron Age sheep sample from Pasvik, northern Norway were excluded (the latter not providing information for the Finnish context; it was used as a reference sample). One cattle specimen from Kõkar and one sheep sample from Raisio were excluded based on unsatisfactory quality criteria (see chapter Results below). In total 32 bone specimens were considered in the statistical analyses which were performed with the MIXED procedure of the SAS v.9.3 software (SAS Institute Inc. Cary, NC, USA). The cattle and sheep data were divided into three temporal categories for statistical analysis based on the radiocarbon dating: prehistory (earlier than AD 1200/1300), medieval (AD 1200/1300–1550) and post-medieval (AD 1550–1800). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from different species and different time periods were considered as independent observations and were statistically analysed using a two-way analysis of variance (ANOVA). The following statistical model was used to analyse any effect

of species and prehistorical/historical period, all considered as fixed effects, on the isotope values:

$Y_{ijk} = \mu + S_i + P_j + (S \times P)_{ij} + e_{ijk}$, where Y_{ijk} = either $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ values, μ = the general mean, S_i = the effect of species (cattle, sheep), P_j = the effect of chronological period (prehistory, medieval, post-medieval), $(S \times P)_{ij}$ = the effects of interaction of species and period, and e_{ijk} = the error term. The statistical significances of these fixed effects were explored through F-tests and the differences between the model-based estimates of means through t-tests. The normality assumption of the residuals was checked by a quantile-quantile (QQ) plot and drawing a histogram of the Studentized residuals using the software SAS. The Studentized residuals for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data were approximately normally distributed (results not shown) supporting the use of ANOVA for the present statistical analysis.

RESULTS

The results for the cattle and sheep isotope analyses are shown in Table 2. The preservation of the analysed collagen, and thus, the integrity of the isotopic data, is typically evaluated based on the carbon and nitrogen content (%) and C/N ratio of the extract (see DeNiro 1985; DeNiro & Weiner 1988; Ambrose 1990; van Klinken 1999; Sealy et al. 2014). The commonly accepted range

of C/N ratios characteristic for well-preserved collagen is 2.9–3.6 (DeNiro 1985; DeNiro & Weiner 1988; Ambrose 1990; van Klinken 1999; Sealy et al. 2014). The acceptable values for C% and N% are somewhat less precisely defined. Fresh and/or well-preserved collagen has been reported to have nitrogen contents of c 11–17% (Ambrose 1990; van Klinken 1999; Sealy et al. 2014). Van Klinken (1999) reports a mean C% of 34.8±8.8 for a suite of acceptable western-European collagen samples, while higher values of 41–47% were suggested by Ambrose (1990) and Sealy et al. (2014).

Of the analysed specimens, two are excluded from further analysis and discussion due to unacceptably low C/N ratios and distinctly anomalous C and/or N contents of collagen (Table 2). Two further specimens show decreased N and C contents. Their C% values are within the range reported by van Klinken (1999), but their N% values at 9.9 and 10.6% are just below the generally accepted 11% for fresh collagen. The slight-

ly decreased C and N contents of the collagen might suggest the presence of inorganic salt residues, e.g. NaCl from the chemical treatments, or perhaps moisture in these samples (Ambrose 1990; van Klinken 1999), which would not alter the C or N isotopic composition of the samples. Furthermore, the C/N ratios are characteristic for fresh collagen, giving no indication of extraneous contaminant C or N in the sample. Thus, considering that the N% values are just below the cut-off value, we include these samples in the dataset, but note that the quality of collagen extracted from these specimens is not quite as good as that of the other samples.

For the cattle bone and tooth samples passing the quality control explained above, the $\delta^{13}\text{C}$ values ranged from -22.5 to -21.1‰ (range=1.4‰, SD=0.4, mean=-21.7‰) and for the sheep -22.1 to -20.3‰ (range=1.8‰, SD=0.4‰, mean= -21.5‰) (Fig.2; Table 2). The $\delta^{15}\text{N}$ values ranged from 2.2 to 7.2‰ (range=5.0‰, SD=1.3‰, mean=4.7‰) for the cattle and 3.1

3A – Species	$\delta^{13}\text{C}\text{‰}$		$\delta^{15}\text{N}\text{‰}$	
	Mean	SEM	Mean	SEM
Cattle	-21.7	0.07	4.4	0.27
Sheep	-21.4	0.09	5.1	0.33
Difference	0.3		0.7	
p-value for the difference	0.011		0.107	

Table 3. Comparisons of model-based estimates of the means of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for species (A) and time periods (B) in the bone data used for statistical analysis.

SEM – Standard error of mean

3B – Time period	$\delta^{13}\text{C}\text{‰}$			$\delta^{15}\text{N}\text{‰}$		
	Mean	SEM		Mean	SEM	
	Medieval		Post-medieval	Medieval		Post-medieval
	Difference			Difference		
		p-value for the difference			p-value for the difference	
Iron Age	-21.3	0.5	0.3	4.2	-1.5	-0.03
	0.10	0.0004	0.095	0.34	0.004	0.953
Medieval	-21.8			5.7		
	0.08			0.28		
Post-medieval	-21.6	-0.2		4.1	1.5	
	0.12	0.097		0.44	0.009	

SEM – Standard error of mean

to 8.6‰ (range=5.5‰, SD=1.4‰, mean=5.9‰) for the sheep (Fig. 2; Table 2). The scatter plot of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values is depicted in Fig. 2. Even though there was a difference in $\delta^{15}\text{N}$ values between sheep and cattle, most of the samples clustered together in the scatter plot except for the sheep sample from Pasvik in northern Norway (OaPas1), that was an outlier showing higher $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ than the other samples.

In the $\delta^{13}\text{C}$ data (bone samples), there was evidence of statistically significant differences in the mean estimates between the species ($F_{1,26}=7.59$; $P=0.011$) and among the time periods ($F_{2,26}=8.28$; $P=0.002$). However, there was no evidence of a species-time period interaction effect ($F_{2,26}=2.24$; $P=0.126$) indicating that the observed differences in species-specific temporal patterns could be due to sampling variation. The statistical significances of the differences between the model-based estimates of the means explored through t-tests under the used model are presented in Table 3. There was a statistically significant ($p<0.05$) difference in the $\delta^{13}\text{C}$ estimates between sheep and cattle (sheep showed a higher estimate for $\delta^{13}\text{C}$ than cattle). The prehistoric bone sample showed higher $\delta^{13}\text{C}$ values than the younger bones (Iron Age vs medieval difference $p<0.001$) and the $\delta^{13}\text{C}$ estimates between the prehistoric and medieval periods differed significantly ($p<0.001$).

In the $\delta^{15}\text{N}$ data, there was a statistically significant difference among the time periods ($F_{2,26}=6.92$; $P=0.004$). The F-test under the present model gave for the species $F_{1,26}=2.78$ ($P=0.107$). Again the species-time period interaction effect, that is the pattern in temporal changes between the two species, was not statistically significant ($F_{2,26}=1.31$; $P=0.288$). Moreover in the $\delta^{15}\text{N}$ data, a statistically significant difference between the prehistoric and medieval periods ($P=0.004$) as well as between the medieval and post-medieval periods ($P=0.009$) was found (Table 3).

DISCUSSION

The results of this study offer insights to changing feeding practices of sheep and cattle in Finland during the prehistoric and historical periods. In general, the present $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values from the Finnish cattle and sheep bones

are comparable with the results from the other Nordic countries, Sweden and Denmark (e.g. Noe-Nygaard et al. 2005). In Swedish Öland, values for Neolithic cattle and sheep/goat ranged between -22.5‰ and -19.8‰ for carbon, and between 4.4‰ and 9.1‰ for nitrogen (Eriksson et al. 2008). Our material included one outlier: a sheep from Pasvik in Norway. The sheep was associated with higher $\delta^{13}\text{C}$ (-20.3‰) and $\delta^{15}\text{N}$ (8.6‰) values, differing from the Finnish values but being within the range found in the Öland sample (Eriksson et al. 2008). The higher $\delta^{13}\text{C}$ value for the Pasvik sample could relate to a seaweed component in the fodder (Balasse et al. 2005), or alternatively reflect increased levels of plant $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ due to salinity stress or marine aerosols (e.g. Heaton 1987; Brugnoli & Lauteri 1991; Ivlev et al. 2013). The Brodtkorbneset site, from where the sheep bone was found, is located almost 100 km from the Arctic Ocean, but the settlement likely belonged to a mobile group, possibly with a summertime connection to the Arctic Ocean shore (Hedman & Olsen 2009). Thus, influence in the form of seaweed or coastal fodder might offer a logical explanation for the high isotopic values in the Pasvik case. The average $\delta^{13}\text{C}$ values of Finnish coastal (Turku, Naantali, Lieto, Loviisa, Nakkila, Kökar, Raisio) and inland (Pihtipudas, Parikkala, Sysmä, Mikkeli, Pälkäne, Vesilahti, Eura, Hämeenlinna) samples do not differ significantly (-21.6 and -21.8 respectively; Student's t-test, $p>0.05$). These values are as expected if the animals in question were feeding on terrestrial plants (Vogel 1978; O'Leary 1988) as the $\delta^{13}\text{C}$ values of seaweed are higher than those of terrestrial plants (Hansen et al. 2012; Ólafsson et al. 2013). Thus, seaweed seems not to be a significant component of the Finnish coastal animal's diet.

The $\delta^{13}\text{C}$ mean value is least negative in the prehistoric data and shows a temporally decreasing trend, inviting an explanation based on the well-known increase in the concentration (e.g. Robertson et al. 2001) and decrease of $\delta^{13}\text{C}$ values (Leuenberger 2007) of atmospheric CO_2 due to the burning of fossil fuels over the industrial period. However, the effect of these changes on plant $\delta^{13}\text{C}$ values (and thus, animals) are only observed after c 1800 (e.g. Heaton 1999) and therefore cannot explain the decrease in herbi-

vore $\delta^{13}\text{C}$ values at the time of the prehistoric/medieval transition. Thus we suggest an enhanced influence of plants grown in forests, i.e. the ‘canopy effect’, to account for the decrease in Finnish cattle and sheep $\delta^{13}\text{C}$ values.

The present $\delta^{13}\text{C}$ data are consistent with a scenario of changes in the land use and feeding practice. It appears that relatively more meadows and other open grasslands were available for cattle and sheep farming during the prehistoric time than in the medieval and post-medieval periods and the use of forest pastures and their importance as sources as winter fodder increased in the course of time. Due to the human population growth more animals, especially cattle, were needed to fertilize fields with their manure, as cereal cultivation was important for the society and human nutrition (Niemelä 2008: 82–3). Thereby less optimal land had to be utilized for pastures and collection of animal feed (Bläuer 2015: 55–8). The change from open pasture to woodland might have had a negative effect on cattle productivity. In a modern study, cattle fodder produced from willow (*Salix viminalis*) leaves was not considered suitable for lactating dairy cows due to its low digestibility (Smith et al. 2014). Moreover, woodland pasture required more active search for feed causing an increased need for energy and an increased risk for predators and accidents. The more intensive use of woodland is also reflected in the Finnish pollen data as increasing numbers of juniper pollen and decreasing numbers of tree pollen (Alenius et al. 2008; Alenius et al. 2014).

In addition to the temporal changes in mean $\delta^{13}\text{C}$ values, we found that the mean $\delta^{13}\text{C}$ estimate for sheep was slightly higher than that for cattle ($p < 0.05$). However, the higher values for sheep are according to our expectation. Historical sources indicate that cattle were typically summer pasturing in forests while sheep were kept in open landscapes on islands (Matti 1960: 427; Papunen 1996: 306). However, the expected more pronounced ‘canopy feeding effect’ for cattle was a weak signal at best, and this might be an indication of an annual balancing of seasonal diets. Cattle may have been pastured in more closed environments during the summer, while sheep were kept on more open island pastures, where available, but the winter feeding period may have balanced out the differences. During winter, the origin of feed from open and closed environments contrasted with the summer situation: winter feed largely comprised plants from the forest for sheep and from open fields for cattle (Soininen 1974). It could be expected that the isotopic compositions of the animals were dominated by the isotopic signals from winter feed: i.e. more closed woods for sheep (lower $\delta^{13}\text{C}$) and open fields for cattle (higher $\delta^{13}\text{C}$). The winter feeding period was longer (31–34 weeks) than that for the summer (18–21 weeks) season (Ström 1932: 12; Sähke 1963: 48). As an additional uncertainty, there are some indications of preferential bone remodelling during certain seasons, with a higher remodelling during the summer (Hillman et al. 1973; Calcagno 2011). Furthermore, any possible residual ‘canopy effect signal’ can easily

Fodder	Digestible protein (%)
Hay (<i>Aera</i> , <i>Agrostis</i> & <i>Phleum</i>)	2.5–3.0
Clover (<i>Trifolium</i>)	5.4–6.0
Water horsetail (<i>Equisetum fluviatile</i>)	4.4
Reed (<i>Phragmites communis</i>)	2.5
Straw: barley (<i>Hordeum vulgare</i>), oats (<i>Avena sativa</i>)	0.9–1
Dried leaves: birch (<i>Betula</i>), aspen (<i>Populus</i>), rowan (<i>Sorbus</i>), willow (<i>Salix</i>), and alder (<i>Alnus</i>)	c 4–6

Table 4. Proportion of protein in different types of fodder according to the early-20th-century data (source: Poijärvi 1927: 100–8).

be drowned out by noise produced by combining data from multiple localities covering a large geographical area and temporal variations in season lengths at the localities.

Temporal changes were also observed in the $\delta^{15}\text{N}$ values. These values were significantly higher in the medieval period compared with the earlier prehistoric period. The mean values in the prehistory and in the post-medieval period were approximately equal. High medieval $\delta^{15}\text{N}$ values could be related to fodder derived from cultivated soil or starvation, as discussed further below.

While the differences in mean $\delta^{13}\text{C}$ values between ancient cattle and sheep observed here are in agreement with the historical feeding practices in Finland, the mean $\delta^{15}\text{N}$ values of these two ruminant species do not unambiguously support expectations based on the known traditions. Our sheep bone samples are associated with a higher $\delta^{15}\text{N}$ arithmetic mean value (5.7‰) than that of the cattle bone samples (4.4‰), but this difference is not statistically significant (Table 3). This is contrary to the expectations for cattle winter diets being more based on cultivated fodder, which typically produces elevated $\delta^{15}\text{N}$ values compared with hay and fodder originating from natural meadows and pastures (Choi et al. 2003; Bateman & Kelly 2007; Bogaard et al. 2007). For example, straw, growing on worked and conventionally fertilized land, should exhibit higher $\delta^{15}\text{N}$ values than wild plants (Choi et al. 2003; Bol et al. 2005; Bogaard et al. 2007; 2013; Fraser et al. 2011). Thus, one can speculate that the amount of straw in the cattle diet was not high enough to alter the nitrogen isotope values and that wild plants were an important source of cattle fodder close to modern times. We suggest, however, that in addition to feeding practices and foraging biotopes, the patterns in isotopic values may reflect other causal factors, such as temporal and regional societal changes in land use, annual balancing of seasonal diets, species-specific differences in grazing traditions, species-specific differences in metabolism and nutritional stress (e.g. Bonafini et al. 2013; Zazzo et al. 2015).

One possible explanation for the opposite than expected difference in $\delta^{15}\text{N}$ values between cattle and sheep is related to metabolism and physiology that also can affect skeletal $\delta^{15}\text{N}$ val-

ues. Sponheimer et al. (2003) conducted a feeding study where cattle consistently displayed significantly lower $\delta^{15}\text{N}$ values than goats on controlled, identical diets. A lower species-specific enrichment of $\delta^{15}\text{N}$ in cattle compared to goats would act to suppress the expected difference between the species. Moreover, dairy cows lose nitrogen obtained from their diet in their milk (e.g. Hof et al. 1997). In Finland, sheep have not been traditionally milked (Bläuer 2015: 120). In previous studies of archaeological bone material, sheep $\delta^{15}\text{N}$ values were either higher or lower than cattle values (higher values: Müldner & Richards 2005; Dürrwächter et al. 2006; Honch et al. 2006; lower values: Bocherens et al. 2006; Hollund et al. 2010). However, the differences and the original input of nitrogen in the diet of these animals are not known. Different animal species may also react differently to the quality of the food and the nitrogen balance of an animal depends on protein nutrition (Hof et al. 1997). In the feeding study by Sponheimer et al. (2003), goats had higher $\delta^{15}\text{N}$ levels than cattle, both for high- and low-protein diets, though the difference was not as marked for low-protein feed. Another important implication of the study was that animals on high-protein diets had systematically higher $\delta^{15}\text{N}$ values than those feeding on lower protein feed, possibly relating to differences in excretion of nitrogen in urea and faeces (Sponheimer et al. 2003). During the winter feeding season sheep in Finland were fed with dry leaves, which are rich in protein compared with straw and hay (Table 4). Thus, one major factor affecting the sheep $\delta^{15}\text{N}$ values could have been the quality of the winter fodder, i.e. nitrogen content.

The nutritional status of an animal also affects on the isotope values. Elevated $\delta^{15}\text{N}$ values were recorded for example in animals under arid conditions (Heaton 1987; Sealy et al. 1987; Fizet et al. 1995). Water stress is not a plausible cause of systematically higher $\delta^{15}\text{N}$ values for sheep in Finland, but physiological or nutritional stress, such as starvation, could elevate $\delta^{15}\text{N}$ values (Sealy et al. 1987; Hobson et al. 1993; Gröcke et al. 1997; Finucane 2007). According to osteological studies the size of sheep diminishes in south-western Finland from the medieval to the post-medieval period, whereas the size of cattle remains the same (Tourunen 2008). This

coincides with medieval period sheep bones exhibiting the highest $\delta^{15}\text{N}$ values. High nutritional stress of the sheep during the medieval period could have led to a stunted growth and smaller individuals.

CONCLUSIONS

In this study we observed a temporal trend in carbon isotope values that is likely to reflect an increasing importance of forest-based fodder in the animal feeding during the historical period. We also observed between-species variation in nitrogen isotope values. Higher nitrogen isotope values in sheep bones might be caused by a combination of high-protein winter fodder (dried leaves) for sheep and deprivation of nitrogen in milking cows. Carbon and nitrogen isotope values are valuable tools for studies concerning animal feeding practises. However, isotope data from archaeological cattle and sheep bones are difficult to interpret solely using historical animal feeding data. It seems likely that the carbon and nitrogen isotope values are not only affected by the quality of the animal fodder but also by other factors, including the location of the site, starvation and possible differences in cattle and sheep metabolism as well as sampling strategy. The variability in the results is likely to reflect complex feeding systems, differences in feeding of cattle and sheep and annual variation in the rate of starvation and available fodder.

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